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Appendix I: Detailed Reviewer Comments and Principal Investigator Responses

Hybrid/Value Added Systems Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geothermal Power Generation and CO2 Capture Co-Production
Principal Investigator: Heldebrant, David. J.
Organization: PNNL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: Conventional coal powered electric generation with the addition of geothermal fluid heat balance modeling has been completed.
Existing coal generation sites have been identified for field demonstration.
The project is a relatively new project and needs to identify other plant/geothermal applications.
Previous literature research is required for this project

PI Response:

Thank you. We have conducted a preliminary literature analysis and have only identified studies that attempt to asses the boiler water preheating application. To date, no publications present any assessment of flow or heat requirements to power the Carbon Capture and Sequestration (CCS) infrastructure. Our study investigates the feasbility and cost analysis for this type of integration, which to our knowledge has not yet been demonstrated before. Another difference with any other prior art is that we are focused on a first of its kind cost analysis and full TEA.

Reviewer 23430

Score: 7.0

Comment: The research addresses the hybridization of geothermal power generation and carbon dioxide capture for coal power plants. This is a worthwhile subject, as the hybridization is expected to improve the energy efficiency of coal power plants, with the geothermal plant producing electricity with low-grade waste heat being used for the CCS regeneration, and with oil and gas refineries expected to realize similar benefits. The project is focused on a techno-economic assessment of the costs of hybridization, with consideration of potential integration strategies and site-specific analysis of a candidate power plant. . The techno-economic assessment performed is meaningful and sufficiently detailed, with consideration of the system as well as the components in the system. The conclusions are well supported. The progress is excellent and is well aligned with the intended timeline and budget.

PI Response:

Thank you.

Reviewer 23465

Score: 8.0

Comment: The opportunity for co-production of geothermal energy and process heat at a coal power plant CO2 capture (CC) may contribute to a substantial reduction in greenhouse gas (GHG) emissions, and increase the economic prospects of geothermal energy.

The hybridization of geothermal with a coal plant is an excellent opportunity to demonstrate CC technology. If successful in this application, this hybridization technology can be easily transferred to natural gas combined cycle (NGCC) turbine power plants, or other facilities that generate industrial-scale amounts of CO2.

The PI's have managed this project intelligently and made good decisions to narrow down project demonstration sites from 10 to four: Apache, Boardman, Hayden and North Valmy. Of these, North Valmy was selected as the best of the four. It is fortuitous that the "Hot Pot" thermal anomaly is located 1.5 to 2 miles from the North Valmy facility. It is premature at the moment to know what the geothermal potential of the "Hot Pots" geology. Reservoir modeling and geophysical testing will be required to determine if the geothermal resource is economically viable. However, this is an encouraging prospective area. Further GTO project funding is recommended, especially for the geotechnical characterization of the area.

The economics for the development of this type of coal-geothermal hybridization with and without CC made sense. The PI's systematically assessed two scenarios, one with no CCS and the other with CCS using Aspen software based on NETL's Case 9 and 10 coal-fired power plants. The cost analysis for Case 9, no CCS, compared the use of boiler feedwater heating or an ORC unit using iso-butane as a working fluid and associated process equipment. Case 10, with CCS, compared boiler feedwater heating, with three different systems:

1) Partial MEA reboiler, BFW heating and 5,500 gpm geothermal fluid
2) Total MEA reboiler, BFW heating and 74K gpm geothermal fluid
3) Advanced CCS reboiler @80% efficiency, BFW heating with 10K gpm geothermal fluid

The geological data provided included flow rates from the Beowawe geothermal resource. The PI stated that if the per-well average flowrates of 1,200 gpm could be replicated at "Hot Pots" the proposed demonstration portion of the project could be justified. Here is where this Reviewer believes the comparison with Beowawe field and the geothermal potential at the "Hot Pots" is too optimistic. Where is the data?

The projected cost parameters and estimates for production and injection wells at North Valmy seem reasonable but this is hedging that the field is similar to the Beowawe field. This is an uncertain proposition. But, if the parameters turn out to be true, then the associated drilling costs may be comparable.

This type of methodology could be widely applied in California where there are numerous NGCC power plants located in low-temperature geothermal regions along the coast where oil and gas production occurs, and other geothermal regions in which NGCC power plants have been built such as in Imperial, Kern, San Bernardino, Lake, Sonoma, Nevada Counties. Many of these NGCC power plants have very favorable conditions including immediate proximity of transmission and distribution systems, load demand and access to water. However, the later may change in the near future and all of existing NGCC power plants along the California coast will be modified for air cooling and water cooling will be eliminated. This may be advantages given that cooling water supply costs will be essentially eliminated. Most of the

NGCC located along the California coast and western portion of the Los Angeles Basin would be affected by this new regulatory requirement.

When considering the tons of CO2 reduction, it makes sense to consider adopting a CCS to a NGCC. The CO2 reduction benefits will be viewed as politically favorable to decision makers and state regulatory agencies thereby facilitating the amendment of existing permits or modifying environmental impact reports.

The presentation itself identified the projected accomplishments, results and progress. The project appears to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule. Given the project's track record of meeting target development goals on time it is reasonable to assume that the accomplishments in comparison to costs are attainable. The achievements against planned goals and objectives, technical targets have been met.

PI Response:

We thank the reviewer for this well considered and thoughtful set of comments. Our current results support the idea of adapting this approach for use at other industrial facilities more widely collocated with geothermal resources, including the possibility for integration with natural gas-fired power production. We have proposed scope under the FY16 lab call to broaden the set of potential sites for analysis, and hope to complete an assessment early in the next fiscal year that will allow us to apply this approach to an NGCC, gas processing facility or refinery, all of which are well represented in California.

<u>Reviewer 25041</u>

Score: 9.0

Comment: This is a very technical techno-economic feasibility of a hybrid coal-geothermal power plant that marginalizes geothermal capital into large infrastructure.
Aspen Economic Analyzer is extensively used to provide cost estimate for different cases of No-CCS and With-CSS scenarios. Highly engineering analyses are provided.

North Valmy power plant was chosen as a real case study where there is a HOT POT geothermal resources can be used. They plan to provide site specific cost parameters and cost estimates.

The PIs plant to visit North Valmy to discuss with the site operators.

Very little geologic information is provided for the North Valmy site.

PI Response:

Because this project was scoped to investigate the specific applicability of this hybrid approach at coal-fired power facilities, the North Valmy site was selected because it represented an existing coal plant with a known hydrothermal resource (Hot Pot hot springs) on which a significant amount of seismic data had been developed under ARRA funding by Oski Energy. While we did present a portion of the seismic data interpretation, we did not go into great detail about the geology at the site, in part because very little exists apart from the Oski seismic data and some shallow gradient wells at the Hot Pot site. The field has not been developed and beyond the characterization presented by Oski (as cited in the slides and discussed briefly during the presentation and Q&A), there is very little to present. Nevertheless, the Hot Pot site, because of its proximity to the North Valmy coal plant, presents the best actual site at which to evaluate the potential for applying this hybrid approach at a coal-fired power facility. To that end, our analysis uses the best data available, including decades-old geothermometry data we were able to access because of conversations facilitated by GTO staff at the Denver review meeting. These data are being used to present a set of possible resource scenarios with associated ASPEN process modeling and cost analysis.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 8.0

Comment: The scientific and technical approach is adequate

PI Response:

Thank you.

Reviewer 23430

Score: 8.0

Comment: The approach involves (i) geothermal resource site mapping for identification of candidate plants that could benefit from geothermal resources, (ii) evaluation of candidate plants in terms of the energetic and economic impacts, and (iii) identification of other industries that could benefit from the technology. The approach is sound and its execution is highly satisfactory, with utilization of process flow diagrams and other resources, in addition to investigation of alternate unit operations. A visit to North Valmy (Nevada) site for on-site analysis is being scheduled. The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

Thank you.

Reviewer 23465

Score: 8.0

Comment: This project has achieved its objective of performing a techno-economic assessment of estimating the costs of hybridizing a geothermal resource with an existing coal fired power plant. The technical methods employed were well executed as the project work unfolded. The PI deployed the proper design criteria.

Candidate plants will be evaluated for energetic and economic, aspects for multiple units of operation.
It is understandable as to why the PIs considered targeting coal operating plants, after all these facilities emit higher amounts of CO2 than NGCC plants. However, there are more NGCC power plants and combined they emit more CO2 that the coal power plants.

PI Response:

Thank you. As noted in response to this reviewer's prior comment about NGCC, while we began with an initial interest in coal-fired power facilities, it has become clear over the course of this project that there may be a better geographic fit when coupling low-temperature geothermal resources with other types of facilities, including gas-fired generation, gas processing, refining and other industrial processes. In particular, we are interested in examining the possibility of using produced brine as a geothermal energy source for industrial facilities associated with oil and gas fields. The potential for co-production of geothermal energy from oil and gas brines for high temperature (> 150 ˚C) fluids via ORC has been previously evaluated, but the use of lower-temperature waters, which are far more widely available in U.S. oil and gas fields than those with temperatures suited to power generation, has not been as widely studied. This resource may offer a significant opportunity to improve efficiency at these facilities in the near-term, and in a carbon-constrained future, it could be used to reduce efficiency penalties associated with CO2 capture not just at NGCC plants but also at gas sweetening facilities and refineries.

<u>Reviewer 25041</u>

Score: 6.0

Comment: Engineering approach is good but at the time of presentation they had not even talked to the site operators of North Valmy.
This worries the reviewer as he thinks that a simple task like this should have been done in parallel to the analyses using the engineering simulation software like Aspen Economic Analyzer.

PI Response:

We agree that it would have been preferable to speak with the operators at North Valmy sooner. However, due to funding delays, we were still working to develop additional data on the geothermal resource at the Hot Pot site to develop a more realistic business case before sitting down with the plant operators. Also, as noted in the talk, efforts had been made to reach the operators of the North Valmy facility, but had been (and remained) unsuccessful. Because of the uncertainties associated with the Hot Pot resource, it is unlikely that any industrial facility, without significant Federal cost share, would invest in developing the Hot Pot field under the current policy and market environment. Nevertheless, we were able to find highly detailed data on the North Valmy facility and individual process elements to allow us to model it at a high level of resolution in ASPEN. Because of the lack of engagement from the plant and the forementioned uncertainty in the resource quality at Hot Pot, we have not pursued this as an industrial partnership for demonstration. While the technoeconomic analysis suggests a good match for hybrid use of geothermal fluids in a coal-fired power facility, the very narrow range of coal power plants for which this would be immediately demonstrable is quite small, but as noted above, we are eager to apply this approach to other industrial processes where there is likely to be a better match between the quality of the geothermal resource and the set of potential facilities that could employ a hybrid design like the one assessed at North Valmy.

STRENGTHS

<u>Reviewer 23412</u>

Score: Not scored

Comment: Heat balance and cost indices show positive applications

PI Response:

Thank you. We agree.

Reviewer 23430

Score: Not scored

Comment: The project addresses an important and worthwhile topic. The offsetting of the cost of carbon capture and sequestration is much needed and this project provides a method of doing so effectively. The project is progressing well, with adherence to the project objectives and work plan. Detailed attention has been given to the technical and economic considerations.

The technical accomplishments are highly adequate for this stage of the overall project. The project results suggest viability of the hybridization from the technical and economic viewpoints. The findings are expected to be technologically valuable to the geothermal industry and related oil and gas industries.

PI Response:

Thank you.

Reviewer 23465

Score: Not scored

Comment: Excellent team credentials.

PI Response:

Thank you.

Reviewer 25041

Score: Not scored

Comment: Strong analytical skills to use Aspen.

PI Response:

Thank you.

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: This is a new project and does not exhibit any weaknesses

PI Response:

Thank you.

Reviewer 23430

Score: Not scored

Comment: The remaining task of techno-economic analysis of the candidate site will be critically important for satisfactory completion of the project. The success of this task will depend on the extent of information that can be obtained concerning the site.

The progress in relation to manuscript preparation and presentations is not adequate.

Considerable work still needs to be performed during the remaining 4 months of the 2-year project.

PI Response:

We agree, and had hoped to have had a manuscript in press by mid-year. However, due to funding delays that resulted in a work stoppage through the end of the second quarter, we are behind schedule on the analysis that will be the basis for that manuscript. We are now on track and hope to complete our scope by the end of the calendar year.

Reviewer 23465

Score: Not scored

Comment: Where is the geothermal potential data for the "Hot Pot" area?

A major weakness of this proposed demonstration is the estimated 30% parasitic load. This is huge. A more detailed energy and mass balance should have been provided.

The costs, for both Case 9 and 10, did not provide engineering, design, materials, equipment were not factored into the analysis.

PI Response:

Geothermal resource data are estimated based in part on data provided by Oski Energy under their previous project for GTO to quantify the size of the reservoir using seismic data. We have also extrapolated flow rates from other projects producing from the Valmy formation, the same reservoir of interest at Hot Pot. Currently, based in part on feedback received during the review meeting in Denver, we are modeling cases that examine both a shallow, convective hydrothermal system and a deeper Valmy system to investigate the sensitivity of the overall efficiency gains and economics to the resource quality and depth.

We believe that the reviewer may have confused the parasitic load of the power plant adding CCS infrastructure with that of our geothermal integration. All coal-fired power plants that would have installed CCS infrastructure would lose approximately 30% of the net power to the coal plant. Thus the parasitic load to the coal plant is due to the introduction of CCS, not any power associated with the integration of geothermal units. The goal of our program is to try to offset some of this potential parasitic energy loss to improve the efficiency of coal plants with CCS, but also to demonstrate integration can also reduce the costs of stand-alone geothermal power units. We regret that the reviewer missed this nuance and that we didn't have the chance to address it during the Q&A, but hope this explanation clarifies our reference to the 30% parasitic load associated with adding CCS to the base plant configuration.

Reviewer 25041

Score: Not scored

Comment: Weak in geological information and understanding.

PI Response:

While we appreciate the reviewer's frustration, there is significant uncertainty associated with the geology at the site, given that no deep wells exist to allow more detailed characterization. The goal of this paper study is to approximate the geothermal resource based on existing data, which we have done, including an attempt to quantify the uncertainties associated with the quality and size of that resource. It should also be noted that a significant amount of funding was invested in shooting and evaluating seismic lines at the Hot Pot site under the Oski Energy project several years ago, so there has been previous interest in understanding this system. However, in the absence of intermediate or deep characterization wells that would allow for confirmation of the resource temperature and flow rate, much of this work was based on the assumptions used by Oski and extrapolation from data available for other projects in this geothermal reservoir. As noted in the talk, there are multiple cases under evaluation to allow for an examination of the range of potential costs and efficiency improvements possible given the uncertainty in the resource quality.

IMPROVEMENTS

Reviewer 23412

Comment: Literature search would be helpful

PI Response:

Thank you. The geologic characterization work has been heavily influenced by the literature and available datasets for the area, including well data. As we had mentioned in the previous comment above, a prior literature search for direct use revealed only geothermal integration for boiler water preheating, not power plants with CCS infrastructure that we present here in this study. All of this prior art will be dutifully cited in our forthcoming publication, but we emphasize our approach is novel in that no work has been done other than ours in the costing and flow requirements for geothermal integration to CCS infrastructure.

Reviewer 23430

Comment: For the remaining 4-month work, the 20% reduction in capital cost and the more than 20% gain in the net power efficiency will need to be substantiated.

An important remaining task relates to the preparation of manuscripts for publications, in addition to presentations. A plan for the manuscripts and presentations is not provided in the report. A tentative list of publication titles and publication venues would be helpful. Venues should include those related to the trade, technology and science. Presentations and manuscripts should be directed to the professionals as well as the general public.

PI Response:

We anticipate publication of the site-specific analysis in ChemSusChem or other specialized journals. We also propose to present this data at meetings geared toward the broader geoscience community (e.g., AGU, GSA, CCUS, GHGT) where we can disseminate the data into the community for a broader impact. To date, we have not presented this data as we preferred to have site-specific analysis done rather than the broad base hypothetical cases as we felt the more specific analysis demonstrates the true viability based on real data and less on assumptions.

Reviewer 23465

Comment: In this day and age of GHG emissions, it will be useful if the project provided an analysis of how many tonnes of CO2 can be systematically captured.

PI Response:

Thank you. We have been evaluating efficiency improvement associated with the use of low-temperature geothermal fluids, agnostic of offsetting use (e.g., increase net power to the grid, CO2 capture, retirement of less efficient train(s), etc.) but will document equivalent estimates associated with each of these potential uses for the cases considered, including costs.

Reviewer 25041

Comment: It is encouraged to work with a group of geologist together with engineers to move the project forward in a more comprehensive way.

PI Response:

Thank you. We are very proud of the integrative nature of this work. It shows in the review comments that some people appreciated the engineering-heavy approach of this while others would have preferred more discussion of the geology; our other talk on compressed air energy storage experienced a similar dichotomy in the review comments, with some finding less engineering discussion than they would like but others appreciating the deeper presentation of the subsurface science. It is encouraging that there were a few comments like this one that show that our colleagues value the integration across disciplines, even if they would have liked to see more of one than the other.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Integrating Compressed Air Energy Storage and Geothermal for Grid-Scale Renewables Integration
Principal Investigator: McGrail, Peter
Organization: PNNL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: This project is in early stages but has completed screening of heat balance and air injector/producer design. Air storage is only effective during on peak hours so the geothermal portion would also needed to be cycled, operational constraints need to be identified.

PI Response:

Air storage would actually occur during off-peak while energy production would occur during peak demand hours. One system design under analysis uses the geothermal resource to run a chiller system for interstage compressor cooling during storage and air reheating during the power production cycle. Hence, the geothermal resource is actually cycled considerably less than one might expect. We are also currently working on sensitivity analyses to address issues of utilization rate and system sizing on cost.

Reviewer 23430

Score: 7.0

Comment: The integration of compressed air energy storage and geothermal energy technology is novel and a worthwhile subject of investigation. This integration will enable broader deployment of intermittent renewable energy generation such as solar and wind. This will in turn decrease fossil fuel use and the associated carbon intensity. In addition, it will increase the stability of the electricity transmission system. The potential impact of the project is substantial. The scope of the project pertains to a techno-economic feasibility study of this hybrid technology, in addition to the production of publications that contain the findings.

Abandoned well bores are the primary locations for the compressed air energy storage. This may be feasible, though the quality of the abandoned steel casings in the wells and the availability of abandoned wells in the desired locations may limit the feasibility. On the other hand, the use of sedimentary reservoirs for the compressed air energy storage is found to be challenging.

Texas has been chosen for site down selection and evaluation, with multiple candidate sites identified. The results mainly relate to the site selection and the costs. The progress in relation to the techno-economic analysis is satisfactory.

PI Response:

We agree that there is considerable uncertainty associated with the reuse of steel casings as pressure storage vessels, and have submitted a proposal under the FY16 AOP call that will allow us to collaborate with Sandia National Laboratory's well integrity experts to develop a testing plan and stand up a field site to test this very issue using actual well completions. We also agree that the applicability of this technology could be significant, particularly as renewable portfolio standards and potential climate change policy increasingly incentivize the deployment of intermittent renewables such as wind. This will drive instability on the grid that currently is met using largely gas-fired peaking generation, and opportunities to provide grid stability using zero-emissions applications, such as this hybrid GT-CAES concept, will become increasingly attractive over time.

Reviewer 23465

Score: 5.0

Comment: This project is a case of situational uniqueness, that is, many factors have to line up for to make it possible. In Texas, there are probably a limited number of salt domes with the appropriate number or wells with the preferred casing properties to handle compressed air. Add to that the following considerations: land ownership, environmental regulations, wind resources and proximity of transmission and distribution system infrastructure. On top of that consideration has to be given to the sufficiency of geothermal and methane resources that are available for the short and long term duration. All of these factors will be improbable for success. If compressed air energy storage with geothermal energy technologies (GT-CAES) is not successful in Texas, it is unlikely it will be successful anywhere else. If that is the case, further GTO funding should be discontinued.

This project evaluated the feasibility of a GT-CAES system to enable broader deployment of intermittent renewable energy generation including wind and solar. For fiscal year 2015, this project focused on evaluating existing abandoned oil and gas wells for CAES purposes. Other tasks included the assessment of the use of high-and moderate-quality geothermal energy to cool compressors (through absorption/adsorption colling) and heating during turboexpansion of stored air would enable a novel, zero-emissions implementation of compressed air energy storage.

At first glance, this Reviewer disagreed with the PI’s findings to conduct the next stage of this research project in Texas but after further consideration of the geological formation and availability of infrastructure this Reviewer reversed his opinion and agrees that the Texas sedimentary looks like a slightly better location than the California oil fields using the identified criteria, which are reasonable. The criteria included proximity of geothermal resource to appropriate storage sites, nearness to market, available infrastructure, reasonable LCOE, etc. California geology is very complex and can be highly variable from well to well and that raised questions of viable economics for use of oil and gas wells. Data available of Texas sedimentary sequences appear to be well documented. The Texan transgressive-regressive sequences and deltaic sequences mentioned may work for CAES because such sequences commonly have portions that are highly porous, offering space for fluid storage and combined with other portions that are low porosity, offering confining layers. California oil fields are much more compartmentalized with faults, fissures and other geologic structural complexities. There are similar problems in the Texas Gulf sedimentary sequence but it's bigger. However, as the PIs pointed out, the overall regional structure in the Gulf is a downward tilting sequence that gets deeper as you get closer to the Coast, and that also is where some of the larger cities are associated infrastructure is located.

In the early project stages, the PI’s didn't find the DeWitt County site suitable, and this Reviewer tends to agree with this analysis based on what was mentioned. The Wilcox group is a bunch of sedimentary formations that largely formed in a deltaic environment and should be variable in character, and the most suitable geologic bodies may be limited in volume. These formations even without faults and bends and upfolds and downfolds -- structural crinkles in the formations are due to the downwarping appear to be an appropriate location for GT-CAES. The resulting sedimentary deposits may be significantly heterogeneous both laterally at some point in time and in three dimensions, as the deposits accumulate sediment and due to the migration of the Mississippi river and tributaries over geologic time.

The PI's analysis of the Brazoria County were found to be more promising composition of sandstone sequences, and presence of methane, however, the PI decided to look at the buried salt domes in the area instead. The salt domes would be more homogeneous. Other research has documented that the salt domes have been proposed for storage for various purposes including CAES and these are somewhat nearer to geothermal resources, infrastructure and markets.

The PI's technical and economic feasibility analysis of abandoned well casing types that are widely used in oil and gas operations is justifiable. The J-55 lower grade steel casing mentioned meets the appropriate criteria for tensile strength (55,000 psi) and resists corrosion. The higher strength P-110 (110,000 psi tensile strength) casing is higher grade steel is more expensive and is used in deeper wells but is less resistant to corrosion and not adequate for sulfide present environments. The PIs wisely choose casings to balance strength vs corrosion resistance. Using yield strength to model the casings' internal pressure resistance is a good conservative selection method.

This Reviewer believes that the criteria and conclusions are reasonable, and suspects that much of the salt domes are somewhat reasonable for an ideal site for the GT-CAES. The presence of the known geothermal resource at Pleasant Bayou, as well as a methane resource, is a plus. Adding thermal energy storage and methane combustion where methane is available will improve the cost-benefits, but there are a very limited number of sites where this might economically work.

The combination of desirable attributes of geology, cost, technical engineering issues, infrastructure, etc. plus the need for a reasonable co-location of geothermal with CAES may be limited but this may be the best location to explore the opportunities.

PI Response:

We thank this reviewer for their thoughtful consideration and very helpful comments. In particular, we are encouraged that the reviewer eventually agreed with the decision to select Texas for continued evaluation during the reservoir- and dome-based CAES investigation. The complexity of California geology, particularly in areas with known geothermal resources, and particularly given the seismogenic nature of many of the faults in the western part of the state, confounded our efforts to find a site with a suitable CAES reservoir and adequate data on the quality of the potential geothermal resource. Despite being a paper study, we believed that the feasibility of siting reservoir-based compressed air storage in areas with a high degree of reservoir compartmentalization was less preferable than looking to Texas.

It is also clear from this reviewer's comments that there was some confusion about the change in direction taken at the end of the study examining the DeWitt and Brazoria sites. We agree with the reviewer's comment that the reservoir-based CAES concept, when including a geothermal component, requires a set of site characteristics that is highly unique -- indeed, the uniqueness of the Brazoria site is the reason its economics are so appealing. In working through that portion of the analysis, it became clear to us that high quality geothermal resources are difficult to find collocated with shallower, large, thick sedimentary sequences suitable for CAES, severely limiting the applicability of the concept. However, driven by the appealing economics seen in previous studies, including the initial development of this concept for the Bonneville Power Administration and the analysis of the Brazoria site, and seeing manufacturers marketing surface pressure vessels for storage of compressed air, we began to look beyond sediemtnary reservoir- or dome-based air storage to consider the possibility that existing well casing could be developed at lower costs (LCOE) than these surface compression vessels, and could utilize geothermal energy to allow for zero-emissions grid balancing. (See response to previous comment.) This is the scope that is underway in FY15 and was presented after the DeWitt / Brazoria discussion. This may have been unclear to the reviewer because of a funding delay that resulted in the project team having only a couple weeks to work on this scope prior to the submittal of slides for the Denver review meeting.

The benefit of this well-based concept is that, unlike anticlines presenting thick, porous, permeable reservoir rocks, existing wellbores are nearly ubiquitous in some parts of the country, and are often present in areas with good geothermal resources, including decommissioned geothermal wells themselves. This greatly expands the opportunities to implement a geothermal-coupled CAES approach, and our preliminary analysis suggests that LCOEs may be within the same range as those evaluated for the reservoir-based GT-CAES at the Yakima Minerals site in Washington State ($0.10-$0.15/kWh). So, while we agree with the reviewer that there is a uniqueness factor at play in the siting of dome- or reservoir-based CAES with a geothermal component, the applicability of combining geothermal energy with this well-based comrpessed air storage approach appears to be much greater.

Reviewer 25041

Score: 8.0

Comment: They presented results after the first quarter into their project.
They indicated difficulties with sedimentary reservoirs for compressed air storage, analyzed a salt dome but now they are trying to down select a cased wellbore to conduct feasibility study as a storage site.

There was not a lot of description as to how to use geothermal heat to compress (for storage) and expand (for power generation) in the presentation. The reviewer wished to see more discussion on the power generation technology.

The project provides large-scale tool to enhance grid stabilization and continues to see the best type of reservoir considering a large number of abandoned oil/gas wells.

PI Response:

We regret that we weren't able to adequately address this reviewer's interest on how the CAES process uses geothermal energy. Because of the need to discuss both the reservoir-based CAES analysis completed in FY14 and the small amount of new scope completed during FY15, we limited discussion of the technology itself to a single slide, with citations in case reviewers wanted to know more, but it appears that additional detail on the load / generation cycle would have been valuable for this reviewer. Our ASPEN modeling uses geothermal heat to run ammonia chillers to provide interstage cooling during the air compression (load) cycle, and to preheat air prior to multistage turboexpansion during the power generation cycle. Because this results in low utilization of the geothermal resource during times when the well is shut-in (neither injecting or producing), several modeled configurations also include an ORC to improve geothermal well utilization rate and resulting LCOE. Using this approach at an existing geothermal production site where ORCs are already installed would improve the fractional LCOE for the CAES portion of the project by amortizing the cost of the geothermal well (capital and O&M) across multiple value streams, but because we wanted to evaluate the cost for CAES as a new project, these are all-in costs that assume no leveraging of existing ORC units.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 8.0

Comment: Scientific and technical approach are adequate

PI Response:

Thank you.

Reviewer 23430

Score: 7.0

Comment: The approach related to site selection and techno-economic feasibility study is sound and suitable for the objectives of the project. The tasks include geothermal and storage resource evaluation, energy storage market assessment, siting criteria development and site screening, and subsurface simulation. In spite of the well bore storage modeling, the feasibility of using steel casing of abandoned oil wells for the compressed air energy storage is questionable, due to the likely degradation of the casing. Without a reasonable degree of this feasibility, the development of optimal design configurations is not very meaningful. The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

We agree with the reviewer that the primary uncertainty associated with reuse of existing wells for rapidly cycled compressed air storage is the mechanical integrity of the well itself. In addition to the potential for degradation of casing, there are also potential impacts to the cement and casing-cement interface. While this is a concern, it is primarily one of cost (in terms of the lifetime of the redeveloped well), reversibility (if the well is to be used during a temporary period of non-production) and safety/permitting (if the well fails, will it do so catastrophically or simply lose its ability to retain air at pressures that favor continued economic use). To address these issues, we will be submitting a proposal under the current GTO AOP call to partner with SNL to do modeling, test design and field site development to try to better understand these issues (see also previous comments).

Reviewer 23465

Score: 7.0

Comment: The technical approach taken by the PIs is appropriate. The method employed is reasonable and logical. It is a practical application to address a significant technical challenge at the conceptual level of integrating CSP technology into an existing geothermal power plant. The technical tasks and deployment of those tasks are being executed in a pragmatic manner. The procedures engaged are proper.

PI Response:

Thank you.

Reviewer 25041

Score: 7.0

Comment: Scientific/Technical approach is well described; however, mechanisms for compression and expansion of air using geothermal heat needs to be explained better.

PI Response:

Thank you. Please see our response to the prior (and thematically similar) comment from this reviewer for a more detailed answer to this concern.

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: Heat balance and well design have been completed.

PI Response:

Thank you. The work on system design presented in Denver was based on a generic range of casings, and we have since undertaken site-specific analysis that includes designs based on actual well and geothermal resources at the site, based on available data.

Reviewer 23430

Score: Not scored

Comment: The concept is novel and the subject is worthy of study. If successful, the potential impact is significant. The reservoir simulations for estimating the storage capacity and the air injection and extraction rates for selected sites are useful. The site screening has been effectively performed. The personnel expertise is adequate. The progress in relation to the timeline is satisfactory.

PI Response:

Thank you.

Reviewer 23465

Score: Not scored

Comment: Strong team credentials

PI Response:

Thank you.

Reviewer 25041

Score: Not scored

Comment: Being careful with the final selection of the reservoir is appreciated.

Disused oil/gas wells are better characterized as reservoir but how do you assess which ones can actually be reopened and used to store compressed air.

PI Response:

Thank you. We have seen from experience on many industrial siting projects that prudent siting is often crucial to sucessful project development.

We share your concerns regarding well reuse for compressed air storage. The purpose of this paper study is to determine whether the economics are attractive enough to do proof-of-concept field testing. Based on work in Q3, it appears that the economics support a more in-depth investigation of the technical feasility of redeveloping wells for CAES. This is being proposed for investigation in FY16-18 by PNNL and SNL under the current AOP call.

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: Properties of saturated air need to be considered when expanding across the turbine.
Water issues and turbine performance need to be considered

PI Response:

We appreciate the reviewer's thoughtful comment, and agree. The ASPEN modeling allows us to do exactly this, as well as allowing for the incorporation of a dehydration step during the process.

Reviewer 23430

Score: Not scored

Comment: The feasibility of the proposed use of the steel casing in abandoned wells for compressed air energy storage is not sufficiently promising. In spite of the Phase 1 report and the ongoing journal manuscript preparation, the extent of results dissemination is not adequate.

PI Response:

We agree that dissemination of results from the well-based CAES phase of this work has been insufficient, but would like to call attention again to the lack of project funds available for primary analysis until only a few weeks before these slides were due. Based on this funding delay, we believe we are in good shape to complete a journal manuscript by the end of the period of performance, which has been revised to account for the gap in funding.

Regarding the lack of promise in the use of steel casing for compressed air storage, we believe this is related to this reviewer's previous comment about casing degradation. In addition to our response to that comment, it is also worth noting that the modeling presented at the review meeting (and used to date in our paper study) is based on API casing grade standards and material strength to reflect the theoretical capacities of the wells to withstand pressures consistent with CAES. It is possible that these theoretical capacities may not be able to be realized at field scales using real-world well completions. However, the degree of impact that this technology could have in both enabling geothermal resource utilization and providing grid stabilization amid increased deployment of intermittent resources, coupled with encouraging economics, suggests that it is worth additional testing and modeling to determine the extent to which the operational scenarios underlying them are feasible to implement in existing well casing. Realistically, it is unlikely that the concept will fail entirely at the field scale, but it may be that wells cannot withstand the maximum pressures used in the current analysis, requiring more wells at lower maximum pressure to store the same amount of air. This finding would be an economic issue, not a technical show-stopper, and bears investigation given the enormous amount of existing capital that could be leveraged using this technology.

<u>Reviewer 23465</u>

Score: Not scored

Comment: The proposed project did not provide an overall GT-CAES energy balance. On the surface, it appears that this type of system may use more energy that it produces.

The project did not adequately provide a discussion on the use of GT-CAES power generated for use as peaker power and for how long, or what percentage of the power generated by the GT facility would be used as transmission base power and not to operate the CAES.

No discussion was provided regarding the availability of geothermal, wind resources and methane resources.

PI Response:

In the slides and during discussion, we provided information on round-trip efficiencies for the GT-CAES systems evaluated in prior years, including configurations that included only the GT-CAES (46%), plus thermal energy storage (74%) and plus thermal energy storage and methane combustion (non-zero emissions, 96%). It was also acknowledged, as this reviewer pointed out in earlier comments, that the uniqueness of the Brazoria site's geothermal and methane resources, coupled with a salt dome for air storage, made a broader examination of the resources across all potential reservoir-based CAES sites a poor use of remaining funding.

The reviewer is correct in noting that we did not include a detailed discussion of geothermal, wind or methane resources. This was discussed briefly as part of the site screening slides, but 20 minutes was inadequate time to do justice to a nuanced presentation of these resources.

<u>Reviewer 25041</u>

Score: Not scored

Comment: No description as to how to evaluate usable and non-usable abandoned wells for storing compressed air.

PI Response:

Agreed. During the few weeks of work time we had on the well-based CAES portion of this scope, we focused on generic volume and pressure modeling of casing using API specs. This continues to be the approach used under this year's paper study. However, as noted in verbal responses during the Q&A and previous responses to comments in this document, we share the reviewers' concerns over the practicality and economics of reusing existing well casing for compressed air energy storage, including how to differentiate usable vs non-usable wells. This is beyond the scope of a paper study, and as such we have proposed new scope under the current GTO AOP call to partner with SNL and field a test site at which we can examine the impacts of rapid pressure loading and unloading on well construction and casing integrity.

IMPROVEMENTS

Reviewer 23412

Comment: No improvements were observed because of a new project

PI Response:

Thank you.

Reviewer 23430

Comment: More attention needs to be given to the feasibility of using the steel casing of abandoned wells for compressed air energy storage. This would require evaluation of the condition of the steel casing. Just assuming that the condition is adequate is not suitable.

More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public.

PI Response:

Thank you. As noted in previous responses, we agree with the concerns regarding casing reuse and hope to address these via site-specific analysis, numerical modeling, and field testing.

We are eager to write a manuscript on this work for publication in a journal and appreciate the reviewer's suggestion of also targeting a general audience. We will work with GTO and PNNL's external media relations team to make the public aware of this work as the analysis wraps up.

Reviewer 23465

Comment: Consider taking another look at California oil and gas fields, in particular, the multiple oil and gas fields in the Los Angeles and Kern County. The Los Angeles Basin has over 30,000 oil and gas wells, the majority of them have been capped, abandoned or retired. There are a series of large network of distribution systems and substations in all oil and gas fields. Also, the Los Angeles Basin is an excellent urban center for electrical demand.

Much oil and gas well information is available on-line at the Division of Oil and Gas, and Geothermal Resources website. http://www.conservation.ca.gov/dog/Online_Data/Pages/Index.aspx.

PI Response:

Thank you very much. Because of California's large and growing wind generation base, grid-scale balancing and integration offers a large potential market for energy storage concepts such as this. While the use of oil and gas wells is one option, California's oil and gas fields are rarely collocated with existing geothermal power production or low-cost geothermal development opportunities. Of nearer-term interest in California is the redevelopment of shut in or retiring geothermal wells in areas with still-productive wells in the vicinity. Also, we are interested in costing projects that use abandoned wells for air storage and near-marginal geothermal producers to investigate the potential as an additional value stream where it can derive incremental value from wells that would otherwise be shut in or abandoned.

Reviewer 25041

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Development of New Biphasic Metal Organic Working Fluids for Geothermal Systems
Principal Investigator: McGrail, Pete
Organization: PNNL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: The impact of this research could be huge if it will work. The accomplishments that it works in the liquid phase but might to work in the vapor phase when expanded across a turbine. The precipitation on the tube walls could reduce that heat transfer negating the effectiveness of the increased thermal properties of the working fluid.

PI Response:

We concur and are working hard towards solutions that will ensure nanoparticle deposition does not occur. Evidence to date strongly suggests that the heat exchanger and specifically the point where the transition to superheated vapor occurs is the only point in the ORC cycle where particle deposition occurs.

Reviewer 23430

Score: 7.0

Comment: The use of metal organic heat carrier nanofluids is novel and worthy of research. If successful, the project may provide a technology that can boost turbine output and allow the reduction of the size of heat exchangers and condenser components. The subject is rich in science, but the risk is high. The high risk relates to (i) the inadequate scientific understanding, (ii) how well the metal organic particles may be able to compete with other nanoparticles, and (iii) how well the particles can be suspended in the vaporized liquid. In spite of these issues, the accomplishments are substantial in terms of showing a degree of feasibility of this material technology for the intended application. The work has included material preparation, material characterization and application-oriented testing.

PI Response:

We don't disagree that the technical risk on this project is high but of course that space is precisely where national laboratories are intended to operate.

Reviewer 23465

Score: 9.0

Comment: The purpose of this project was to synthesize a mixture of stable, well-dispersed nanoparticles of superfluorophilic (metal organic heat carriers ((MOHCs)) with a fluorochemical refrigerant with to superior heat capacity and thermal conductivity properties for improved thermal efficiency in an ORC cycle.

This research project, if successful, can be an important technological incremental improvement for binary ORC power plants or other related industrial processes that utilize a similar working fluid.

If the reported research results of 5% cycle efficiency improvement are achieved at the microturbine testing level, this could trigger a quick adoption of MOHCs by just the geothermal community and perhaps by the HVAC (refrigeration) industry. It is this Reviewer's opinion that this is exactly the type of research the DOE GTO should be funding.

Overall project productivity appears to be positive for fiscal year 2014. The PI reported to have successfully synthesized MOHCs that have exceeded performance expectation including mass loading and binding energies with working fluids and obtained the expected results. Based on past work and progress achieved in reaching specified technical goals/targets there is a very strong likelihood that the project will achieve the microturbine test research results for remainder of 2015. The PI has done a commendable job in managing this project despite of the high degree of difficulty. The project has progressed according to the identified milestones and performed within budget.

PI Response:

We appreciate the reviewers comments and will continue to focus on solving the particle deposition issue and complete remaining project scope on time and within budget.

<u>Reviewer 25041</u>

Score: 10.0

Comment: Introducing nano metal organic heat carrier into geothermal field is excellent.

There are many operating parameters that will be fine-tuned to maintain stable dispersion of MOHC. This is a large budget project and in order not to waste the findings DOE should consider keep funding until desired results are obtained.

Challenges are well described. Agglomeration, deposit, interfacing with system components are all challenging issues in handling nano-particles.

PI Response:

We concur and will continue to address these issues through the remainder of the project performance period.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23412</u>

Score: 9.0

Comment: The scientific approach is impressive

PI Response:

Reviewer 23430

Score: 6.0

Comment: The approach involves the use of novel metal organic nanoparticles to form nanofluids that exhibit improved heat transfer characteristics for achieving improved efficiency in an organic Rankine cycle. The approach involves material development and cycle performance testing. .The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

Reviewer 23465

Score: 8.0

Comment: The technical approach undertaken by the PIs is appropriate. The methods employed were based on good science and technical soundness. This is a practical problem that has been investigated for decades. The technical tasks and deployment of those tasks are being executed in a pragmatic manner. The procedures engaged are proper.

PI Response:

Reviewer 25041

Score: 9.0

Comment: Synthesis of nano-particles.
Handling of nano-particles and processes are well described.

Good understanding of particle behavior from this project under more sever environment will impact the nano-particle field in general.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: The investigators are honest with their results.
It is a strength when the project shows objective results for DOE if the research works or doesn't.

PI Response:

Reviewer 23430

Score: Not scored

Comment: The material concept is novel and is promising for the intended application. The project includes the preparation of the novel nanoparticles, the preparation of the nanofluids and testing of the nanofluids in terms of the cycle performance. The approach is sound and the results are promising and meaningful.

PI Response:

Reviewer 23465

Score: Not scored

Comment: Excellent project team credentials.

Subcontracts with EthnosGen, LLC, and University of Padova.

PI Response:

Reviewer 25041

Score: Not scored

Comment: Well-designed procedure for investigating behavior of nano-particle.

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23430

Score: Not scored

Comment: The absence of comparative performance testing data between the novel nanofluid and competing nanofluids is a serious weakness. Comparison relative to the base liquid alone is not adequate. Furthermore, the basic properties of the nanofluid in terms of the thermal conductivity and the rheology should be characterized.

PI Response:

We strongly disagree. The purpose here is to introduce the nanoparticles into a standard ORC system and obtain the performance improvement with minimal or no changes to the system, including the base working fluid. Consequently, the directly relevant comparison is between the base working and the amended nanofluid. Comparing among various types of nanofluids may be worthy R&D but definitely not on target in terms of meeting the objective of this project. We have measured both rheological and thermal conductivity properties of our MOHC nanofluids. Space and time limitations for the presentation were the only reason these data were not discussed. MOHC additions have shown <0.1% change in viscosity of the base fluid, essentially within experimental error.

Reviewer 23465

Score: Not scored

Comment: No discussion was provided on what role pH plays into the chemical binding.

What work was subcontracted out to EthnosGen and University of Padova?

PI Response:

pH of course only applies to water and does not play a role in the selected materials because the adsorption is occurring with water molecules and not H+ ions. No work was subcontracted. EthosGen is interested in this technology for application in an ORC system they are developing. A student from the University of Padova completed her Master's thesis work under an internship at PNNL.

Reviewer 25041

Score: Not scored

Comment: None

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: Please find a nano particle that will perform in two phases and not precipitate on the tube walls.

PI Response:

We are working very hard on this issue and are testing a couple of promising approaches.

Reviewer 23430

Comment: Increased attention on the materials science and the comparative performance evaluation is recommended. The extension of the work from non-aqueous fluids to aqueous fluids is challenging, but is important. Work is also recommended for providing decrease in the required amount of surfactant in the nanofluids. The durability of the nanofluids under the application conditions also needs attention .More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public.

PI Response:

The use of surfactants is common by nanofluid researchers but the PI wants to emphasize again that no surfactants of any kind were added to our working fluids. Completely stable dispersions of MOHCs in water were obtained with no additives. We don't understand the comment on results dissemination. A comprehensive list of publications and presentations generated by this project was provided in the Project Summary.

Reviewer 23465

Comment: A very important aspect of this project that was not discussed is how MOHC's will react with power plant equipment such as turbines, condensers, pumps composed of dissimilar metals.

Will MOHCs have a corrosive or erosive effect on equipment because it is a much larger compound than a R245 working fluid for example?

While project material mentioned stabilizing ligands, they were not identified nor were there any discussion on what amounts or concentrations were needed.

What are the estimated costs of producing the selected MOHC? Is it toxic, ignitable, corrosive or reactive? What materials will be susceptible to galvanic effects? What materials will it reactive with? If there is an industrial accident and the fluid is spilled what are its acute and chronic toxicity levels? What are its environmental effects?

What is the cyclic life of a MOHC before it degrades to a point where it will no longer be effective in improving the thermal conductivity or coefficient of thermal conductivity?

A discussion or diagrams of the binding mechanics at the molecular level would have been useful.

PI Response:

MOHCs have no reactivity towards metals. The metal centers in the materials are coordinated with an organic ligand and so not free to bind or interact galvanically with another metal. Erosion is something we intend to address in our test plan but does require that we solve the particle plateout problem first. Capping agents were used to control the size of the MOHC during synthesis. These are disclosed in papers listed in our Project Summary.

MOHCs are not flammable, corrosive, or reactive. They decompose to a metal oxide, CO2, and water if burned. MOHCs are not toxic and similar materials are being studied for use in delivering cancer drugs in vivo for example. Cost estimates for producing the MOHCs were given in the slide set and in our paper published in NanoEnergy.

<u>Reviewer 25041</u>

Comment: Laminar vs Turbulent flow on agglomeration and deposit should be better understood.

PI Response:

We are working on this. Testing is currently being extended into the fully turbulent flow regime.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Forward Osmosis Purification of Co-Produced Water
Principal Investigator: Mines, Greg
Organization: INL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: The reuse of produced waters is important until it is mandated the O&G operators are still going to opt for the lowest cost solution.
The project is a new start. Being a new start the project has identified prototype apparatus fluids.
The project is planning in next steps to test prototype system.
This project needs to identify an approximate to commercialization

PI Response:

Reviewer 23430

Score: 7.0

Comment: This project is directed at validating the technical feasibility of purifying co-produced fluids from oil and gas operations using a switchable-polarity-solvent forward-osmosis process, in which the energy content of the co-produced fluids is sufficient to operate the process. If successful, this technology will provide a cost-effective method of treating produced water and, in addition, will reduce the volume of wastewater that requires disposal. The key challenges include (i) establishing the membrane fluxes and the rates at which the reactions producing the change in solvent polarity occur, and (ii) the ultimate separation of the product water and solvent. The accomplishments include (I) the development of models of the individual process operations, (ii) the identification of equipment and process conditions, and (iii) the completion of a feasibility study involving the application of the technology to the treatment of NaCl feed streams.. The feasibility study shows that the amount of water that can be recovered decreases as the feed stream salinity increases. It further shows that the temperatures ranging from 100 to 120 C are adequate. An additional accomplishment relates to the initial design of a degasser for lab scale testing. The results are encouraging.

PI Response:

<u>Reviewer 23465</u>

Score: 7.0

Comment: For fiscal year 2014, this project achieved the stated accomplishments and obtained the expected results. Based on work underway and progress made in reaching the identified technical goals/targets, there is a very high likelihood that this project will achieve the research results for 2015. The project has progressed in accord with the timetable and arrived at the acknowledged milestones within budget. The use of forward osmosis (FO) for treating thermal waste waters from oil and gas production is an area that should be encouraged by the DOE through continued financial and technical assistance.

The purpose of this project is to validate the technical feasibility of purifying co-produced fluids from oil and gas operations using a switchable polarity solvent forward osmosis (SPS-FO) process. The PIs postulated that the energy (low temperature) content of the co-produced fluids from oil and gas fields are sufficient to operate the FO process even without an ORC. The SPS-FO process uses a forward osmosis (FO) membrane technology to separate water from the incoming brine stream. This technology employs a hydrophobic or hydrophilic draw solution and is regenerated using low-grade thermal energy input in the range of 60°- 80°C. The required thermal energy could be provided by the one of the following examples: 1) Working fluids or geothermal brines used at an ORC power plant; or, 2) Geothermal fluids that do not have sufficient temperature for use in an ORC but can be deployed for a FO process.

There are abundant possible locations to demonstrate the economic viability of (SPS-FO) technology in mature or abandoned oil field wells where coproduced wastewaters contain sufficient energy to maintain the required chemical potential. SPS-FO technology could significantly reduce waste water disposal costs. As presented, there are several essential components to this project. First, is the selective membrane; second, is the effectiveness of the switchable polarity solvents; third, is the gas contactor, and fourth, is the CO2 degasser.

The opportunity to incorporate a SPS-FO system on a binary power plant will enhance the payback economics. In many oil and gas reservoirs, there also exists a tremendous potential to produce electricity from co-produced wastewaters by means of a small-scale ORC binary power plant. Power generation from coproduced fluids using a binary-cycle power plant are underway at the Rocky Mountain Oilfield Testing Center in Wyoming, Texas, Louisiana, Florida, and Arkansas. The 2006 MIT report on the future of geothermal energy estimated that between California, Oklahoma, and six other states along the Gulf Coast over 11,000 MW could be generated from coproduced fluids which would double the world's current geothermal capacity. A more conservative estimate predicts at least 2,000 MW from these states. While Gulf Coast states receive much attention for potential coproduction application California is another promising area for development, particularly in the Los Angeles (LA) basin.

The LA basin is home to many giant oilfields, and although currently there is no electricity generated from coproduced fluids in California, a study by Sanyal et al. 1993, suggested that the oil and gas fields in the LA basin have a promising geothermal gradient of 36C/km (2.0F/100 ft) while data collected by the DOGGR for 2009 reveals a 97% water cut for production in Los Angeles County oilfields. In some oil fields coproduced waters temperatures range between 100C and 180C. The combination of a favorable geothermal gradient and large volume of water produced is promising for electrical generation. Improvements in binary power plant working fluid properties are ideal for exploiting moderate temperature resources.

The LA basin has a decent geothermal gradient of 33C/km and over 30% of its reservoirs reach to at least 1,800 meters. Extrapolating these depths to temperature estimates may reach 80ºC. The LA basin has had a long history of water flooding and steam flooding. The LA basin is attractive because of its proximity to urban centers. The oilfields in the region are intermingled with the city and have immediate access to the electrical grid infrastructure.

Out of the 365 actively producing oil fields in the Los Angeles basin, 189 had initial coproduced wastewater temperature data and a geothermal gradient of approximately 33ºC/km (2.0ºF/100ft). Of the 189 reservoirs with initial temperature data, 21 (11%) recorded temperatures exceeding 100ºC and 60 (32%) recorded temperatures above 80ºC. Reservoirs with depths exceeding 2,500 meters account for 12% of all the reservoirs which, by following the geothermal gradient, can indicate temperatures exceeding 100?C. Reservoirs with depths exceeding 1,800 meters account for 33% of all reservoirs which, again by following the geothermal gradient, can indicate temperatures exceeding 80?C. Temperature and production data from oilfields in the Los Angeles basin are available from the State of California, Division of Oil, Gas and Geothermal Resources (DOGGR) databases.

All of the abovementioned LA Basin oil and gas fields would be prime candidate locations for a demonstration-scale SPS-FO technology.

PI Response:

The information on the potential application of the technology in CA will be considered when selecting a site for the field testing of the prototype unit.

<u>Reviewer 25041</u>

Score: 9.0

Comment: The project predicts to recover as much as 90% of water produced from oil/gas operation by introducing the proposed purification technique.
If this is done, it has a huge impact in oil/gas/geothermal industry.

Testing gas contactor and degasser is well explained and despite funding intermittency, the project is moving fine.

Aspen model describes system process and estimates reasonable water recovery and energy requirements.

For FY15 experimental campaign is well explained.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23412</u>

Score: 8.0

Comment: Scientific and technical approach is adequate. This project needs to be more firm on where the low temperature fluids will be used in the process

PI Response:

The low temperature fluids will be used as the heat source for driving the chemical reaction to 'degas' the draw solution and change its polarity allowing the water and solvent to be separated. In subsequent reports/papers/presentations we will make sure that how and where the low temperature geothermal fluids will be utilized is clearly defined.

Reviewer 23430

Score: 8.0

Comment: The approach is sound, involving process modeling and lab-scale testing for the purpose of identifying equipment and process conditions and selecting and designing equipment. If the lab-scale demonstration is successful, field testing will be conducted after the end of this project. The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources. Thus, the results are adequate in providing an initial assessment of feasibility of the proposed technology.

PI Response:

Reviewer 23465

Score: 5.0

Comment: The technical approach taken by the PIs is appropriate. The method employed is reasonable and logical. It is a practical application to address a technical challenge to produce potable water or water for industrial use. The technical tasks and deployment of those tasks are being executed in a pragmatic manner. The procedures engaged are proper.

PI Response:

Reviewer 25041

Score: 9.0

Comment: This project is innovative and impactful in its scientific approach and we should expect significant impact in water recovery from oil/gas wells if the scale up is successful.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: The strengths of this project is that knows that co-produced waters can have high levels of TDS and TSS and identifies the challenge

PI Response:

Reviewer 23430

Score: Not scored

Comment: The subject is worthy of investigation. If successful, the project can have a positive impact on geothermal development and deployment. The approach is sound and appropriate. The results are promising, as supported by modeling and experimental results.

PI Response:

Reviewer 23465

Score: Not scored

Comment: Excellent team credentials.

Not a complicated technology and can be applied in many locations.

Minimal investment costs.

PI Response:

Reviewer 25041

Score: Not scored

Comment: Solid technical understanding of solvents and quantitative studies of mass transfer.

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: This project being a new project it is hard to identify weaknesses

PI Response:

Reviewer 23430

Score: Not scored

Comment: Comparison of the proposed method with competing methods should be conducted in terms of performance and cost. The decrease of the amount of water that can be recovered as the feed stream salinity increases is an issue that should be addressed. The temperature requirement for the process should be decreased from 100-120 C to 60-80 C.

PI Response:

The volume of available water before precipitation of dissolved solids declines as a solution becomes concentrated. The precipitation of dissolved solids is a limiting threshold for nearly all water treatment technologies; removing more water usually requires a crystallization system of some sort. In our discussions we do not usually normalize our volumes to available because we want to show the impact on a feed stream volume. If we normalized there would be very little decline in the removal of available water with increasing concentration.
We will continue to explore the potential to utilize geothermal fluids with temperatures less than 100C. At this point lower temperature fluids could be utilized to provide some, but not all the thermal energy needed.

Reviewer 23465

Score: Not scored

Comment: In the next phase consider providing any information on resultant water quality total dissolved solids.

Provide a list of demonstration sites.

A diagram providing an energy balance analysis should have been included.

PI Response:

The quality of the treated product water is part of the planned testing to be done prior to field deployment. The potenital sites for demonstrating the technology will be identified during the coming year as testing is completed that is needed to establish the characteristics needed at the demonstration site to show technical viability. A more thorough presentation of the system energy balance will be provided in subsequent papers and presentaitons to the public. The energy requirements have been provided to the DOE in progress reports that have been submitted.

Reviewer 25041

Score: Not scored

Comment: None to be mentioned.

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: Improvements could be more direct where low temperature geothermal fluids will be used in the process.

PI Response:

Reviewer 23430

Comment: The data gaps in relation to the solvent thermophysical properties and reaction kinetics data need to be addressed to enhance the rigor of the work. The design of the degasser needs to be completed. More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public. Extension of the work from NaCl to other constituents in the feed stream should be made. More effort should be given to results dissemination in written and oral means, with the targeted audience including professionals and the general public.

PI Response:

We recognize that gaps exist in the thermophysical properties and reaction kinetics, and will perform additional testing to obtain specific data when ongoing testing does not adequately provide sufficient information.

Reviewer 23465

Comment: Provide more information on selected membranes.

PI Response:

We are using a commerical membrane. We can identify the manufacturer, but can not provide information beyond what the manufacturer provides.

Reviewer 25041

Comment: Connection between bench top experimental results to field scale implementation.

What are the challenges?

PI Response:

The challenges include 1) how much pretreating of the feed stream is necessary; 2) the adequacy of the thermophysical properties and reaction kinetic data to allow for adequate sizing of components; 3) will membrane flux be sustained over an extended period; 4) finalizing a 'degasser' design that is based on commerically available equipment; 5) complete (or nearly complete) separation of water and solvent in order to minimize the need to makeup solvent and to meet standards for water quality.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Freeform Heat Exchangers for Binary Geothermal Power Plants
Principal Investigator: Sabau, Adrian
Organization: ORNL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: This research is investigating new materials and geometries for heat exchangers. Testing to date includes corrosion testing, pressure drop measurements of several materials and geometries

PI Response:

Reviewer 23430

Score: 7.0

Comment: Heat exchangers are critical for geothermal technology. The development of better heat exchangers has the potential to impact the geothermal field broadly. The objectives relate to the development of compact and efficient heat exchangers for geothermal power plants. The specific target for the overall heat transfer coefficient is 140 W/m2.K. There is considerable room for the improvement of heat exchangers, with consideration of materials selection, fabrication method, geometry and fluid mechanics. This project addresses the possible avenues of heat exchanger improvement quite broadly, with considerable rigor and up-to-date knowledge involved in the work associated with each avenue. The results include multi-scale evaporator architectures and subcomponent fabrication using additive manufacturing. The accomplishments relate to a heat exchanger with a novel bifurcating concept and a heat exchanger with triangular cross-sectional pipes. The progress is satisfactory.

PI Response:

Reviewer 23465

Score: 7.0

Comment: On the surface this project appeared to be unclear of what its intent was because from this Reviewer's perspective this project could have very easily been separated into three or more research projects. This project had five technical tasks. The three significant tasks were the following:
1. Working fluid selection
2. Fabricate bifurcating HX

3. Carbon foam Ti-HXs
- Triangular flow
- Square cross flow

Much CDF, time and money could be spent on each proposed heat exchanger (HX) design, and associated manufacturing techniques, and materials selection. Granted this is an innovative project with several moving parts, so to speak, with interesting HX geometries, and novel fabrication processes, and these research areas should be pursued.

The project proposes to develop novel HXs designs for geothermal applications. However, it is unclear from the project material provided which of the proposed HXs geometries or designs would be used as an evaporative HX or as a condensing HX. The same design parameters will not work for both applications. The project should have been described as the development of a novel HX either as an evaporating HX or as a condensing HX for use in small power generation packages such as those that are currently marketed by ElectraTherm.

It is this Reviewer's opinion that using any of the proposed HX concepts as an evaporating HX is unlikely to be successful. It is, however, highly likely that the any of the proposed HXs concepts can be successfully deployed on any of ElectraThem's power plant package units as a condenser application. If successfully integrated, the chosen novel design could improve the overall thermodynamic efficiency of their units. It is unclear if the proposed novel HX designs will result in any space reduction for packaged ElectraTherm units.

This Reviewer has serious concerns about this project being deployed as an evaporative HX. There is no question that the proposed HX designs will scale at whatever geothermal location is chosen. Scaling rate will be highly dependent on brine characteristics and HX material composition.

The overall conclusions and progress made in achieving the intended project goals for FY 2014. However, this Reviewer is less supportive of the proposed work for FY 2015. While ElectraTherm is a reputable organization with years of experience in the small-scale (< 1.1 kWe) ORC power market, and could be a beneficiary of the current research, it is difficult to envision that they would incorporate these type of novel HXs into their customized power plant packages, simply because geothermal brines are notoriously known to scale just about any HX on the market.

There are several factors that will initiate scaling even before the brine reaches the HX. These factors may include, but not limited to, the following:

1. Brine characteristics: composition of total dissolved solids (TDS) in the brine.
2. Affinity of TDS to precipitate out including pH, and changes in pressure and temperature. This may vary from well to well.
3. Brine conditions: Two-phase flow, liquid and gas
4. Distance the brine is pumped from the production well to HX
5. Pipeline temperature loses due to distance from wellhead, number of bends and internal roughness
6. Changes in pipeline diameter
7. Turbidity influenced by Reynolds number

After examining the proposed HXs designs, this Reviewer concludes that some of the abovementioned scaling factors will affect HX performance acting as an evaporator (assuming steady state conditions) including the following:

1) HX geometry
2) HX interior roughness
3) Pressure drop
4) Brine residence time
5) Heat transfer rate
6) Brine residence time, for optimum heat transfer from brine to working fluid.

7) Brine conditions, two-phase flow
8) Changing boundary layer conditions
9) Amount and rate of scaling
10) Scaling locations particular in corners, entries, bends, and HX walls
11) Changes of internal surface area
12) Two-phase flow: gas-liquid and liquid.

It is reasonable to believe ElectraTherm's interest in a project like this one, where it may be possible to reduce the size while increasing the heat transfer capability of their HX in compact units. Even if a shell and tube HX could be lined or manufactured with titanium tubing, it would be cost prohibited.

The presentation itself identified the projected accomplishments, results and progress. The project appears to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule. Target development goals have been met on time, and it is reasonable to assume that the accomplishments in comparison to costs are attainable. The achievements against planned goals and objectives, technical targets have been met.

PI Response:

<u>Reviewer 25041</u>

Score: 8.0

Comment: This project proposed to develop freeform heat exchangers for binary power plants.

The PI does understand heat and mass transfer and focuses on the cross sectional geometry to improve efficiency using CFD modeling.

Two fundamental questions were not answered and will be difficult to be answered by following the current approach: how to lower pressure drop of two-phase flows and silica precipitation for low temperature resources.

Results and progress presented at the time of peer review were according to their plans.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23412</u>

Score: 9.0

Comment: The scientific approach for measuring corrosion and heat transfer geometries is adequate

PI Response:

Reviewer 23430

Score: 7.0

Comment: The approach is sound and involves some novel concepts. The concepts used pertain to materials, geometry, manufacturing and fluid mechanics. However, the approach is too broad, with inadequate focus. The variable in the design are too numerous. The use of additive manufacturing is not adequately justified.

The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

Reviewer 23465

Score: 6.0

Comment: The technical approach taken by the PI is appropriate but could have been clearer. The method employed is reasonable and logical. It is a practical application to address a significant technical challenge at the conceptual level of integrating a HX technology into an existing geothermal power plant. The procedures engaged appear to be proper.

PI Response:

Reviewer 25041

Score: 6.0

Comment: Too much focus on the physical design of the heat exchanger based on fluid dynamics.
Their innovative design procedure must be combined with the understanding of chemical-mechanical-thermal coupled influence on the design.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: this project investigates heat transfer geometries and materials that could be applied to low temperature geothermal and have shown results of what products could work

PI Response:

Reviewer 23430

Score: Not scored

Comment: The project addresses an important technology that can impact the geothermal field broadly. Some of the concepts are novel. The interdisciplinary team is highly qualified and encompasses a number of areas of expertise, including materials, fluid mechanics and additive manufacturing. The accomplishments are not just on paper, but are in terms of real parts that have been fabricated.

PI Response:

Reviewer 23465

Score: Not scored

Comment: Subcontracts with Duke University, University of Tennessee, Yankee-Scientific, CD Adapco, ElectraTherm, and Koppers, Inc.

Strong team credentials.

PI Response:

Reviewer 25041

Score: Not scored

Comment: Good understanding of CFD and innovative method of fabrication.

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: Investigations need to include geothermal fluid inorganic scale, thermal cycling and structural support.

PI Response:

Reviewer 23430

Score: Not scored

Comment: Although additive manufacturing can provide intricate geometries, its ability to provide high thermal conductivity is questionable. This is because of the thermal resistance between the layers in the component made by additive manufacturing. The absence of testing of the component made by additive manufacturing is a weakness.

The choice of materials is not adequately justified. In fact, the choice is titanium to separate the carbon foams is not good, due to the high cost and low thermal conductivity of titanium. Copper and carbon are better choices. The carbon can be a carbon-matrix continuous carbon fiber composite.

The issue of silica precipitation needs to be addressed.

PI Response:

Reviewer 23465

Score: Not scored

Comment: The PowerPoint presentation provided way too much information on a limited number of slides.

PI Response:

Reviewer 25041

Score: Not scored

Comment: No mentioned about a coupled of thermal-mechanical-chemical influence on the cross sectional design.

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: There are no apparent improvements required.

PI Response:

Reviewer 23430

Comment: The approach should be more focused. The choice of materials should be improved. More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public.

PI Response:

Reviewer 23465

Comment: Consider conduct a comparative analysis between the proposed HX designs with the shell and tube HXs used by ElectraTherm. It is a safe bet that ElectaTherm uses stainless steel, inconnel or a similar corrosion resistant metal in their power plant packages.

PI Response:

Reviewer 25041

Comment: When a multi-scale heat exchange concepts is married to a coupled design, then the quality of the project will significantly improve.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Low-Enthalpy Geothermal Desalination
Principal Investigator: Turchi, Craig
Organization: NREL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: Research includes desalination processes that low temperature geothermal fluids could be included to reduce the energy requirements for operation.
Progress needs to include other large scale service providers of desalination processes and integrate this technology

PI Response:

Reviewer 23430

Score: 7.0

Comment: The project is directed at using geothermal energy to desalinate water, thereby expanding the direct use of low-enthalpy geothermal resources and alleviating the water crisis in regions in the country. In this technology, geothermal brine is used as both source water and warm water. The specific objective is the identification of promising options of desalination, with consideration of the performance, cost and commercial development barriers. If successful, the project will impact both geothermal and water sectors. The technical accomplishments include (i) the development of a decision support tool for assessing the feasibility of geothermal desalination (including the analysis of sites where impaired water and geothermal resources are collocated), (ii) identification of membrane distillation to be the water treatment method to be used, and (iii) completion of a conceptual design of the desalination equipment.

PI Response:

Reviewer 23465

Score: 7.0

Comment: The project objective is to investigate the technical and economic feasibility of utilizing of low-enthalpy geothermal energy as a heat source to desalinate impaired waters such as surface water, brackish water, seawater, waste water effluent, and geothermal brine. The project will evaluate options and assess the barriers to commercialization and consider a field demonstration.

This is a very simple project that did not require a huge dollar or time investment. However, it is this Reviewer's opinion that this project may remain at the demonstration scale simply because if deployed at a geothermal site it will most likely fail in a short amount of time, unless chemical inhibitors or filtration equipment are not used. This of course will add to the O&M cost which was not discussed in the provided material. Geothermal brine will scale pipe and heat exchangers even at low temperatures (<90C). There is a high degree of confidence that the Idaho lab staff can make this prototype-scale technology work at the lab-scale but at the moment it is difficult to assess if the geothermal industry will adopt this technology, if it reached the commercial stage.

In this case the value of the treated the source water must be higher than the cost of treating the source water. Even at the suggested price of $.50/M3, this membrane distillation technology is still expensive. The simplicity and minimal development cost of this desalination technology makes it attractive to duplicate for other industrial applications, where water is a high price commodity.

This technology can be easily applied to a concentrated solar trough (CSP) application where the working fluid is heated by the sun. In this scenario, the challenge may be selecting the right membrane that can be adopted to higher temperatures and a suitable working fluid. There are other industrial heat sources that may be considered to desalinate impaired waters.

Recognition should be given to the PI and the excellent work provide by graduate students at Colorado School of Mines (CSM) for achieving project results and milestones for FY14. For the work projected for FY 15 there is a very high likelihood of success.

PI Response:

Reviewer 25041

Score: 9.0

Comment: This project investigate feasibility of an emerging thermo-desal method, Membrane Desallination MD.

Together with MD the project indicates possible use of forward-osmosis method with INL.

The analytical tool has already been developed by experts at Colorado School of Mines and they are refining it to better suit for the project.

All accomplishments and progress have been checked.

Currently looking for pilot-scale test sites.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 9.0

Comment: Technical approach and testing is adequate

PI Response:

Reviewer 23430

Score: 6.0

Comment: The approach involves development of a decision support tool, identification of regions of collocated water scarcity, impaired water sources and low-temperature geothermal resources, assessment of the best integration of geothermal energy and desalination technologies, and determination of the economic viability of this desalination technology. The approach is sound, with adequate consideration of the desalination options, cost and performance. The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

Reviewer 23465

Score: 5.0

Comment: The technical approach taken by the PIs is justifiable. The PI provided an excellent analysis of overlapping GIS drought, brackish water aquifers and geothermal temperature maps. Another aspect of the project that deserves affirmation is the work conducted by the graduate students and faculty at CSM. CSM was able to produce a GDsalt decision tool to provide a realistic economic analysis. The methods employed were logical. The technical tasks and deployment of those tasks are being executed in a pragmatic manner.

PI Response:

Reviewer 25041

Score: 8.0

Comment: Justification for selecting Membrane distillation method and forward-osmosis as opposed to Reverse-Osmosis and other high pressure electrical methods for binary power plants are adequately described.

A reputable software GDsalt is in use and this project offers opportunities to improve this software as well.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: This project has thoroughly investigated the desalination processes and energy requirements and how low temperature geothermal fluids could be applied to reduce energy requirements

PI Response:

Reviewer 23430

Score: Not scored

Comment: The subject is technologically attractive, due to the relevance to both geothermal energy use and water resource enhancement. The conceptual design shows technical feasibility and suggests economic viability.

PI Response:

Reviewer 23465

Score: Not scored

Comment: Excellent team credentials.

Subcontract with Colorado School of Mines.

PI Response:

Reviewer 25041

Score: Not scored

Comment: Seamless collaboration with experts at Colorado School of Mines.

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: Investigators need to investigate integration with large scale service providers.

PI Response:

Reviewer 23430

Score: Not scored

Comment: More attention should be given to the membrane material development and the lab-scale testing. The proposed field testing must be preceded by lab-scale testing.

More comparative evaluation of the proposed membrane distillation method and competing methods, such as reverse osmosis, is needed.

The suitability of the membrane distillation method for high flux situations is questionable. In addition, the lifetime of the membrane is an issue to be addressed.

The need to remove the organic constituents from the water first is not desirable.

PI Response:

Reviewer 23465

Score: Not scored

Comment: A diagram providing an energy balance analysis should have been included.

PI Response:

Reviewer 25041

Score: Not scored

Comment: No mention about the process as to how to select a site for a pilot-scale demonstration.

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: Project in near conclusion so no improvements are required it would be helpful to know if the process could be ran in batch mode or it is more efficient at continuous operation

PI Response:

Reviewer 23430

Comment: More effort should be directed at lab-scale testing and membrane material selection, development and tailoring. More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public.

PI Response:

Reviewer 23465

Comment: For the next phase consider contacting an industrial processing plant that uses heated water that will not scale the spiral membrane or piping system such as a thermal power plants, food processor, industrial laundromat, etc.

Consider demonstrating this desalination technology in an industrial setting such as a sewage treatment facility, food processing plant that are located within shallow geothermal resources.

PI Response:

Reviewer 25041

Comment: More detailed description of how membrane distillation works would be helpful.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geothermal risk reduction via geothermal/solar hybrid power plants
Principal Investigator: Turchi, Craig, Wendt, Dan
Organization: NREL/INL
Panel: Hybrid/Value Added Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 9.0

Comment: This project is very comprehensive detailing a hybrid solar and low temperature geothermal system. Detailed heat balance, cost and efficiency.

PI Response:

Reviewer 23430

Score: 7.0

Comment: This project is aimed at examining the viability of using a solar-thermal source to augment the energy input to a geothermal power plant. This hybridization is expected to mitigate the risk associated with the uncertainty in future geothermal production capacity. If the viability is indeed adequate, the project can impact the geothermal industry, particularly in relation to scenarios with declining geothermal resource productivity. However, the technical viability of the hybridization in terms of the performance in comparison to the case of no hybridization is not adequately shown by the results of this project. The questionable technical viability is mainly due to the limited time of solar availability in a given day. In addition, the economic viability of the hybridization is not adequately shown, due to the difficulty of obtaining economic data such as those associated with power purchase agreements.

PI Response:

The use of solar heat to augment degraded geothermal resources provides advantages in scenarios where drilling additional makeup wells involves too much risk or is not possible. The relatively high cost of solar heat somewhat limits retrofit options, as a power plant that has experienced significant geothermal resource performance degradation is likely to have economic challenges that would favor minimizing retrofit costs. Use of thermal storage for solar heat will further increase retrofit capital costs.

However, use of solar heat during daytime hours does present advantages for increasing power generation during periods when air-cooled plant output is generally lowest (due to increased ambient temperatures) and electrical demand tends to be greatest.

While it is true that obtaining representative power purchase agreement information is problematic, this project has performed analyses that indicate that retrofit of an air-cooled geothermal power plant using a brine preheating configuration can result in positive NPV for a range of geothermal resource temperatures, solar collector costs, and wholesale electricity sales prices (Wendt and Mines. "Use of a Geothermal-Solar Retrofit Hybrid Power Plant to Mitigate Declines in Geothermal Resource Productivity," GRC Transactions, vol 38, 2014). This analysis excluded site- and project-specific costs such as PPA penalties, renewable energy tax credits, etc. For retrofit hybrid projects, NPV is an appropriate measure of the economic viability of the hybrid project. LCOE could also be applied, if it is limited to cost and benefits resulting from the retrofit itself, i.e., the LCOE should be estimated for the energy produced due to the retrofit. This marginal cost of energy can be compared to market values to assess project viability.

Additional reports documenting scenarios in which LCOE could be reduced by 5% for both retrofit and greenfield scenarios in which solar heat input is provided to an air-cooled binary geothermal plant have been completed (Wendt, et al. "Draft report to DOE confirming potential for up to 5% reduction in LCOE from hybrid configuration" January 2014. & Wendt, et al. "Milestone Report: Identify Greenfield hybrid plant configuration and scenario capable of reducing LCOE by a target value of 5%" June 30, 2014). The scenarios evaluated in these reports include assumptions for power purchase agreement terms that are believed to be generally representative of the geothermal industry. A greenfield hybrid concept where geothermal heat is used to provide boiler feedwater heating to a steam Rankine cycle solar power plant also concluded that 2% to 6% decreases in bid price are possible depending on availabilities (Turchi, et al. "Q3FY14 Milestone - Greenfield hybrid benefits - feedwater heating design", June 20, 2014); this analysis did not involve the offset of PPA penalties.

<u>Reviewer 23465</u>

Score: 9.0

Comment: The concept of hybridizing renewable energy resources such as geothermal with concentrated solar power (CSP) is overdue, and should be encouraged by the DOE through continued financial and technical assistance.

This project’s objective is to confirm the feasibility of deploying a hybrid geothermal/concentrated solar power systems to improve geothermal economics, and reduce levelized cost of electricity (LCOE).
This project was divided into two essential components: (1) examine ways to mitigate risk associated with the uncertainty in future geothermal production capacity by using solar thermal heat to offset any lack of geothermal resource productivity, and (2) explore synergistic integration of geothermal and solar thermal heat sources. It is this Reviewer opinion that the PIs were able to address the technical barriers and challenges including when and how to incorporate a CSP system for two different designs.

In California, many energy development projects including geothermal ones, are not even considered or shelved because of costs and environmental regulations. The reason why geothermal/CSP hybridization has not been considered in California is because the economics have not been proven to be competitive with natural gas fired power plants, solar PV or wind generation.

This type of geothermal/CSP hybridization could be a game changer in California. There are several candidate facilities that could conceivably benefit by improving generation output capacity and the economics from this type of hybridization. For example, Format’s North Brawley binary facility is currently operating at around 50% or 25MW of operational capacity. This is mostly due to very high TDS in the brine. A solution to this unexpected problem may not be resolved in the near future outside of perhaps drilling new wells but this approach is a huge investment risk that is probably not going to happen. However, it is very conceivable to consider adding a CSP system to the operation could improve plant performance and provide a certain degree of operational flexibility at lower cost and risk.

This Reviewer believes the best opportunity to deploy the CSP system is to increase the temperature of the working fluid. The other, and probably the less effective option, is to install a CSP system to increase the inlet brine temperature. The second option may be more difficult given the high TSD brine levels, however, in theory, it may be possible that by adding heat to the brine there may be a possibility to keep the particulates from precipitating out, thus resulting in the ability to extract more heat from the brine.

Other candidate facilities include Ormat binary facilities in Heber and East Mesa where the geothermal fields have experience a drop in enthalpy and temperature. In all of Ormat's operations in Southern California land requirements or modifications of existing permits for the addition of a CSP system should not be an issue.

In addition, at the local or state level, governmental agencies should streamline their respective permitting processes to facilitate the development of renewable energy resources.

The presentation described the project accomplishments, results and progress and appears to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule. Given the project's track record of meeting target development goals on time it is reasonable to assume that the accomplishments in comparison to costs are attainable. The achievements against planned goals and objectives, technical targets have been met.

PI Response:

Reviewer 25041

Score: 8.0

Comment: The projects conduct feasibility study for a geothermal and solar hybrid power plants to augment the loss of production of geothermal power plants.

SAM and Aspen Plus are used to conduct comparative analyses.

Simulation of the Stillwater power plant before and after solar-thermal integration is completed. Parabolic trough solar-thermal output model decoupled from SAM power block assumptions. Retrofit design and greenfield design modeling were conducted.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 9.0

Comment: Technical approach and economic justification are adequate

PI Response:

Reviewer 23430

Score: 7.0

Comment: The technical approach is sound and incorporates adequate considerations of performance, cost and implementation issues. The emphasis on retrofit application is reasonable. The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

Reviewer 23465

Score: 8.0

Comment: The technical approach taken by the PI is appropriate. The method employed is reasonable and logical. It is a practical application to address a significant technical challenge at the conceptual level of integrating CSP technology into an existing geothermal power plant. The technical tasks and deployment of those tasks are being executed in a pragmatic manner. The procedures engaged are proper.

PI Response:

Reviewer 25041

Score: 8.0

Comment: Strong industrial collaboration with Enel Green Power, NREL, INL and CRADA is commended.

SAM and Aspen Plus are the computational tools. Many comparative studies were conducted.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: Knowledge of both solar and geothermal power generation is a strength

PI Response:

Reviewer 23430

Score: Not scored

Comment: The concept of geothermal risk reduction via geothermal/solar hybrid power plants is attractive. The feasibility study that constitutes this project is conducted with enough rigor, with adequate consideration of the performance, cost and implementation issues.

PI Response:

Reviewer 23465

Score: Not scored

Comment: Strong team credentials

Demonstration site, Stillwater, Nevada

CRADA with INEL

PI Response:

Reviewer 25041

Score: Not scored

Comment: Strong collaboration and access to EGP Stillwater

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: Project is near conclusion and no apparent weaknesses

PI Response:

Reviewer 23430

Score: Not scored

Comment: The viability determination of the hybridization is not conclusive enough. Reaching conclusiveness is needed during the remaining 4 months of the project. The approach for the remaining months should probably be modified to increase the chance of reaching conclusiveness.

PI Response:

The technical viability of geothermal/solar-thermal hybrid power plants has been indicated by the analyses completed in this project, and demonstrated through the successful operation of Enel Green Power's Stillwater hybrid geothermal/solar-thermal power plant.

An analysis performed during this project (Wendt and Mines. "Use of a Geothermal-Solar Retrofit Hybrid Power Plant to Mitigate Declines in Geothermal Resource Productivity," GRC Transactions, vol 38, 2014) identified economic conditions (wholesale electricity sales price and solar collector capital costs) where solar retrofit of air-cooled binary geothermal power plants could yield a positive NPV. This analysis was performed for a number of geothermal resource conditions with representative rates of geothermal resource performance decline. Additionally, the Q3 FY15 project milestone report (Turchi, et al. "Predicted Electricity Cost as a Function of Site Conditions, Project Cost and System Efficiencies" July 13, 2015) evaluates conditions necessary for the commercial viability of hybrid geothermal/solar-thermal plants. The final project report will include and build upon these previously disseminated results.

Reviewer 23465

Score: Not scored

Comment: The electric grid and the requirements to manage it are changing and geothermal/CSP hybrid systems may satisfy a portion of the electricity demand, and may provide flexible grid capabilities to ensure reliability. Reliability requires balancing supply and demand to meet the net load demand in real time. This is a component that should be considered when integrating a CSP system to base-load generation.

Historically, in California the grid operators (e.g. California Independent System Operator, CalISO) direct conventional, controllable power plant units to move up or down with variable demand. With the growing penetration of renewables on the grid, there are higher levels of non-controllable, variable generation resources. Because of that, grid operators must direct controllable base-load geothermal/CSP system power. A geothermal/CSP system may be able to react to and adjust electricity production to meet the changes in electricity net demand. Grid operators must continuously balance supply and demand, steps must be taken to mitigate over generation risk. These steps include increasing exports, expanding resource capabilities, and requiring renewable generation curtailment. The ability to export power depends on the needs of neighboring entities and balancing agreements. To reliably manage the grid, the grid operators need flexible resources with the right operational characteristics in the right location that support and encourage the development of flexible resources to ensure a reliable future grid.

PI Response:

Reviewer 25041

Score: Not scored

Comment: Non-technical possibilities that may prohibit this project vision?

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: No improvements were observed because project is almost complete

PI Response:

Reviewer 23430

Comment: The challenge of designing a single power block to operate efficiently under the regime with solar-thermal input and the regime without solar input needs to be addressed. The inadequacy in the economic data also needs to be addressed. More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public.

PI Response:

The greenfield boiler feedwater heating hybrid plant analysis performed by this project addresses many of the challenges associated with efficient plant operation with fluctuating input from available heat sources. This project has also identified strategies for designing a single power block to operate efficiently during heat input from single and dual heat sources, which will be described in the final project report and/or evaluated in future projects.

While the project has disseminated milestone reports that included assumed economic data assumptions (Wendt, et al. "Draft report to DOE confirming potential for up to 5% reduction in LCOE from hybrid configuration" January 2014. & Wendt, et al. "Milestone Report: Identify Greenfield hybrid plant configuration and scenario capable of reducing LCOE by a target value of 5%" June 30, 2014), the project team realizes that many of these economic variables are site- or project-specific. Therefore, papers that exclude site specific terms or do not rely on publicly unavailable data have also been disseminated by the project (Wendt and Mines. "Use of a Geothermal-Solar Retrofit Hybrid Power Plant to Mitigate Declines in Geothermal Resource Productivity" GRC Transactions, vol 38, 2014 & Turchi, et al. "Geothermal / Solar Hybrid Designs: Use of Geothermal Energy for CSP Feedwater Heating" GRC Transactions, vol 38, 2014).

Reviewer 23465

Comment: Anytime CSP is discussed in California the subject of energy storage should also be part of that discussion. For the next project phase consider adding a molten salt energy component. In addition, consider the addition of a smart grid component also. This will be useful in coordinating plant flexibility operations with the grid operator.

Contact Charlene Wardlow, Ormat, to initiate discussions regarding the North Brawley Geothermal Faculty in California.

Charlene Wardlow
Business Development
Ormat Nevada, Inc.775.356.9029
cwardlow@ormat.com

PI Response:

Dispatchable power has not been a requirement in the retrofit scenarios evaluated by this project. Retrofit scenarios where addition of solar heat is being considered to augment a degraded geothermal resource require maximization of heat input for minimized capital cost; thermal storage has therefore not been considered in these scenarios.

Dispatchable power is an attribute that hybrid plants could be well suited to address. Energy storage is included in the analysis of the geothermal boiler feedwater heated solar steam Rankine cycle hybrid plant (Turchi, et al. "Geothermal / Solar Hybrid Designs: Use of Geothermal Energy for CSP Feedwater Heating" GRC Transactions, vol 38, 2014). Additionally strategies for using hybrid plant technology in dispatchable power markets will be described in the final project report and/or evaluated in future projects.

Reviewer 25041

Comment: Geothermal provides the consistent base-load. Solar-thermal provides high temperature but transient in nature.

No clear information how these two electricity can be controlled to merge. List reasons why a geothermal power plant wants to have a hybrid concept that has to constantly meet the change of performance of the geothermal power plant?

PI Response:

Air-cooled geothermal power plant performance constantly changes with variations in air temperature; solar heat input from a fixed collector array size changes with changing solar insolation. The retrofit hybrid concept attempts to maximize power generation from the heat sources availabile at any given time of day, while a greenfield design could utilized thermal storage for dispatchable power generation.

In the event of declining geothermal resource performance, the solar array could be resized to counteract decreases in brine flow rate and/or temperature.

Low Temperature, Co-Production Demonstration Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002854
Project: Recovery Act: Electric Power Generation from Low to Intermediate Temperature Resources
Principal Investigator: Gosnold, William D.
Organization: University of North Dakota
Panel: Low Temperature, Co-Production Demonstration

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23498

Score: 7.0

Comment: It is very important to make use of the co-produced fluids with low temperature from oil and gas fields because the amount of geothermal energy stored in these fluids are huge. The research team has collected and analyzed many types of data in the Williston Basin. The total geothermal resource base in pore fluids in the Williston Basin could provide 78.8 PWh of electrical power (1 PetaWatt = 1015 Watts). These data are very useful for the future development of the geothermal energy in this area. More importantly, two Access Energy ORC engines are generating 250 kW using 98C water produced at 875 gallons per minute (55.2 liters per second) from two 8.75” (0.222 m) diameter water supply wells. The quality of the accomplishments, results, and progress made towards technical goals/targets and project objectives are good. The level of productivity in work is good too, considering the accomplishments and the value of the accomplishments compared to the costs. The researchers found that the temperatures in aquifers deeper than 2.3 km in the Williston Basin are sufficient for electrical power generation with ORC systems and the production of the power from low temperature geothermal in the studied area could avoid generation of approximately 10 million metric tons of CO_2.The impact will be significant.

PI Response:

Reviewer 23532

Score: 8.0

Comment: The approach is reasonable and particularly interesting because it allows entry of low-temperature geothermal generation into the petroleum arena in North Dakota without undue time on the part of very busy oil field operators. The technology, once demonstrated, should be easily transferred to operating oil and gas fields.
The approach has included a great deal of public outreach and education which may lead to additional applications of the technology after the conclusion of this demonstration project.

PI Response:

Reviewer 23456

Score: 10.0

Comment: Bringing power on line through innovative program cost-shared with industry fits very well with mission and goals. This is a high quality program that is demonstrating high productivity. It will be interesting to follow issues that arise as power is finally generated.

PI Response:

Reviewer 29855

Score: 9.0

Comment: This project started under the recovery act and has dragged on for many years on account of many difficulties. However, the project team has been highly resourceful and persistent to obtain needed funding from different agencies to keep the project going. University of North Dakota (UND) has produced large amount of information and has graduated many students. The project must be assessed as a very notable success. The two power plants are yet to come on line and produce electricity, but this can happen anytime now.

Quality of the results are high and well worth the effort put in. This will pave the way for many of these types of systems to be deployed in the surrounding region. I would like to see more publications come out in the journals and literature. Continued efforts to monitor the power plant and establish their performance over one or two years and the accompanying experience must be made and the results published. Objectives 1 and 2 are old and have been accomplished by the program. However, it is important to see the plant operating in this large field in ND for the surrounding operators to see and feel. The horizontal production wells are unique to this project and their performance over time will shed new insights for such systems.

Productivity from this project is high despite major delays in schedule. Accomplishments and results presented are impressive and well done.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23498

Score: 7.0

Comment: 1. The researchers demonstrated that heat flow, thermal conductivity, & stratigraphy and BHT data have improved the determinations of the subsurface temperature.
2. The researchers have been running two Access Energy ORC engines for generating 250 kW using 98 C water produced at 875 gallons per minute. Will it be better if different types of ORC engines from different companies were used?

3. The statement "Conventional vertical water wells may be inadequate due low- permeability, drawdown and lift" may not be supported by enough evidence. For example, fracturing the existing vertical wells may increase the production rate significantly and may be cheaper than drilling horizontal wells or branches.

PI Response:

The engines are currently scheduled for installation the summer of 2015, so the engines haven't been run yet. For clairy sake, while there are two Access Energy engines, they are packaged and delivered as one single 500 kW power plant. Access Energy has designed their system based upon a 250 kW design. The package includes two engines to generate 500 kW, the entire package (cooling tower, control system, system containment, etc.) is designed around a 500 kW system. Therefore, in essence, the demonsration is for a 500 kW system. If a second ORC system had been selected for testing, all of the extra infrastrucutre would have required duplication to match that system design. This would have required essentially double the budget.

Hydrofracture can only pull fluid from the "fracture wings" and this is not an EGS where hydrofractured rocks connect a water supply well to a production well. High permeability zones in horizontal to sub-horizontal layers can produce significantly greater fluid volumes than finite-length hydrofractures that would cross zones of differing permeability and mechanical properties due to significantly greater wellbore exposure. Also, achieving shear fractures, which are necessary, rather than tension fractures, which require propants, in a basin having only minor differential stresses would be a major challenge. The key to greater fluid production is well-bore exposure to the permeable formation and that is why horizontal drilling is preferred. Horizontal drilling for oil production in tight formations yields good produciton for a few weeks and then production drops to very low levels. Such a condition would not be good for geothermal power production.

Reviewer 23532

Score: 8.0

Comment: The approach is reasonable and particularly interesting because it allows entry into the petroleum arena in North Dakota without undue time on the part of very busy oil field operators.
The project made an effort to choose an appropriate ORC. Hopefully the effort will pay off.

PI Response:

Reviewer 23456

Score: 10.0

Comment: Solid scientific basis of understanding water supply and thermal conditions has led to great success. The PI has demonstrated great persistence in obtaining additional funding and in solving many hurdles that were placed in the way of this project.

PI Response:

Reviewer 29855

Score: 9.0

Comment: The team from the University of North Dakota has established its competence exceptionally well here. The approach clearly shows how the geothermal system can accompany the simultaneous production of oil and gas, with each operation complementing the other.

The selection of the power producing ORC appears thorough. However full details were not presented or included in the summary. It would be nice to have that process described in a report or publication.

Considering the amount of effort that has gone on in this project, we are anxiously awaiting the commissioning and operation of the two power plants. High quality power production data will round out the accomplishments for this project. A one or two year operational data would be most valuable now.

The staffing and all aspects of scientific approach are of high quality.

PI Response:

STRENGTHS

Reviewer 23498

Score: Not scored

Comment: The main strength is the overcoming of the challenges during the implementation of the project: identification and access to suitable water supply, selection of optimum power generation system, and gaining industry Interest and support. Eventually the team brought two Access Energy ORC engines generating 250 kW using 98 C water produced at 875 GPM on line. The study demonstrated, to some extent, that a distributed network of binary ORC power plants could generate power at a levelized cost of electricity of $0.05 per KWh in the Williston Basin.

PI Response:

Reviewer 23532

Score: Not scored

Comment: Binary technology will be demonstrated to the Williston Basin oil and gas well operators without their having to utilize their very busy workers with assistance to a demonstration project.
There is a large need for additional power in the Basin that can be met using this technology without building large base-load power stations that could become obsolete as need for power decreases in the Basin. Small binary systems could be relocated as power needs change location.
Application of low-temperature geothermal electrical generation technology to fluid produced on the margin of an active oil and gas basin. The project resulted in the collaboration of the UND researchers, an oil industry service firm and electric utilities.

PI Response:

Reviewer 23456

Score: Not scored

Comment: Scientific and technical approach, as well as ability to work through extensive barriers, is a real strength. The number of students trained and number of publications produced is excellent. The publication record of this project should serve as a model for outreach and education from other projects.

PI Response:

Reviewer 29855

Score: Not scored

Comment: The project team is highly capable and of very high caliber.

This team has been dedicated and quite persistent to keep the project going despite difficulties in funding.

Their approach to selection of the ORC system is a good example of their thoroughness in evaluation of various options.

The results were presented well and provided a clear picture of the work carried out by the team.

I commend the team for their excellent work in expanding the scope of low-temperature geothermal applications.

PI Response:

WEAKNESSES

Reviewer 23498

Score: Not scored

Comment: The main weakness is the demonstration time of the two Access Energy ORC engines generating 250 kW using 98C water produced at 875 gallons per minute is very short. This is very difficult to accomplish the Objectives 1, 2, and 3.

The report and presentation were not prepared carefully. For example, the researchers stated in the presentation slides (# 13): "Heat flow, thermal conductivity, & stratigraphy and BHT data have led improved heat flow and subsurface temperature determinations". "Heat flow" improved "Heat flow"

PI Response:

It is difficult to determine what the reviewer mean by the first two sentences in the comment. Maybe they were not carefully prepared? The concern may be that the demonstration period will be shorter than the two years planned in the original proposal. While the original DOE grant has expired, the demonstration will continue under funding provided by the North Dakota Industrial Comimssion and results will be published.

Yes, the wording on heat flow could have been stated better. What was intended was that the 24 existing heat flow data are insufficient for understanding the thermal regime of the basin. The other thermal properties and geological information allowed us to determine heat flow in parts of the basin where no conventional data exist. The result was a good understanding of the potential for application of the project throughout the basin and the development of a roadmap for assessing other sedimentary basins.

Reviewer 23532

Score: Not scored

Comment: Other than lengthy delays in getting the project on line the only weakness might be locating the test on a water supply operation rather than actual oil wells.

PI Response:

Reviewer 23456

Score: Not scored

Comment: Other than taking longer than expected to get power on line, this program has been highly successful. No weaknesses, thanks to incredible persistence.

PI Response:

Reviewer 29855

Score: Not scored

Comment: Clearly one of the major weakness is the long delay in getting the plant installed and operating.

Presenter did provide explanations for the delays and how many aspects were beyond their control.

It is critical that at this time, the plants be put in operation as soon as possible and the team to start gathering operational data and publish those results. Economics for the power production operation is yet to be assessed based on the plant performance.

Another weakness appears to be that the publications from the team were not enumerated in their accomplishments. Project team must publish their results more widely and hold seminars at the many well operators in that region.

Regional conferences must be attended by DOE and this project team to expand the co-production process widely in that region where many operators are conducting similar operations.

PI Response:

There were several factors beyond our control that caused delays. Those factors were reported in quarterly and annual reports and in previous Peer Review session. Mindful of the short time permitted for the presentation, we focused on present activities. A brief summary of delays follows:
1. Initial industry partner, Berrendo, was not performing any tasks so we changed to Calnetix in 2010.
2. New contract with Calnetix indicated that the ORCs would be ready by summer 2011. - They did not become available until 2015.
3. Contract with Continental Resources, Inc. required that UND hold harmless and indemnify CRI, but UND would not accept. This required two trips to CRI headquarters in Enid, OK with UND counsel and set back the project by 1.5 years. Finally, Calnetix agreed to take over the contract with CRI.
4. Estimates for installation costs for the ORCs based on information from Calnetix and CRI were of the order of $20,000. We budgeted $30,000. When we contacted a contractor who had an agreement with CRI and could do the site preparation and install the systems, the quote was $278,000. We raised the additional funds through a proposal to the North Dakota Renewable Energy Council and cash support from Basin Electric Cooperative. This took more than two years to accomplish.

We did state that the team has produced 26 peer-reviewed articles and made 62 presentations at professional meetings.
We participated in the Bakken Conference in Grand Forks in 2014 and will do so again in 2015.
We have participated in the Great Plains EmPower ND Conferene and continue to provide them with updates on our project.

IMPROVEMENTS

Reviewer 23498

Comment: 1. it may be better if different types of ORC engines from different companies were used. By doing so, it may be able to tell which type of ORC power generator works better.

2. It may be interesting to compare drilling horizontal wells with fracturing in terms of cost and increasing production rates.

3. It will be very helpful to study the sustainability of formation temperature with time under the situation of high production rate. This can be done by using numerical simulation.

PI Response:

1. Our initial thoughts were to test several different ORC engines. Unfortunately, we did not have the funds to purchase more than one type of engine.
2. Good point on comparing costs of drilling horizontal wells and fracturing althoug we did address this somewhat in our response to this reviewer's comments on sceintific and technical approach.

Reviewer 23532

Comment: The team appears to have worked very hard to keep this project moving forward as well a successfully getting financial support from outside organizations. It is hard to see what they could have done better.

PI Response:

Reviewer 23456

Comment: Hopefully this demonstration power plant will lead to many more being built. See Senate mark up for FY 2016 DOE budget!

PI Response:

Reviewer 29855

Comment: Operational data over one or two years are needed.

Final economic assessments for power production must be established and disseminated.

Publications and participation in information dissemination (especially for the local operators) must be given high priority to expand use of geothermal electricity.

There is a large projected demand for electricity in that region; Co-production can address this need.

Regional conferences must be held to disseminate this work and results to the local communities and operators who are involved in similar well operations.

PI Response:

We will be operating the system for two years after installation. We will put the information on a website that can be accessed any time. We did present this concept at the Bakken Conference in 2014 and will be there with information in a booth in 2015. We plan to hold a major ribbon-cutting event with participation by the power industry and the jpetroleum industry in addition to DOE and ND State officials when the system is running in late August, 2015.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Low Temperature Project Analysis
Principal Investigator: Mines, Greg, Williams, Tom
Organization: INL/NREL
Panel: Low Temperature, Co-Production Demonstration

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23498

Score: 7.0

Comment: This project has conducted detailed analysis of data being produced from DOE's low temperature geothermal projects. Two examples have been used: Dixie Valley and Beowawe Binary Plants. The researchers also identified the challenges for predicting low temperature project performance as well as the lessons from the analysis to the example power plants.

The quality of the accomplishments, results, and progress made towards technical goals/targets and project objectives are good. The level of productivity in work is good too, considering the accomplishments and the value of the accomplishments compared to the costs.

The results will be useful and helpful to the existing and future low temperature power plants.

PI Response:

Reviewer 23532

Score: 9.0

Comment: This project is collecting data necessary for industry to decide whether or not to utilize bottoming cycle technology. The effort and cost are minimal by comparison to possible benefit to the industry. The quality and understanding of the data by the PIs is excellent.
Accomplishments and results are not what have been expected. However, most of this is outside of the control of the PIs. For additional comments see Weaknesses.

PI Response:

Reviewer 23456

Score: 7.0

Comment: The project started with an ambitious set of goals, not all of which will be reached by the conclusion of the project. In particular, data were presented on only two electric generation projects, Beowawe and Dixie Valley. Other proposed projects either have not yet generated electricity or have not proven to be viable (at least yet).
Even given the reduction of scope, the results of this project will serve well to support future GTO decision making. This project is building broader awareness of some of the issues operators face in bringing smaller projects on line. The data comparing manufacturer stated plant productivity, modeled productivity, and actual productivity, are very telling about how far short actual production can fall from original goals. Some of the shortfall is due maintenance issues that were not anticipated (system fouling).
The project has done a good job working with the data they have been able to collect, but it is worth noting that there are several critical gaps, such as power plant down time or operator failure to provide data, that impact the ultimate utility of the results.

PI Response:

Reviewer 29855

Score: 8.0

Comment: This project aims to gather relevant data from the DOE's various low-temperature demonstration projects. Thus far only three projects have been attempted for analysis. Of these, only one of them appears to have yielded some useful information.

This research is important in that many lessons can be learned from each of these projects to provide the technical community with data for making best decisions.

Accomplishments have been limited mostly because of lack of adequate data supplied by the project teams with large data gaps. As stated, the biggest challenge has been the lack of quality and details in the data. This makes it difficult to generate any economic projections.

However, the results have been impressive. On account of this project problems related to two demonstrations have been identified and corrected. In Beowawe, fouling in the condenser was identified and corrective measures have been taken. In the Dixie Valley plant, fouling of the boiler was identified as limiting the performance of the plant and corrective measures have been taken.

Progress has been slow, on account of the lack of data and prolonged time to implement the demonstrations and obtain meaningful data over a year or two. However, this project team has very high capability. From discussions, apparently 8 other projects are yet to be evaluated as the demonstrations get implemented over time.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23498

Score: 6.0

Comment: The project team aggregated performance and cost data provided by each project and evaluated the discrepancies between predicted and actual experience. They also developed models of plant operation and compared to expectations. The quality of the technical approach, rated for the rigor and appropriateness of the employed technical approach to achieving the project's objectives with the available resources is good.

It is interesting to learn that the power output in these low temperature power plants was more sensitive to changes in resource and ambient conditions than those high temperature power plants.

PI Response:

Reviewer 23532

Score: 8.0

Comment: The approach on the part of the PI's is excellent. They appear to be focused on accessing the data required to understand installing and operating low-temperature binary bottoming cycles and also understand the pitfalls and problems associated with such technology.

PI Response:

Reviewer 23456

Score: 8.0

Comment: The project should have been able to achieve its goals with the supported staff and the technical approach. However, it appears that there were no contingencies for data gaps, which inevitably occurred. These data gaps reduce the overall usefulness of the final results.

The data that have been collected and analyzed will be very useful for DOE in future analyses of power plant viability.

PI Response:

Reviewer 29855

Score: 8.0

Comment: The project team is highly capable.

Scientific approach is excellent with detailed plant modeled on an hour-by-hour basis, based on weather data, and economic analysis based on well-established approach. Simulation results were presented with varied assumptions on the condition of the equipment at each site so that the analysis matches the plant operational data. Such analysis helped identify key problems at the two sites evaluated.

PI Response:

STRENGTHS

Reviewer 23498

Score: Not scored

Comment: 1. A lot of lessons have been learnt from the existing low temperature power plants. These lessons will be useful to design new power plants or improve existing ones.
2. Plant performance model has been developed to predict output and compared the model results with the actual data.

PI Response:

Reviewer 23532

Score: Not scored

Comment: Very well qualified PI's with intimate knowledge of the operation, maintenance, and idiosyncrasies of binary power production.

PI Response:

Reviewer 23456

Score: Not scored

Comment: The attempt to gather, analyze and model data from power plants to support future DOE decision making is a very good idea.

The PI clearly has the background, skills and ability to have done an excellent job.

PI Response:

Reviewer 29855

Score: Not scored

Comment: The team covered all aspects of the analysis thoroughly with no stones unturned. Commendable work.

Substantial amount of work has been done on the detailed hour-by-hour analysis.

The team is highly capable both in technical and economic evaluations.

This project will help assess the importance of the various demonstration projects currently underway by DOE.

PI Response:

WEAKNESSES

Reviewer 23498

Score: Not scored

Comment: 1. The number of examples are few. There are many low temperature power plants worldwide. The required data may not be enough but some analysis and comparison could be done.
2. The analysis to the reasons behind the lessons and challenges obtained for the low temperature power plants is not detail enough.
3. Comparison to high temperature power plants has not been conducted enough.

PI Response:

The plants that the project evaluates are those that received DOE grants/awards. These plants are required by their agreements with the GTO to provide both cost and operating data. The analysis could be extended to other plants, however it is unlikely that the owners/operators of those facilities would provide the data necessary to make the types of analyses that were made for the Dixie and Beowawe. There are other plants that received DOE grants to develop plants using low temperature resources. Those plants either have not started up or have yet to operate long enough to perform a detailed analysis.
At the conclusion of this project, there will be a report to the GTO with a more thorough assessment of the lesson's learned. Note that the awardees are to provide this information. What was present was largely based on our observations and discussions with the operators.
Comparions with high temperature plants, as well as other low temperature plants, is outside the scope of the project, other than identifying those aspects of these projects that allow them to be able to produce power at costs similar to the high temperature plants..

Reviewer 23532

Score: Not scored

Comment: Somewhere along the course of this project operators were not required or chose not to provide adequate data for the PI's to collect valuable data necessary for complete study of the efficiencies, costs and operating characteristics of the bottoming cycle plants. Such data requirements and timely release of the data should be required in the language of all future DOE funded projects with minimal, or no, restrictions based on proprietary interests.

PI Response:

We agree.

Reviewer 23456

Score: Not scored

Comment: As the PI recognizes, the lack of critical data from operators can dramatically reduce ultimate ability to provide DOE with rigorous analytic data to support future decision making.

PI Response:

Reviewer 29855

Score: Not scored

Comment: Clearly the major weakness of this project is the lack of quality and details in the data as the presenter reiterated.

This weakness makes any projections from the analysis questionable.

I am sure enormous amount of time was spent in telephone calls and conferences to identify and correct the missing pieces of information on each project. Sometimes this can be highly frustrating and wasteful.

This project will have to be extended beyond 2016, because some of the pending demonstration projects may not be completed in time or the operational data over one year may not be available.

PI Response:

IMPROVEMENTS

Reviewer 23498

Comment: 1. The number of example low temperature power plants used for analysis may be increased.

2. The reasons behind the lessons and challenges for the low temperature power plants may be analyzed in more detail.

PI Response:

Reviewer 23532

Comment: Grants should be awarded with a clear understanding of the requirements of timely and complete data submittal to Doe.

PI Response:

Reviewer 23456

Comment: The final economic analysis, even based on incomplete data sets, should be well documented so it can be applied to future power plant assessments. Also, while the program will provide an analysis based on operator-provided data sets, an analysis of what additional kinds of data not gathered in this program would help DOE assess viability of future proposed lower-temperature electrical generation projects.

PI Response:

Reviewer 29855

Comment: DOE should use a carrot and stick model for obtaining the critical data from these demonstration projects. Despite DOE's participation and support and varied requests for data, the project teams are not forth coming with proper data.

DOE should consider withholding funding till all required data are made available; and should also consider imposing penalties (that hurt) for not complying with requests for the data.

This project team must make a comprehensive list of data requirements that addresses all details such that all demonstration teams are aware of the detailed requirements for the data.

The current model used for the analysis must be made available to the geothermal community as the project evolves on a continual basis.

PI Response:

Mineral Recovery Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Recovery of Rare Earths, Precious Metals and Other Critical Materials from Geothermal Waters with Advanced Sorbent Structures
Principal Investigator: Addleman, Raymond
Organization: PNNL
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23414

Score: 8.0

Comment: They've made a good start, seem to understand the obstacles and the possible approaches, and have put together a good team. They have a neat idea that is particularly attractive because of its modularity and the fact that it might produce energy as well as extract metals.

PI Response:

Reviewer 29853

Score: 6.0

Comment: The projects ability to successfully demonstrate economic recovery of REE, and of valuable critical materials from geothermal waters would be a game changer for the geothermal industry, which always struggles to be profitable. The project addresses a critical need identified by the USDOE through their Critical Materials Hubs, and supports the overall objectives of the US to reduce the reliance of other countries to provide critical materials that are needed for economic growth. It has long been postulated that thermal brines contain elements that can increase the economic viability, the funding of these types of projects is a critical step in addressing this potential. This multidisciplinary team has made progress towards meeting the early objectives of the study. However, it is unclear if the approach (using solid state sorbents to remove valuable materials from geothermal fluids) used by the team is appropriate for the high temperature brines. Because the project is only 6 month old, it is difficult to tell if the approach has merit.

PI Response:

All materials being evaluated, and ultimatedly utilized, will be:
- stable to 150 C
- possibly stable to over 200 C
- some will be stable to over 400 C

Reviewer 23456

Score: 7.0

Comment: Good progress in meeting the goals was reported at the meeting. The project is on schedule. The technology is being adapted from previous research, and at this stage looks to be feasible. They have identified a good list of critical challenges (p. 9 of presentations).

PI Response:

As reviewer 23526 noted we have made a serious effort "understand the problem".

Reviewer 23526

Score: 6.0

Comment: This project, like many others in this topical area, has the potential to be highly impactful. Being able to selectively recover specific REE minerals can be a very powerful tool, especially when they are found in such low concentrations in otherwise high TDS brines. As the project is just now getting underway, and really no results are available, time will have to be the ultimate judge of the impact of this project.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23414

Score: 9.0

Comment: These folks are juggling lots of technical balls at once. I doubt they can keep them all in the air. But it's auspicious and encouraging that they've already dealt with problems - e.g. low Li uptake on one MnOx, changed course and kept moving forward.

PI Response:

The first year of the project we intentionally took a broad view of the technology (broken down into the separate challenges of chemistry and structure) and are exploring a lot of options/parameters. We wanted to evaluate a wide varity of promising options. We will down select (end of FY15) to the most promising chemistries and structures and demonstrate preferred solutions. FY16 work will be much more focused on delevopment of the most promising methods.

Reviewer 29853

Score: 5.0

Comment: The approach of this team to address critical material recover from thermal brines require that the new solid state extraction must be a significant improvement over existing materials. To my knowledge there are not any pilot-scale technologies currently deployed in the market space that this project would compete with; so I am not sure what the metrics of comparison would be. The approach while novel and interesting, the project appears to be looking to develop a technology in the absence of knowing much about the system. That is, how does one develop a technology tuned for a specific application without a fundamental knowledge of the system for which it is to be applied? This is a general comment for all of the projects presented in this session. Which is, engineers and scientist are looking to exploit an opportunity, but they are not sure what they opportunity is.

PI Response:

No technology exists which can accomplish the desired goals and hence there is not comparable systems (and hence the need for research)
This phase of the project is focused on technology development with testing and evaluation being done in geothermal fluids. Once the best fundamental options (chemistry and structure) have been identified it will enable us to develop and demonstrate viable piolet scale technology in the next phase of the effort. During this phase we will be engaging/collaborating with the goethermal experts.
As reviewer 23526 noted we have made a serious effort "understand the problem".

Reviewer 23456

Score: 7.0

Comment: The technical approach of the program, with a major exception noted under weaknesses, seems sound. Their criteria for sorbent selection seem well founded, assuming that by stability they include high temperature operating conditions. The broad expertise of the team is well suited to accomplishing this program.
The team reports that they are making good progress.

PI Response:

Reviewer 23526

Score: 9.0

Comment: This project stood out for me in their approach. This was the only project in my estimation that took the time to understand the problem—it is not easy!! While I am not convinced that the sorbent materials and capture methods will withstand geothermal conditions, I do find that their end goal of a prototype is both realistic and reasonable give the time available.

PI Response:

We share the reviewers concerns about this, or any, technology being able to solve the challenging problem of trace extraction from geothermal brines. It’s a very hard problem.
However, there is only one way to determine what technology will function within, and withstand, geothermal conditions--do the research (with the best materials avialable) and let the data/results speak.

STRENGTHS

Reviewer 23414

Score: Not scored

Comment: Total system analysis, modularity, dual production of energy and minerals.

PI Response:

Reviewer 29853

Score: Not scored

Comment: By far the strongest attribute of this project is that it is a multi-disciplinary multi-organizational effort that includes a National Laboratory, university, and industry all of which have a vested interest in seeing a successful completion of the project.

1. Multi-institutional effort that has key partners with expertise in recovery of constituents from fluid streams
2. Game changing technology potential
3. The project personnel recognized area where they have strengths and where they need input help from elsewhere.
4. Lead organization is highly competent and has the depth of capabilities required to conduct the research

PI Response:

Thank you.

Reviewer 23456

Score: Not scored

Comment: The team is highly qualified. The staged approach seems well conceived.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Targeting “gross” capture of classes, and then separating later may be more feasible than targeting single species. Appears to have a good cross-disciplinary team

PI Response:

The chemical reality is that we have not choice but to capture general classes of minerals. Separation will have to be done later with established processes. This is a fundamental premise of our approach.

WEAKNESSES

Reviewer 23414

Score: Not scored

Comment: none

PI Response:

Reviewer 29853

Score: Not scored

Comment: Although the project team is highly competent and is well suited to address fundamental issues associated with the extraction of targeted materials from thermal water, namely though the demonstrate flexible, scalable mineral extraction technology for geothermal brines based on the development of advanced solid phase sorbent materials. The fundamental lack of understanding regarding geothermal systems and the associated brines is a major issue. I fail to understand how the team can design a technology to extract components from a "waste stream" without knowing how much of the component of interest is in the stream, and what other constituents such as SiO2 may present challenges to their technology.   The absence of a geochemist with at least some geothermal expertise is a major weakness for the team. Without a fundamental understanding for how geothermal systems operate and their chemical makeup the Team will spend a great deal of unnecessary time struggling to get their arms around the problems facing them. To their credit the presenter spend a great deal of time in his talk elucidating their short comings, however, without outside support or the addition of geochemist they will struggle fulfill the their mission to GTO.

PI Response:

As reviewer 23526 noted we have made a serious effort "understand the problem".
We agree that our understanding of geothermal systems is lacking. Finding expertise in the area has been challenging. We are using the project review board as well as contacts made at the March meeting to address this short coming. In the next phase of the project we plan to have an expert in geothermal power systems as an integral part of the program.

Reviewer 23456

Score: Not scored

Comment: As stated in their talk, this work will only be conducted at room temperature. Their statement of work, however, suggests that they are targeting 125 - 400 degrees C for operating temperatures. There is lack of match between the SOW and what they are actually doing.

Early investigation of thermal stability of the solid-state sorbents is critical. It does not support the needs to the geothermal program if promising sorbents or collection materials are not stable or effective in field production conditions of much higher temperatures and complex chemistries. If promising materials are not tested for thermal stability early in the program, DOE may end up spending money on development of materials that are doomed to fail once tested in power production cycles.

PI Response:

No material is being evaluated that is not stable to at least 150 C (or higher). So no material is being consider that would not function in geothermal systems. How well the various collection material functions will be determined by testing. Initial performace tests, on a wide variety of promising materials, were done at room temp to enable more effective use of research dollars (room temp testing ~10x more cost effective). Final tests, on a limited number of preferred materials, will be done at geothermally relevant temps.

Reviewer 23526

Score: Not scored

Comment: I think you will find that fouling of your proposed sorbent structures may become problematic, and result is cascading problems resulting from too great a pressure drop. Although perhaps I shouldn't call this a weakness, only a concern. Operating temperatures are a concern, but this concern is shared among all the projects in this topical area.

PI Response:

We share the reviewer concern about fouling being a major problem. Fouling is the primary reason we are consider alternative structures (that are fouling resistant) to the traditional packed bed configuration typically employed (and almost certianly doomed to fail in geothermal applications).
Operating temp is a real concern but we are selecting for materials which should be effective at relevant temps. (as previously discussed in response to reviewers)

IMPROVEMENTS

Reviewer 23414

Comment: getting preliminary economic analyses would be very, very useful

PI Response:

A techno ecomonic analysis based bad data is would be erronous and misleading. We intend to pursue the techno-economic analysis as soon as we have preliminary data that would provide accurate input and (hopefully) and meaningful output from an economic process analysis. This will occur in the Q4 of the first year.

Reviewer 29853

Comment: Several things could be done to improve this project. My suggested improvements are not unique to this particular project but rather are a need that was observed across the projects in this session.

1. Better understanding of the systems for which their technology would be deployed

2. Using standardized feed water with a known concentration of targeted elements. This could be either through using a few representative water sources from producing power plants or thermal hot spring, or making up a series of standardized solutions. This would prevent the project from concentrating on a thermal system that is minimally applicable to the global need, and would prevent the project from scrambling to make the appropriate contacts with industry to collect and manage water samples from a huge number of producers.

3. The project should make an effort to understand (likely through modeling) how would temperature, flow rate, and chemistry impact the selectivity of their proposed technology

4. They project should spend some time with a geochemist to better understand geothermal systems

PI Response:

1. As reviewer 23526 noted we have made a serious effort "understand the problem".
We agree that our understanding of geothermal systems is lacking. Finding expertise in the area has been challenging. We are using to program review board as well as contacts made at the March meeting to address this short coming. In the next phase of the project we plan to have an expert in geothermal power systems as an integral part of the program.
2. We have expresssed concerns to the geothermal program office about the lack of standard test solutions as well and the impact of heterogeneity of geothermal solutions on the performance of (any) technology. We are now working with geothermal brines we have obtained. Next FY we hope to work with program approved solutions.
3. We agree. Presentation time prevented a full discussion of the relevant parameters. The parameters listed by reviewer (in addition to durability, materials manufacturing and processing cost) will form the basis for our down selection of viable sorbent structures and chemistries. Please see our Q3 resport for details. Modeling at this stage, with many/most variable undetemined, may not be the best utilization of resources. However, modeling will be essential to determine the optimal technology configuration and its viability once fundamental parameters have been experimentally resolved.
4. This sort of expertise is surprisingly hard to find. We have identified several INL staff with expertise in the area and are utilizing them as opportunity and their avaiability allows.

<u>Reviewer 23456</u>

Comment: Remember that this project is being funded by the geothermal program.

It is stated in the presentation (slide 9) that there must be a balance between kinetics and efficiency. Recognition of power production cycles and identification of how this recovery technique will fit into such cycles is critical.

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

Once the basic technology (structure, chemistry process) has been nailed down we will determine the best way to configure it for geothemal plant operations (with the help of appropriate experts).
We are complete cognizant that if the technoloygy does not work within the geothermal plant its relevance to DOE-GTO is nonexistant.
QA/QC methods are those DOE has approved for R&D efforts. Specifically for this effort all the samples are run in triplicate. Results are correlated to certified standards and calibration curves. Matrix effects are corrected for with matrix spikes and internal standards (of certified standard materials). All data reviewed for consistancy and accuracy.

Reviewer 23526

Comment: Bound your future experiments pH and composition range (synthetic solution) to that of some "common" geothermal brines. Move away from seawater.

PI Response:

We began with seawater because representative geothermal brines were not available. We are now working with geothermal brines we have obtained. We have expresssed concerns to the geothermal program office about the lack of standard test solutions as well and the impact of heterogeneity of geothermal solutions on the performance of (any) technology.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Engineering Thermophilic Microorganisms to Selectively Extract Strategic Metals from Low Temperature Geothermal Brines
Principal Investigator: Ajo-Franklin, Caroline
Organization: LBNL
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23414

Score: 8.0

Comment: somewhat of a one trick pony - pursuing the biological path - but a potentially very powerful pony

PI Response:

Reviewer 29853

Score: 5.0

Comment: This project proposes use of thermophyillic microorganisms to extract metals from produced thermal brines represents a novel if not incredibly optimistic approach. Because geothermal plants have very interest in keeping return flow waters at as high a temperature as possible to maintain long-term reservoir stability, it will be extremely difficult for a microbial community to thrive at these temperatures. Even getting a microbial consortia to thrive for long enough time periods to be tested in these systems will be difficult. That is making the transition from the bench-scale into a flowing geothermal system is going to be problematic. While the study itself in incredibly interesting, I have trouble understanding how this particular project can be successful under the conditions necessary for geothermal application as few organisms can even survive 100 degree Celsius water, let alone the temperature experience in a low temp binary plant. Therefore I struggle to see how this project meets the GTO offices mission in this particular area. That being said, the fundamental science and potential learnings from this work may have merit.

PI Response:

Reviewer 23456

Score: 7.0

Comment: The project is proceeding well. The team reports good progress. The focus at this time is on engineering microbes for capacity and selectivity of valuable elements.
This is a challenging approach to mineral recovery given the operating parameters of geothermal power plants.

PI Response:

Reviewer 23526

Score: 5.0

Comment: This project, like many others in this topical area, has the potential to be highly impactful. Being able to selectively recover specific minerals can be a very powerful tool, especially when they are found in such low concentrations in otherwise high TDS brines. As the project is just now getting underway, and really no results are available, time will have to be the ultimate judge of the impact of this project. The genetic engineering of the microbes may have farther-reaching implications.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23414

Score: 8.0

Comment: These folks are making progress.

PI Response:

Reviewer 29853

Score: 5.0

Comment: The project lead is very capable and the approach being taken is consistent with other microbiological type studies for which I have some familiarity. The PI is going to great lengths to insure that the microbes used in this study are well documents. The overall approach is well thought out and with clear milestones and go-no-go decision points. Again as stated earlier, even a well thought out project that is potentially incapable of meeting the overall program objectives is difficult for me to review positively. As I do not see the connection between what is being done and the ability of the approach to ever be deployed. The presenter was bright and articulate, but was not able to answer these fundamental problems, in fact, she stated in that microbes simply cannot exist at the elevated temperatures seen at producing geothermal facilities. And I don't see a scenario where a plant would allow water to cool sufficiently as a large enough scale to ever make mineral recovery economical.

PI Response:

Reviewer 23456

Score: 7.0

Comment: This is a high-quality team clearly capable of engineering microbes. The approach being taken of engineering to bench-scale testing is appropriate. They are making good progress.

PI Response:

Reviewer 23526

Score: 5.0

Comment: The scientific/technical approach being employed by the project is sound, but I have concerns regarding the "Key Risk" of "imprecise relation between design and function" identified by the team. All the engineering in the world in regard to designing the capture selectivity will be for naught if the microbes cannot function (or at least function well) and reasonably low geothermal temperatures. From what I understand the microbes may survive at temperatures in excess of 70C, but will they thrive? What about at 100C, 140C? This needs to be considered and thoroughly thought out.

PI Response:

STRENGTHS

Reviewer 23414

Score: Not scored

Comment: the organic functional analysis is top-notch. If there's a biological trick to extracting REEs from geothermal brines, I'm sure these folks will find it

PI Response:

Reviewer 29853

Score: Not scored

Comment: Although I struggle to see the application of this project to an operating geothermal system, I was very impressed with how thorough the PI's scientific approach is. Additionally, from a pure research point of view, this project is one of the best I saw during the review meeting. The major strengths include:

1. Rigorous investigation of the appropriate microorganism to be studied.

2. Fundamental understanding of the binding mechanisms that microbes us to capture metals from solution

3. Recognition of some of the difficulties that must be overcome to be successful. As an examples the presenter discussed a key risk is the proposed design of engineered proteins and microorganisms as being untested and imprecise, and at the current time it is not clear which design parameters will lead to highly selective binding that is thermally reversible

4. The host institution has a history of producing high quality research particularly in the microbiological field.

PI Response:

Reviewer 23456

Score: Not scored

Comment: This is an innovative technique that suggests a distinct approach to element recovery from geothermal brines. If successful, this research could have broad implications across a wide range of geothermal systems.

The skill of the team to accomplish the research is excellent. They are demonstrating the capability to engineer the microbes. The concept of doing continuous flow bench scale testing is critical. Documenting microbial metal uptake rates at different temperatures will be very important. If the creatures are stable to 95 degrees C, but only happy at 65 degrees C, their uptake rates in operating conditions may not be optimum for economic recovery. The bench scale tests will help provide critical data to assess uptake rates and temperatures.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Very interesting and innovative approach. Many potential application outside of the geothermal space

PI Response:

WEAKNESSES

Reviewer 23414

Score: Not scored

Comment: this is down the road but I worry about competition of other ions and reversibility of re-release

PI Response:

Reviewer 29853

Score: Not scored

Comment: From a pure science point of view there are not many weaknesses associated with this project. However, because the science is tied to a specific goal there are some significant issues that need to be dealt with.

1. This is a single institution team; the lack of recognition of some critical issues associated with deployment of a microbiologic approach to mineral extraction at elevated temperatures is obvious.

2. The team seems to have chosen a set of metals Gd and Zn as the targets for their effort no mention was made for why these metals were chosen.

3. The presenter made no mention of the type of brine or brines that would be investigated using their chosen microbe. Does TDS, chemistry, or other components represent issues that could poison the selected consortia?

4. The biggest issue is, if successful, can this technology ever be applied to a thermal system, and if so what type of system and what is the highest temperature that could be theoretically achieved.

PI Response:

Reviewer 23456

Score: Not scored

Comment: The lack of vision for how the results of this research would interface with a power production cycle limits the final utility of the research. Will this kind of approach work in very high flow rate, very short contact time conditions likely to be encountered in the field? What are the plans for recovery of the microbes from the production stream?

If a microbe is developed for Zn selectivity, will it work for REE and other valuable elements in geothermal brines? Zn is now about $1 per pound, which suggests that extraction of more valuable elements is more likely to result in an economic process.

The authors note that they expect to use heat to trigger metal release from the microbes, but they do not provide documentation to support their suggestion that using heat for release will cost only $5 per 1000kg.
Bioprospecting for microbes that already can selectively bond with REEs and engineering them to withstand heat (if none are found that can do this already), is an approach worth investigating.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Questionable if this will work for even extremely low geothermal temperatures. Perhaps too much of a first principle project, more appropriate for Office of Science?

PI Response:

IMPROVEMENTS

Reviewer 23414

Comment: if you've got time, think more about the tops down bioprospecting angle

PI Response:

Reviewer 29853

Comment: This project would be well served to reach out to the community of thermophile researchers who have a vast wealth of information regarding the types of thermal system that microbes cannot only exist but thrive to the extent necessary.

The project would benefit from a mission statement that incorporates the known limitation of microbes at elevated temperatures, and how that limitation is not relevant to the work they are doing. Based on what was presented and the materials provided this review could not make the connection to the overall program objectives.

The project would state path forward in their work plan to overcome one of the stated issues "The most critical aspect of the technology is the selectivity of the metal binding; without specificity, the remainder of the extraction process becomes elaborate and costly".

PI Response:

Reviewer 23456

Comment: Be sure when testing binding selectivity of engineered microbes that brine samples used contain a representative mixture of possible interfering elements. A lab test on an isolated sample may be scientifically interesting, but it is important that this research demonstrate applicability to actual geothermal operation conditions.

PI Response:

Reviewer 23526

Comment: I would suggest that perhaps this project should be targeting “natural” systems, low-temp geothermal springs where temperatures may be more appropriate for the living conditions of the microbes.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006749
Project: Chelating Resins for Selective Separation and Recovery of Rare Earth Elements from Low Temperature Geothermal Water
Principal Investigator: Karamalidis, Athanasios
Organization: Carnegie Mellon University
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23480

Score: 5.0

Comment: The project is on schedule and performing the work outlined in the SOW. Several functionalized adsorbents have shown encouraging results, but adsorption levels do not meet overall expectations. PI has adjusted by adding new ligand candidates. Work in this area (M1) should continue into the next quarter. A patent application has been filed. So far, brines for testing do not come close to what can be expected from real geothermal brines in terms of salinities and constituents. Results are still too preliminary to draw conclusions.

PI Response:

We thank reviewer for their constructive comments. Extracting REE from such a complex aqueous matrix is very challenging, however, we strongly believe that our methodical approach will bring the desired results of selectively complexing REE in a viable manner, which can eventually translate to a commercial application. Our experiments so far have indicated that functionalizing fine particles with various ligands can lead to REE uptake up to 96% even in the presence of a high concentration of Ca in solution. However considering the high cost of using those fine particles for field application, we recently switched to larger silica particles as supports for the REE-binding ligands. These are low cost supports and comparable to particles used in field applications of fixed-bed adsorption technology. We have been successful in grafting linkages on the silica surface and attaching our previously-identified top-performing ligands on these linkages. Experiments with the larger functionalized beads are underway. We are testing the functionalized adsorbents with simple one-REE element solutions, and also investigating effects of ion competition with bulk electrolytes (e.g. NaCl, $CaCl_2$) and major competitor-adsorbate cations (e.g. Zn, Fe, Al).

The team has completed the contracting paperwork with the geothermal power engineering firm ThermoChem as a consultant to our project, and once the ongoing batch adsorption experiments are completed we will ask for their guidance for designing test conditions closer to operating conditions with geothermal fluids.

We are making plans for eventual testing of our adsorbents with brines from the field. The team has contacted Dr. Robert Podgorney from INL, and we requested to be included as one of the groups to receive a round-robin brine (mimicking geothermal fluids) for further testing of our functionalized adsorbents. Also, the UC Davis group - another awardee of the same program - has agreed to share natural geothermal brine samples with us. In addition, the CMU team has made arrangement with the Salton Sea geothermal power plant to receive natural brine from their facilities; needed contractual arrangements between the two entities are in development.

Reviewer 23414

Score: 8.0

Comment: project looks to be on track, they've had some hits and some duds, and are changing course as they go. They are doing all the right tests and are pursuing the goal of targeted REE sorbents in a logical methodological fashion.

PI Response:

We appreciate the positive comments of the reviewer about our progress to date and our planned steps going forward.

Reviewer 23456

Score: 7.0

Comment: Accomplishments so far seem adequate for a program in a very early stage.

PI Response:

The team, recognizing the fast pace of the program, has taken measures to expedite experimentation, testing and synthesis of functional adsorbents by bringing in two more members for a short period of time. A CMU graduate student (supported externally to this program) has started working on the column design during the summer. Another CMU graduate student (supported externally to this program) will assist with some of the experiments for a short period of time starting in September. The additional personnel will help us complete the experimental matrix that the team would like to explore.

Reviewer 23526

Score: 6.0

Comment: This project, like many others in this topical area, has the potential to be highly impactful. Being able to selectively recover specific REE minerals can be a very powerful tool, especially when they are found in such low concentrations in otherwise high TDS brines. As the project is just now getting underway, and few results are available, time will have to be the ultimate judge of the impact of this project.

The preliminary selectivity for Gd seems encouraging, although contact time was quite high for flow rates I'd expect from an operating geothermal facility.

PI Response:

We agree with the reviewer and their overall assessment of the state of the project. We recognize that Gd does not represent the breadth of the elements in the lanthanide series, but given their chemical and physical similarities, Gd is a good model element for the initial development work. We have designed experiments with REE mix solutions and we expect that neighbor elements to Gd will complex with our functionalized adsorbents in similar fashion. Previous experience with development of a liquid-liquid extraction protocol for REE extraction and recovery from brines (Noack et al, Environ. Sci. Technol, DOI: 10.1021/acs.est.5b00151, 2015) showed that the choice of ligands used in this project should sufficiently complex all lanthanides. More experiments are necessary though.

Regarding the contact time, we agree with the reviewer that shorter contact times would be more realistic than the 3 hours chosen for the screening experiments. For consistency among various experiments with fine functionalized particles we maintained the initial contact time. Since we changed direction to using larger functionalized particles, experiments with shorter contact time have been attempted showing partial uptake of Gd. The team recognized the low loading of ligands on the surface of the silica beads and took action in grafting adsorbents with higher ligand density. Experiments for surface characterization of the new larger beads and REE uptake are underway.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23480

Score: 6.0

Comment: The approach is logical, including batch tests of candidate adsorbents. The CMU team has tested two more adsorbents than originally planned, but only one candidate had an adsorption rate greater than 80%. Adding Thermochem to the team should enable more realistic brines to be included in the testing mix.

PI Response:

We intend also to test additional types of adsorbents, such as multi-valent phosphonates. In addition, we will be screening other candidate ligands while the lead adsorbent formulation is taken into further tests with brines and in column configurations. Although we expect to be able to separate lanthanides from brines in small groups, having one adsorbent that selectively complexes lanthanides in this matrix will be a significant advance if we can achieve it. This is our goal. We agree with the reviewer that ThermoChem will help us design our future experiments to be closer to geothermal power plant operating conditions.

Reviewer 23414

Score: 9.0

Comment: while designing better sorbents, they are working out the competing effects of pH, other ions, and so on.

PI Response:

More data about surface characterization of the larger functionalized particles and lanthanide uptake from different matrices are being developed and will be available soon.

Reviewer 23456

Score: 7.0

Comment: The overall technical approach seems sound and the team seems highly capable.
The adaptability of water treatment technology to high flow, high temperature, and complex chemical systems is an interesting idea.

PI Response:

We thank the reviewer for their positive view of our proposed technology and team. The work of adapting water treatment technology and adjusting it to the needs of this project has been already initiated.

Reviewer 23526

Score: 8.0

Comment: The proposed technical approach appears to be sound and valid; I especially like the logical breakpoint between budget periods 1 and 2. The preliminary work on selecting the most promising functionalized adsorbents, followed by the proposed batch testing should provide the required information needed to decide of the project should move forward into a second budget period. Actually flowing the batch experiments with column experiments should provide necessary data for commercial (at least prototype) scale up if warranted.

PI Response:

Although the EERE geothermal program is fast paced, we believe that our previous experience working with high saline solutions, functionalizing adsorbents and engineering separation columns, in conjunction with the proposed layout of the work in two phases will enable us to develop a lab scale prototype column system at the end of budget period 2.

STRENGTHS

Reviewer 23480

Score: Not scored

Comment: The project is well-conceived and logical with each task building on the results of the previous ones. The pathway to achieving a working modular system in the field is reasonable. A geothermal development company has been added to the team to advise on geothermal brine chemistry. Off-the-shelf components are being used which should facilitate scale-up for commercial applications.

PI Response:

We thank the reviewer for their positive view of the project goals and work plan.

Reviewer 23414

Score: Not scored

Comment: surface chemical analysis, sorbent synthesis, reaching out to geothermal industry, patent submitted

PI Response:

The team has filed a disclosure of invention internally to CMU. That disclosure will be filed as a provisional patent application in the near future once more data are generated (e.g., additional surface characterization data, and uptake data with the larger silica particles).

Reviewer 23456

Score: Not scored

Comment: Solid chemical approach to the issue of REE recovery.
Presence of industry partner should help greatly with understanding variability of brine chemistry. It also should help with general comments like "millions of gallons" in presentation (slide 7).
Logical progression in development of chemistry.

PI Response:

We agree with the reviewer about the industry partners. In our response to the first comment in this compilation we describe our plans for acquisition of and testing with actual brine samples.

We understand that our comment about the volume of produced geothermal fluids in slide 7 may have needed clarification. Our intention was to convey the magnitude of the produced geothermal fluids from domestic geothermal operators rather than giving an exact number for the total installed geothermal capacity in the US. We agree with the reviewer that due to variation in production of geothermal fluids per power plant and because of the different type of technology used among those power plants, the CMU team needs to discuss with ThermoChem specifics for the volume production and composition of those fluids.

Reviewer 23526

Score: Not scored

Comment: I liked the use of students as an integral part of the research. It was good to see a presented actually thank GTO for the funding to do the work! Engagement of Thermochem will greatly enhance the potential results of the project.

PI Response:

As described in previous responses, we will engage Thermochem to assist us in designing experiments closer to geothermal power plant operating conditions when have completed further testing with our leading adsorbent(s).

The presenter and the CMU team had submitted a white paper on REE recovery from alternative resources to DOE few years ago, recognizing and highlighting the necessity for exploring this new field of applications, developed technologies of which will partially mitigate the lack of domestic supply of crucial elements for the advancement of modern technologies and create potentially a new market for the domestic industry. We are thankful for the opportunity to explore this potentially promising field of applications given to us by the Office of EERE (DOE). This program is a good example of a vision which may prove to be transformative to the traditional mining industry.

WEAKNESSES

Reviewer 23480

Score: Not scored

Comment: The performance of the adsorbents tested to date has not been outstanding. Using Gd as an adsorption target may not reflect the adsorption capacities of other REEs. Salt solutions are not credible analogs for geothermal brines. Real world brines are especially complex and diverse, with large variations in physical-chemical properties---entrained solids and dissolved gases may be especially troublesome. An operational temperature goal is not stated. The ligands may have preferential binding for chemical elements similar to REEs (e.g., Y, Sc). On the other hand, testing must demonstrate that all members of the series can be bonded.

PI Response:

While we agree with the reviewer that the tests conducted to date are with relatively simple saline solutions, we plan to conduct tests with solutions that represent conditions closer to those in the field, we felt it was necessary to screen ligands and validate the approach using a model brine tested under batch conditions. We are rapidly expanding the complexity of our tests and are implementing many of the reviewer's suggestions in our current experiments.

As discussed in previous responses, the chemistry of properties of REEs have similarities, and Gd is a good representative of the REE group of elements. Our experience with developing a liquid-liquid extraction technique for analysis of REEs, also discussed previously, gives us confidence in using Gd as model REE. We plan to eventually examine the performance of the designed adsorbent(s) with the full range of REEs, but for the initial development work we are focused on Gd, an element with representative REE properties.

Reviewer 23414

Score: Not scored

Comment: none

PI Response:

-

Reviewer 23456

Score: Not scored

Comment: Remember that this is a geothermal program, and early testing at high temperatures will help identify possible successful adsorbents.

PI Response:

We agree with the reviewer. New experiments at higher temperatures have been designed and will be implemented. First experiments will be conducted at 60C, followed by another series of experiments at higher temperature (> 90C). Discussions with geothermal operators have indicated that 90C is a reasonable temperature for lab-scale testing. ThermoChem will be consulted about the design of these experiments.

Reviewer 23526

Score: Not scored

Comment: I wasn't clear on the thermal stability of the materials. I didn't get an understanding regarding the kinetics of the process, I think I heard the presenter state he was using equilibrium constants.

PI Response:

The amide linkages between the ligand and the solid support are highly robust against hydrolysis, even at elevated temperatures. (Amide hydrolysis is often only observed at pH values below 1.) As we refine our testing protocols and move to elevated temperatures, we will re-evaluate the supports to verify that the ligand density has not changed appreciably.

IMPROVEMENTS

Reviewer 23480

Comment: Team should consider targeting only a few REEs (those with the best combination of economic value and concentration in geothermal brines) to permit better tailoring of adsorbents. In particular, finding recyclable adsorbents (and solid supports) that can withstand multiple acid elutions is highly desirable, and work in that area should be started sooner. Integrity of the support-ligand bond deserves attention. Thermochem should be involved in the project at an early stage to avoid "blind alley" experiments.

PI Response:

We agree with the reviewer's view about targeting of the most valuable REEs. However discussions with geothermal operators indicated that brine composition varies greatly among geothermal sites. Our goal is to develop a technology that would initially separate REEs from brines and develop it further in separating REEs in smaller groups. The team is using recyclablesilica adsorbents that are resistant to acid elution from the beginning. While initial work was with fine particle material, we have moved to larger silica particles as supports for the REE-binding ligands.

As noted previously, the amide linkages between the ligand and the solid support are highly robust against hydrolysis, even at elevated temperatures. (Amide hydrolysis is often only observed at pH values below 1.) As we refine our testing protocols and move to elevated temperatures, we will re-evaluate the supports to verify that the ligand density has not changed appreciably.

Reviewer 23414

Comment: none

PI Response:

-

Reviewer 23456

Comment: A comment was made during the presentation that the early testing was taking place with three hours contact time. Shorter contact times would better model potential chemical extraction cycles in geothermal power plant production cycles. Perhaps trying some very short times at geothermal temperatures to assess kinetics would help document the likelihood of eventual success for this program.

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

We agree with the reviewer that shorter contact times are more consistent with fixed-bed adsorption technology than the 3 hours chosen for the initial screening experiments. For consistency among various experiments with fine functionalized particles, and to get an estimate of adsorption capacity, we employed a 3-hour contact time in initial screening experiments. Since we changed our experimental design to using larger functionalized particles experiments with shorter contact time have been attempted showing partial uptake of Gd. The team recognized the low loading of ligands on the surface of the glass beads and took action in grafting adsorbents with higher ligand density. Experiments of surface characterization of the new larger beads and REE uptake are underway.

We are assuring the accuracy and precision of our ICP-MS analyses of Gd and other elements through calibration with each run, evaluation of experimental and reagent blanks, and replicate analyses. All analyses of dissolved REE are performed using an Agilent 7700x ICP-MS with octopole reaction cell. This system allows for direct analysis of high dissolved solids (<1 wt%). Through the course of all analyses, matrix-matched standards are utilized for calibration and are periodically rechecked to monitor and correct for instrument drift; drift in excess of ±10% is deemed unacceptable. Instrument parameters are optimized before each run to maximize analyte response, while limiting formation of polyatomic (primarily oxides) and doubly-charged species.

<u>Reviewer 23526</u>

Comment: Bound your future experiments pH and composition range (synthetic solution) to that of some “common” geothermal brines.

PI Response:

We agree with the reviewer. As discussed in previous responses, we have been conducting initial screeing and development work with relatively simple electrolyte solutions that are relevant to but certainly don't replicate the complexity of geothermal operating conditions. We have developed an experimental matrix that involves increasing complexity of test solutions, eventually moving to tests with actual brines. Our approach was to test our functionalized adsorbents at conditions relevant to geothermal, but also extend the testing to outside the upper and lower boundary geothermal conditions to account for the variation of conditions found among geothermal sites. The last batch of experiments has been conducted with REE concentrations representative of geothermal fluids (i.e. 100 ppb) instead of higher REE concentration that was used in initial screening (i.e. low ppm level). Similarly, we target pH closer to geothermal fluid pH values. Regarding the synthetic solution composition, we refer to our responses at the beginning of this form, as other reviewers expressed similar comments.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Magnetic Partitioning Nanofluid for Rare Earth Extraction from Geothermal Fluids
Principal Investigator: McGrail, Peter
Organization: PNNL
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23414

Score: 10.0

Comment: good that 2 multiple, but limited number of, sorbents is being used. Full life-cycle is being used to inform process. The surface understanding and chemistry is top-notch.

PI Response:

Reviewer 29853

Score: 9.0

Comment: This was by far the best presentation in the group. The approach was innovative, advanced, and has real potential to be a game changer in the field of element recover from produced thermal water. Nano particle are showing promise in a wide range of scientific applications and is an outstanding fit for this particular application. Because any attempt to recover critical or valuable materials from a geothermal stream will be have a tough time being profitable, any technology that can reduce the energy penalty has the potential to be marketable. The research team is making significant progress and is meeting their goals. The lifetime of the particles shows evidence of being longer than 5000 hours, a significant from improvement over competing technologies.

PI Response:

Reviewer 23456

Score: 9.0

Comment: The project has made good progress so far. The researchers are working well to identify solutions to issues they have encountered.
The understanding of the context of element recovery in power plant production cycles is excellent, and lends this project great credence in its ability to achieve its ultimate goal.

PI Response:

Reviewer 23526

Score: 8.0

Comment: This project, like many others in this topical area, has the potential to be highly impactful. Being able to selectively recover specific REE minerals can be a very powerful tool, especially when they are found in such low concentrations in otherwise high TDS brines. The proposed approach stood out as being highly informed of the operational environment at a working geothermal plant.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23414

Score: 10.0

Comment: good blend of theory and experimental verification guided by strong recognition of geothermal conditions

PI Response:

Reviewer 29853

Score: 9.0

Comment: The project is a good example of a properly conducted study (at least in the early phases). The procedures are well documents, and the testing mechanisms appropriate for demonstrating the experimental results. The choice of seawater as a test media is reasonable at this phase of the effort, as seawater is a known quantity with uniform properties and concentrations of REE that can provide reproducible results. Although at later phases of the work the team will need to test the technology on a geothermal bring and associated scaling\deposition issues. The instrumentation used in the study are state of the art provide good results.

PI Response:

Reviewer 23456

Score: 9.0

Comment: The technical approach is excellent. Starting with the end goal, recovery from high flow thermal regimes in ways that do not impact power production is excellent. The selection of magnetic particles for easy recovery enhances the ultimate chance of success for this method.

PI Response:

Reviewer 23526

Score: 9.0

Comment: This project stood out for me in their approach. The team seemed to understand the problem and is offering a solution that should be implementable into a working geothermal operation. At present, I am not convinced of the claims that the capture methods will function as described (80-90% capture with 30-60 second contact time), but I eagerly await testing results.

PI Response:

STRENGTHS

Reviewer 23414

Score: Not scored

Comment: chemistry, nanoparticle syntheses, the microfluidic additive manufacturing angle was particularly impressive. MOF work too.

PI Response:

Reviewer 29853

Score: Not scored

Comment:
Strengths are:

- The team is solid and technically capable
- experimental facilities are well suited to carry out this research

The technology represents a true game changer in this application, and certainly has applications outside of the geothermal field

PI Response:

Reviewer 23456

Score: Not scored

Comment: Excellent recognition of how mineral extraction can fit into power plant production cycles, and the limits these cycles place on possible element recovery strategies. It is nice to see a project that starts with the context, and keeps in mind throughout the realities of working with geothermal fluids. It is also good to incorporate techno-economic analyses throughout the project.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Project is well informed of operational constraints a real world system will emplace, and seem to have a design that can function.

PI Response:

WEAKNESSES

Reviewer 23414

Score: Not scored

Comment: none

PI Response:

Reviewer 29853

Score: Not scored

Comment: By comparison to other projects presented in this session this one is far and away the best. While the other projects had noticeable weaknesses mainly because the presenters were willing to be upfront about them, this project did not have any notice short comings of any significant at this early stage. There are two minor issues that should be considered in the as the project proceeds.

Consider testing the technology on a common geothermal fluid that will allow comparison with the other project.

Incorporate a better understanding of the range of geothermal waters for which such a technology would be applied to.

PI Response:

We thank the reviewer for this suggestions and will do our best to accommodate within time and budget constraints on the project.

Reviewer 23456

Score: Not scored

Comment: Issues with unexpected crystal structures are being resolved.

PI Response:

Reviewer 23526

Score: Not scored

Comment: None noted

PI Response:

IMPROVEMENTS

Reviewer 23414

Comment: none

PI Response:

Reviewer 29853

Comment: At this point the project was well presented, technically sound, is on budget, and is meeting its objectives. The only recommendation for improvement that I can suggest is to identify the path forward to potential I.P.

PI Response:

PNNL Patent Office staff are being kept informed of this project. Normal procedure is to collect sufficient proof-of-principle data before patent application filing and we are well under way in collecting the necessary data so expect a filing decision to be made well before the end of the project.

Reviewer 23456

Comment: Keep up the good work.

Hopefully successful testing will be done on real samples of a range of actual geothermal fluids at operating temperatures, pressures, and chemical conditions.

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

NIST traceable standards for accuracy of the ICP-MS work. Once downselection is made on sorbent, test design will emphasize replication to ensure good statistics on precision.

Reviewer 23526

Comment: I would like to see testing at temperatures in excess of 100C if possible, perhaps up to 120-130C.

Find a geothermal operator to add to your team, even as only an advisor if necessary.

PI Response:

We will incorporate temperature as a test variable once sorbent downselection is made. So we should be able to extrapolate process to higher temperature operations. However, focus of this project is on low-temperature geothermal resources and design is targeted at brine post-heat exchanger so these high temperatures are less likely to be encountered. The PI will definitely reach out to geothermal operators.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006746
Project: Geothermal Thermoelectric Generation (G-TEG) with Integrated Temperature Driven Membrane Distillation and Novel Manganese Oxide for Lithium Extraction
Principal Investigator: Renew, Jay
Organization: Southern Research Institute
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

<u>Reviewer 23480</u>

Score: 8.0

Comment: This project has potential to be a game-changer if all performance criteria are met. Project appears on schedule for technology-based tasks despite delayed start and very ambitious one-year performance period. Good progress reported on development of both major subsystems. No results are reported from the commercial feasibility study, which ultimately affects viability.

PI Response:

A comprehensive technical and economic feasibility study will be conducted during the final quarter of the project, based on all of the data obtained from the various lab and bench scale tests. We agree that this commercial feasibility study will be critical to the viability and potential commercialization of this technology concept.

<u>Reviewer 23414</u>

Score: 10.0

Comment: I SCREWED UP. THE PRESENT REVIEW AND SCORES ARE FOR ADDLEMAN/PNNL. THE REVIEW AND SCORES MARKED "ADDLEMAN" ARE FOR RENEW/SOUTHERN. SORRY.

These folks obviously know what they're doing - impressive analysis of all aspects of the problem, sorption chemistry, sorbent configuration (very exciting), and how to test both adsorption and desorption of REEs. Some early data.

PI Response:

No response. Please provide correct response from reviewer if possible so we can respond to any comments.

<u>Reviewer 23456</u>

Score: 7.0

Comment: This is a highly innovative, very ambitious program with lots of places for significant problems. So far, the progress reported by the team seems adequate. During the upcoming testing of the two subsystems (mineral extraction and power generation), early confirmation of the overall likelihood of success should be known.

PI Response:

We agree. It should be noted that in addition to the testing of the two subsystems, numerous components of each subsystem are being tested independently prior to integration to ensure that targets can be reasonably achieved before full subsystem testing. If specific component targets are met, full subsystem testing will proceed, otherwise, adjustmnets will be made, improved components tested, and decisions to proceed revisited. For example, lithium sorption testing is ongoing at the Carus Corporation, including lithium sorption under simulated geothermal conditions. Additionally, testing of individual thermoelectric generator materials and p-n couples is ongoing to ensure targets can be achieved for full modules. All data produced in these sub-tasks will be utilized in early and regular confirmation of the project and technology potential.

Reviewer 23526

Score: 7.0

Comment: This project appears to have some of the most aggressive proposed objectives, that being to develop and validate thermoelectric generation from low temperature fluids and also to capture/extract lithium from the fluid. Not much comment can be made regarding accomplishments to date, as much of the reported activities seem preliminary.

If successful, this research may open up exciting avenues for low temperature generation. However, while is aspect is outside my area of expertise, I do believe these approaches are being used elsewhere, authors should provide a detailed technology review.

PI Response:

A review of the technologies utilized in this project was contained in the original proposal. Providing a detailed technical review with the requirements of the peer review presentation is difficult and was not requested. Note that the commercial viability, techno-economic assessment, and business plan will contain assessment of the state of the art, competitor techologies, and a thorough review of the technologies and approach utilized in the project.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23480

Score: 8.0

Comment: Project defined by two major subsystems: chemical/brine processing and power generation. This allows for improved work flow/control and better integration within each system. The interface between the subsystems (distillation membrane) will be examined for any performance issues during testing. An innovative design modification (T glide) was incorporated into the membrane distillation subsystem. Both major subsystems will be tested during the project, but the extent to which a fully integrated system will be tested is unclear. The sizing of the TEG at 100 kWe is quite adequate for prototype testing, but the economics should be evaluated at MWe scales.

PI Response:

The latter portion of the project will include integrated testing - with the sole exception of the TEG module. Planning for a larger pilot-scale evaluation is also ongoing. The techno-economic evaluation, commercial viability assessment, and business plan will focus on a specific set of potential commercial scales as well as brine conditions to determine optimum commercial applications as well as range of benefits and feasibility.

Reviewer 23414

Score: 10.0

Comment: Good all around. I particularly appreciate their humility - the awareness that they are probably going to have to shift directions as they go forward.

PI Response:

We appreciate the comment.

Reviewer 23456

Score: 7.0

Comment: The step-wise approach to this program is well thought out, especially given the multiple points for failure of either the Li extraction system or the power generation system. The team has the capability to attack these problems, and has or is building the equipment needed for testing.

It would be nice to have integrated at least bench scale data, to provide substantive data for economic models.

PI Response:

Integrated bench scale testing will occur in the latter stage of the project - Task 3 for the brine treatment process (including memrbane distillation) and Task 4.4 for the integrated membrane distiallation and power generation subsystem. The full, complete system including the TEG will not be tested in an integrated fashion. However, system modeling using results of the aforementioned subsystem testing will be fed into a fully integrated thermodynamic and process flow model for commercial scale integrated system evaluation.

Reviewer 23526

Score: 5.0

Comment: I have concerns that their approach lacks realism, and is overly optimistic and lacks specificity. The process modeling needs/should be carefully and independently reviewed, as many questions I posed I don't believe an adequate answer was provided. A detailed justification for their design assumptions should be provided, or at least considered, for items such as pressure drop across filters, reaction/contact time, and even things such as SiO2 precipitation potential.

All in all, I am encouraged by the presenter's enthusiasm, and   I believe their approach is innovative—albeit perhaps overly aggressive and optimistic.

PI Response:

We appreciate the comment and would be glad to provide additional information regarding the process model, assumptions, and issues if needed. However, our team offers that the project and the proposed integrated multi-component system are feasible and realistic. For example, instead of proceeding with a one step lithium extraction process, a robust pre-treatment system to remove calcium, mangnesium, and silica was included in the project. The inclusion of this system represents a realistic approach to the challenges experienced by low-temperature geothermal fluids with many constituents. This pre-treatment system will undergo research and development side-by-side with the lithium extraction system. We believe this multi-step, integrated approach provides a more realistic scenario for succesful lithium recovery than other options, although we do realize the challenges associated with integrating multiple subsystems.

The proposed system design for both the bench-scale project system and commercial design did incorporate engineering design considerations regarding the hydraulic and chemical aspects of the system, and are an ongoing part of the project. Additionally, the modeling of the system accounts for many of the requirements mentioned in the reviewer comment. Through the bench scale validation process experimental data will be obtained that will enhance the accuracy of the system model and ensure it presents a realistic view of the potential performance, bottlenecks, and costs associated with the commercial scale system. This analysis and supporting data will be provided in the final report that will, hopefully, address the reviewers concerns.

STRENGTHS

Reviewer 23480

Score: Not scored

Comment: Project has well-defined numerical performance criteria for both major subsystems. A hybrid system as proposed here could have a major impact on the use of low-temperature geothermal resources which are plentiful and widespread. Removal of Si, Ca, and Mg greatly improves the chances of success for both power generation and Li recovery. A range of brine compositions are being used, but the degree these formulations are representative of real brines is not indicated. The team is well-balanced and capable, including a geothermal developer.

PI Response:

Brine compositions were developed from available information on real world low-temperature geothermal brines and are considered representative of real brines. Brines formulations included consultation with our geothermal partner.

Reviewer 23414

Score: Not scored

Comment: cited before. Also, if they fail at geothermal extraction, I have confidence that their research will be very applicable elsewhere.

PI Response:

We appreciate the comment. Because of the multi-process integration, we agree that various aspects of the research will be useful independently.

Reviewer 23456

Score: Not scored

Comment: The team is composed of innovative thinkers who have the technical skills to tackle the problem posed.

PI Response:

Thank you.

Reviewer 23526

Score: Not scored

Comment: Very aggressive and enthusiastic. Perspective is from areas largely outside the status quo.

PI Response:

Thank you.

WEAKNESSES

Reviewer 23480

Score: Not scored

Comment: "Steam" is being used for heat delivery to the G-TEG across the membrane. The mass rate of delivery will be affected by the inherently low temperature (<150C) of the brine. The flow rate for the TD DCMD are not given for the bench-scale system. The issue of regeneration/cleaning of the distillation membrane is not addressed. Incorporation of a temperature "glide" in the membrane could exacerbate this issue. The target testing metrics (e.g., >80% silica removal) seem somewhat arbitrary and aren't related to real geothermal brines. Ideally, filtration of major cations should be tied to membrane performance. Adjustments to acidity in the flow stream could lead to problems in process performance. Membrane maintenance and handling of waste streams could have a significant impact on final costs. Results from the economic feasibility task are not presented.

PI Response:

Part of the bench scale project is to analyze and optimize the TD DCMD flux for geothermal brines under different conditions (brine chemistry, temperature, etc.). Impact of membrane maintenance will be taken into account in the feasibility study, based on membrane performance in the bench scale testing. The silica target was set based on reducing the higher silica content in geothermal brines to levels that would be acceptable for TD DCMD systems. We appreciate the comments regarding cations and acidity and will ensure that we pay attention to these issues in our testing programs.

The economic feasibility was not presented as we have not progressed to that protion of the project scope of work yet. After completion of bench testing, the data will be utilized to further advance preliminary modeling and assessment. This will be performed under Task 5 in the final quarter of the project and will include operation and maintenance costs (including membrane maintenance) and waste stream management, as suggested by the reviewer.

Reviewer 23414

Score: Not scored

Comment: none

PI Response:

NA

Reviewer 23456

Score: Not scored

Comment: The first step in the overall process is to precipitate silica. What is the fate of lithium at the temperature (>150 degrees C), pressure, production flow rates, and complex chemical environment of a production fluid as silica is precipitated? Will it precipitate or be incorporated into any clay minerals that might form?

Will silica removal at >80% and Ca and Mg removal at >85% be enough to prevent fouling of the membrane or interfering with the lithium recovery process?
Testing has not yet been done at 100 degrees C, so thermal stability has not been established. If the system doesn't work at 100 degrees C, it's applicability to geothermal sites will be compromised.
Data shown on slide 12 only go up to 250 degrees K. This is about -20 degrees C, or about - 10 degrees F. Not many geothermal systems exist at this temperature range. What data exist that extend to geothermal operating conditions?

The presentation stated that power can be generated in this system for $2500 per KWH. The calculations behind this number, given the innovative nature of the project, should be well documented.

PI Response:

It is very unlikely that lithium will preciptate under these conditions. We will confirm in our bench scale experiments. The sillica, calcium, and magnesium removal targets were set for the higher dissolved solids low-temperature geothermal brines to prevent problems in the system. The silica removal is targeted to prevent fouling in the membrane distillation system. Calcium and magnesium are targeted to prevent interference with the manganese oxide sorption system. Testing at higher temperature conditions is underway under Task 3.

The power specific capital cost of the power generation subsystem is estimated at $2,500/kWe, not per kWh. Thorough documentation of the cost estimation (both capital and operating) will be presented, along with all assumptions and performance parameters utilized in the process model and technoeconomic analysis, in the Final Report.

Reviewer 23526

Score: Not scored

Comment: Much of the preliminary process modeling seems to be in isolation. Haven't considered, or at least carefully thought out, some very preliminary processes that can have a dramatic effect on their process.

PI Response:

We would appreciate elaboration of this comment, as there is not enough detail to determine what the reviewer is referring to. It should be noted that the initial economic analysis and process modeling were indeed preliminary and showed potential of the system, but that an objective of the project is to prove the concept, obtain further data, and perform a thorough process model and evaluation of the system and commercial viaiblity. We believe our geothermal project developer will provide the adequate insight to ensure that we address all processes that may impact the proposed system.

IMPROVEMENTS

Reviewer 23480

Comment: Factor the volume and value of reclaimed water from the system into the economics. Consider volumes and cost of waste streams as well as life-cycle costs of the membrane and filtration/recovery systems. Try to incorporate real geothermal brines into the testing schedule as soon as practicable. Look at feasibility of incorporating other metals, besides Li, into the recovery process. For instance, consider collaborating with other DOE awardees to extract REEs.

PI Response:

We appreciate the very helpful and useful comments. Those factors will be taken into account.

Reviewer 23414

Comment: none

PI Response:

NA

Reviewer 23456

Comment: What are the real power requirements for fluid preparation and Li extraction? Slide 15 states that the "TEG system can provide all power for mineral harvesting, allowing for off-grid operation in remote locations." While this will be a real advantage at some sites, it also suggests that net power production from TEG will not be enough to provide net power to the grid. What is the real power balance here?

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

While the brine treatment and mineral extraction systems will be able to be operated off-grid, with all electrical power provided by the TEG system, the full system will nominally be a net power generator. The power requirements of the brine treatment and mineral extraction subsystems will be evaluated as part of the full process model and economic viability analysis that will be completeted in Task 5. We appreciate the comment and willl consider the issue in our analysis.

Standard laboratory QA/QC procedures are in effect including duplicate analysis, regular calibrations, and utilization of standard, certified analytical methods. It should also be noted that our environmental laboratory is ISO 17025 certified for certain analyses and our energy & environmental department focusing on the membrane distiallation and TEG power generation is ISO 9001 certified. Metal analysis is conducted on ICP-MS.

Reviewer 23526

Comment: Consider effect of scaling on thermo-generation efficiency. Get a closer relationship with a geothermal operator, gain clarity on operating envelopes and rates.

PI Response:

We appreciate the comment. As we progress further and obtain data validating the many subcomponents of the process, we will begin further analysis of the entire system and its subcomponents. This will be completed under Task 5 in the final quarter of the project. During this period, we anticipate significant involvement from our geothermal project developer to provide insight into specific operating conditions, ranges, and rates. This will allow us to produce a realistic process model and economic evaluation, which is critical to advancing the technology.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006751
Project: Environmentally friendly economical sequestration of rare earth metals from geothermal waters
Principal Investigator: Stull, Dean
Organization: Tusaar Corp.
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23414

Score: 9.0

Comment: wish they could give more details - media composition, etc. They have obviously done a great deal of testing. Their familiarity with geothermal brines is impressive. Using a real brine for sorption studies a big plus. These folks know their sorption chemistry very well.

PI Response:

Reviewer 29853

Score: 7.0

Comment: This conceptual design and implementation of this project appears to be very responsive to the overall mission of the Geothermal Office and its stated goal in the mineral recovery program. The researchers show a keen willingness to address the identified knowledge gaps from a technical basic. Their experimental design is well thought out and has a reasonable set of testable goals. The team is on time and on budget with accomplishable goals in the sort and long-term.

PI Response:

Reviewer 23456

Score: 5.0

Comment: This seems to be a solution in search of a problem, and geothermal might be the problem. Some progress is reported as being made toward project objectives. Written materials and the presentation were couched in general and vague terms (e.g., there is "good" capacity), so actual progress is difficult to assess.
They express surprise at the amount of matrix effects in their synthetic brines. It should have been apparent that there would be issues from a chemist's understanding of detection levels and interference patterns in selected analytic methods.

PI Response:

Reviewer 23526

Score: 7.0

Comment: This project, like many others in this topical area, has the potential to be highly impactful. Being able to selectively recover specific REE minerals can be a very powerful tool, especially when they are found in such low concentrations in otherwise high TDS brines. As the project is just now getting underway, and really no results are available, time will have to be the ultimate judge of the impact of this project.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23414

Score: 9.0

Comment: this is an engineering demonstration effort that leans on a lot of difficult science.

PI Response:

Reviewer 29853

Score: 6.0

Comment: Based on the presentation and supplied information the projects scientific and technical approach is at or above average for comparable projects. The approach while logical and reasonably well thought out is not particularly innovative or challenging. That being said, the team is accomplishing the tasks they committed to in a timely and technically sound manner. Over all I rank the projects technical approach as above average compared others that were reviewed during the session.

PI Response:

Reviewer 23456

Score: 5.0

Comment: The researchers seem capable of the chemistry but not strong in knowledge about geothermal fluids and operating conditions. They report adequate but slow progress on the statement of work, but were not strong in linking their work with DOE programmatic goals. They state that "The basic laboratory operations being used are well known." in their project summary, but said during their presentation that they still are doing experimental design. These two statements apparently conflict. The lack of specificity in their written documents and presentation does not provide sufficient data to judge which statement is correct or even if there is a conflict.

PI Response:

Reviewer 23526

Score: 7.0

Comment: This team seemed much more applied than many of the others in the topical area, and is a good compliment to other approaches. I did get the feel that Tusaar has essentially built their hammer and are looking for nails. The matrix approach to rapidly down select designs and/or operational parameters is well thought out. I can empathize with the challenges they have had in creating brines for testing, but I think their approach is solid, although I don't think there is room for IP in the analytical space.

PI Response:

STRENGTHS

Reviewer 23414

Score: Not scored

Comment: real data with real brines, >200 regenerations(!), analytical acumen

PI Response:

Reviewer 29853

Score: Not scored

Comment: The team is very efficient and well organized. They set reasonable and achievable goals though testable hypothesis and supporting experiments. In the absence of any real data regarding REE concentrations in geothermal systems, the team decided upon a target concentration, this shows good initiative and a reasonable approach to the project.

PI Response:

Reviewer 23456

Score: Not scored

Comment: If their proprietary materials work to concentrate selected elements from the high flow rate brines given short contact times, complex physical and chemical operating conditions at high temperatures, if a way can be developed to fit the materials into a power plant energy production cycle, and if element recovery can be done economically, then they might be onto something. That is a lot of ifs, however, that the researchers seem to be downplaying in their project.

PI Response:

Reviewer 23526

Score: Not scored

Comment: The artificial brines they defined appear to be reasonable.

PI Response:

WEAKNESSES

Reviewer 23414

Score: Not scored

Comment: none

PI Response:

Reviewer 29853

Score: Not scored

Comment: Because it is still very early in the projects lifespan it is difficult to identify significant weaknesses. The one area that could be improved is not unique to this project but is systematic across the program as a whole. That is, most of teams including this one, lack a fundamental understanding of the aqueous geochemistry of REE in geothermal systems. Furthermore, this project would benefit from the inclusion of another partner

PI Response:

Reviewer 23456

Score: Not scored

Comment: This project looks like a solution (proprietary materials) in search of a problem. The work so far apparently has not incorporated evaluation at geothermal operating temperatures or chemical conditions.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Low temperature testing (21 deg C) will limit applicability of results, batch testing at 70 deg C will be more useful.

PI Response:

IMPROVEMENTS

Reviewer 23414

Comment: none.

PI Response:

Reviewer 29853

Comment: The only improvement I could suggest at the early phase of this project is not unique to this particular effort. It seemed that many of the projects in this session suffered from a fundamental lack of understanding regarding the geochemical behavior of REE in geothermal systems. This project along with one other seemed to have a better understanding of the geochemistry. It is my opinion that all of the projects would benefit from a common point of reference for their solute concentrations or range of concentrations.

PI Response:

Reviewer 23456

Comment: Remember that these are geothermal dollars that are being spent. It was stated that the goal is to understand the system before testing at higher temperatures. It is important, however, to test your proprietary materials early at high temperatures. If they break down under typical geothermal operating conditions, there is no need to continue this project (as development of alternative material is not part of the project).

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

Reviewer 23526

Comment: None t this time

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006747
Project: Selective Recovery of Metals from Geothermal Brines
Principal Investigator: Ventura, Susanna
Organization: SRI International
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23414

Score: 7.0

Comment: Very interesting analysis of a novel separation technique for Li and Mn. This is more of a longer term effort. Lots of things have to happen for this to be used in geothermal fields; in particular high capacities and recycle performance must be demonstrated.

PI Response:

Reviewer 23480

Score: 5.0

Comment: Project is behind schedule; results are limited. Mn imprinted polymer beads are still in preparation. Batch testing of beads for uptake performance is reported to be in progress, but preliminary results are not given. Li polymer beads have been prepared and surface areas determined. Separation efficiency goals of 95% for Li and 90% for Mn are impressive, but how do they compare with commercially available materials?

PI Response:

Reviewer 23456

Score: 7.0

Comment: The team reports that good progress is being made on their tasks. The level of productivity so far has been adequate.

PI Response:

Reviewer 23526

Score: 6.0

Comment: I think this work has the potential to be highly impactful. Functionally, being able to selectively recover specific minerals can be a very powerful tool, not only for the mineral recovery aspect, but also perhaps for manipulation or as an interjection activity for plants with certain problem minerals.

This work is really just beginning; it will be good to observe progress as time progresses.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23414

Score: 6.0

Comment: The focus is kind of' narrow but, within the goal of optimizing a specific polymer-templated sorbent, these folks are doing what they should.

PI Response:

Reviewer 23480

Score: 5.0

Comment: Approach is straightforward and logical. Sufficient allowance may not have been given to the complexities of real geothermal brines which could interfere with polymer performance. Work on the performance lifetimes (regenerative cycles) of the imprinted polymer beads is not clear from the work plan.

PI Response:

Reviewer 23456

Score: 7.0

Comment: The technical approach is adequate. The researchers are clearly capable of performing this work. The focus on geothermal production environments could be improved.

PI Response:

Reviewer 23526

Score: 6.0

Comment: I have mixed feelings regarding the team's approach. Overall, I believe the methods presented are sound and justified, and the creation of the imprinted beads is novel. Testing in a batch model at temperatures ranging from 45-100C, and then proceeding to flow through tests is also logical. I do have some concern about the plan to add single species into the initial binary mixtures—with the concern being that if you find one of the added species to cause the whole notion to fail it might be better to start with a (or several) representative brine(s). If that works in general then you can specifically look at individual species.

PI Response:

STRENGTHS

Reviewer 23414

Score: Not scored

Comment: sorbent synthesis

PI Response:

Reviewer 23480

Score: Not scored

Comment: Ion imprinted polymer sorbents have notable advantages over other extraction methods, notably the ability to extract just the target ion. This is extremely useful in geothermal brines with large concentrations of undesirable species.

PI Response:

Reviewer 23456

Score: Not scored

Comment: The team has the skills to carry out this research.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Specificity in targeting specific minerals to be recovered.

PI Response:

WEAKNESSES

Reviewer 23414

Score: Not scored

Comment: real world synthesis and how it fits in the larger geothermal system

PI Response:

Reviewer 23480

Score: Not scored

Comment: The impact due to the loss of the project partner needs to be addressed. Success of the project may be in jeopardy. The project has less than a year to run and is already behind schedule; results to date have been slow in coming. Not clear the PI has a plan to remedy the situation.

PI Response:

Reviewer 23456

Score: Not scored

Comment: How these polymers might fit into a geothermal power production cycle is not clearly identified. How will they be introduced in to the working fluid? How will they be recovered from the working fluid? How will captured elements be released quickly?

Their lab tests are allowing for overnight reactions. Will the kinetics of the reaction be scalable to the very short reaction times (seconds to minutes) and very high flow rates of typical power plants?
What other more valuable elements than just Mn and Li might be recovered using this technique?

There did not seem to be recognition that Salton Sea brines are unique, not typical of other geothermal systems in the western US. How will this system work at sites with different chemistries? How will high silica concentrations impact the beads?

Testing beads early in complex fluids with interfering chemistries, high temperatures, and short contact times, will help better define likely future success or failure of this approach.
And please remember that the funding is coming from a geothermal program. Only mentioning geothermal in passing during the presentation, and stating in your summary that the "sorbents should be useful" to 100 degrees C did not instill confidence that this is actually geothermal-oriented research.

PI Response:

Reviewer 23526

Score: Not scored

Comment: Testing of uptake rates may require more thought as adding one species at a time may be problematic. Didn’t come through in the presentation, but way is the possibility for “fouling”, or capturing minerals with similar atomic radi and charge.

PI Response:

IMPROVEMENTS

Reviewer 23414

Comment: bead recycle testing

PI Response:

Reviewer 23480

Comment: Given current status, consideration should be given to focusing on one species (Li?) rather than running a parallel track dual effort.   Several geothermal operators should be sought out who could provide representative samples from their well fields for testing and advice about brine chemistry. An economics analysis should be done during the latter portion of the project (as test results become available) to assess the technology's commercial feasibility.

PI Response:

Reviewer 23456

Comment: See weaknesses and address those issues. Overall, early testing in complex fluid chemistries at high temperatures is critical. Reaction rates must be established early in the program to assure potential viability in field production conditions. If reaction rates are too slow, the technique will be a failure.

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

Reviewer 23526

Comment: Bound your future experiments pH and composition range to some “common” geothermal brines.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006748
Project: Maximizing REE Recovery in Geothermal Systems
Principal Investigator: Zierenberg, Robert
Organization: University of California - Davis
Panel: Mineral Recovery

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23414

Score: 10.0

Comment: this is an outstanding effort to perform a very necessary task - sorting out the basic REE thermochemistry of REEs - which is presently a blank spot. These folks have done a lot of work and have made a great deal of progress. They seem well aware of the analytical difficulties and have made a good start at sorting them out.

PI Response:

Reviewer 29853

Score: 4.0

Comment: This project is really struggling in its technical approach, lack of awareness of procedures already published in literature, a poor choice of test cases. As this project is currently configured, I don't see it being able to make a meaningful contribution to the GTO mission or to meet the objective laid out in the scope of work. The model as presented during the review is not well suited for the task it is being used for. This reviewer also struggles with the Teams concentration on deep sea vents, and the Icelandic seawater recharged system. Certainly these systems represent geothermal waters worth study, but are clear outliers that would not be my first choice to evaluate. Especially since there are so many geothermal systems close by that cover a wide range of normal behavior. Furthermore their sampling methodology (post flash to steam) is poorly considered. Overall this was by far the poorest presentation I viewed during the review.

PI Response:

It is clear from the reviewer's comments that my presentation at the GTO program review did not do an adequate job of clearly explaining our project approach. This was my first experience with a DOE program review, and it appears that I prepared the wrong presentation for this audience. In retrospect, there are several aspects of the presentation I would change. I incorrectly assumed the purpose of the review was to present our progress to date, rather than present the details of our project approach for scrutiny. I had assumed that reviewers had been provided with a copy of our original proposal and that they would have sufficient familiarity with it that it was not necessary to review the details of our analytical approach, but the reviewer's comments show that I was mistaken.

Procedures published in the literature:

The reviewer is concerned that we are unfamiliar with published procedures, and lack experience to complete this project. On the contrary, we have a thorough grasp of the sampling and analytical procedures, as we demonstrate in the original proposal and in our preliminary findings. Unfortunately, the reviewer provides no specific or constructive information that we are able to respond to directly . The reviewer may be concerned we are not employing the Fe-coprecipitation preconcentration technique originally developed in the early 1980's (i.e. Weisel et al., 1984; Greaves et al 1989). The Fe-coprecipitation technique requires large sample volumes (>1.0 liter) and is time consuming. According to a literature review of REE analytical and preconcentration techniques employed between 2000 and 2010 (Zawisza et al 2011), the method we have chosen for our study (use of chelating and ion exchange resins) has become routine for REE preconcentration prior to analysis. These resins require much smaller sample volumes (0.01 to 0.02 liters), and are proven to be effective at a range of brine salinities (Zhu et al., 2010; McLing et al., 2014). We are also familiar with typical QA/QC procedures that accompany ultra trace metal analysis. Perhaps the reviewer is concerned that we did not recite the extensive list of protocols outlined in documents such as EPA 200.8, EPA SW846-6020, as referenced by Shannon and Wood (2005), but we did not think that level of detail was appropriate for a progress review. The graduate student on this project has 6+ years of professional experience sampling and critically evaluating laboratory QA/QC procedures for trace metal sampling and analysis on for EPA, DTSC and Super Fund sites. The PI on the project has extensive experience with projects that have recovered samples from seafloor vents for trace element analysis. The opinion that we lack experience to perform our proposed sampling is not supported by examination of the data we presented in our proposal and summarized in our oral presentation, all of which were collected in advance of our project funding. The data establish that we are capable of conducting the analyses we propose. The QA/QC protocols we employ, and results of our LA-ICP-MS analyses will be available for inspection and evaluation when we submit the data from geothermal fluids sampled and analyzed as part of this project, which is scheduled for the end of the first year's funding (Milestone 3.2).

Test cases:

The reviewer is concerned that we have chosen poor test cases for our evaluation, in reference to our samples from the seafloor and the Reykjanes Geothermal Field, Iceland. On the contrrary, our test cases demonstrate our ability to measure very low REE concentrations in fluids that have an especially challenging matrix. As explained below, the high pressure regime of our seafloor samples will help constrain our thermodynamic models, and are analyzed as a value added component of our research. It is apparent now that our presentation should have made more clear that the bulk of the data to be collected as the core of this project will be comprised of both high enthalpy and lower enthalpy geothermal fluids sampled in actively producing US geothermal fields. We did not focus our presentation on these US samples because we are in the process of obtaining sampling agreements with operators, so no results were available, nor were any of the analyses scheduled to be completed by the end of Quarter 2.

Contrary to suggestions of this reviewer in the “Scientific/Technical Approach” section of this peer review, we have completed an extensive literature search of existing data and procedures. Existing REE data for US fluids are restricted to groundwater, low-temperature surface hot springs, acid sulfate hot springs in protected areas (Yellowstone and Valles Caldera), wells from two geothermal fields in the Basin and Range, and one field from the Imperial Valley. While these data have answered valuable questions about parameters that may influence REE mobility in geothermal systems (Wood, 2001), these existing data cover a restricted range of geothermal fluid types currently being economically utilized in the US. While our presentation may have over emphasized high enthalpy systems in comparison to our more inclusive sampling plan, our emphasis on high enthalpy systems was motivated by the priorities of the DOE program that funds us, which is to enhance the economics of geothermal energy though co-production of REE from produced fluids. Our sampling targets will provide data for a range high-temperature and high-salinity US geothermal systems that are the most likely candidates for carrying elevated REE concentrations. REE show a strong prograde solubility due to enhanced formation constants for various ligand complexes (Wood, 1990), so all other factors being equal, we anticipate REE concentrations will be higher (in the subsurface fluids) in the hotter geothermal systems. The lowest temperature geothermal systems are typically produced using binary-generation power plants and the fluid is directly re-injected in most, which means that recovery of REE form these systems faces the double economic challenge of lower initial REE concentration (again assuming equivalent range of pH, ligand concentration, etc.) and significant redesign of the power production facility to enable mineral recovery.

Technical approach:

The main objective of the project is quantification of REE in geothermal fluids from characteristic geothermal fields in the US, but we can also make a contribution to understanding REE behavior in hydrothermal environment, and thereby better frame the approach for potential economic recovery of REEs. This is clearly an area that we are excited about, because our approach of comparing the measured REE in geothermal fluids with in situ measurement of REE in individual alteration minerals will prove to be a useful contribution to REE geochemistry. High enthalpy wells flash to steam in the subsurface as a consequence of producing the well, unlike the Basin and Range systems where fluids can be pumped to the surface under pressure. Our approach, criticized by this reviewer, of comparing geothermal fluids in high enthalpy systems collected at the well head to pre-flashed fluids collected down-well is critical for addressing behavior of REE in these systems. Phase separation in the well bore will lead to cooling of the fluids and partitioning of acid generating gases into the vapor phase resulting in increased pH in the remaining brine. Changes in temperature and pH are the two biggest controls on solubility of REE. Our sampling strategy will provide the first quantitative observational data as to the consequences of phase separation on REE content of high enthalpy geothermal fluids in producing geothermal fields. In my presentation, my emphasis on what I believe will be one of the most important contributions from our project led to the misperception that this was the primary goal of the project. Our proposal makes it clear that we intend to quantify REEs in multiple geothermal systems, including geothermal systems located in extensional setting such as the Basin and Range, where fluids are pumped from geothermal wells at pressures above the boiling point. There are several characteristics that we know should affect REE geochemistry (i.e. source rock composition, integrated water-rock ratio, ligand concentration) that are best addressed at some of these sites, and they have always been part of our sampling strategy. I should have emphasized this in my oral presentation.

Greaves, M.J., Elderfield, H., Klinkhammer, G.P., 1989. Determination of the rare earth elements in natural waters by isotope-dilution mass spectrometry. Analytica Chimica Acta 218, 265-280.

McLing, T., Smith, W., Smith, R., 2013. Utilizing Rare Earth Elements as Tracers in High TDS Reservoir Brines in CCS Applications. Energy Procedia 00, 1-12.

Shannon, W.M., Wood, S.A., 2005. The analysis of picogram quantities of rare earth elements in natural waters, Rare earth elements in groundwater flow systems. Springer, Netherlands, pp. 1-37.

Weisel, C.P., Duce, R.A., Fasching, J.L., 1984. Determination of aluminum, lead, and vanadium in North Atlantic seawater after coprecipitation with ferric hydroxide. Analytical Chemistry 56, 1050-1052.

Wood, S.A., 1990. The aqueous geochemistry of the rare earth elements and Yttrium 2. Theoretical predictions of speciation in hydrothermal solutions to 350 C at saturation water vapor pressure. Chemical Geology 88, 99-125.

Wood, S.A., 2001. Behavior of rare earth elements in geothermal systems: A new exploration exploitation tool? Final Project Report, DOE Geothermal Reservoir Technology Research 36pp

Zawisza, B., Pytlakowska, K., Feist, B., Polowniak, M., Kita, A., Sitko, R., 2011. Determination of rare earth elements by spectroscopic techniques: a review. Journal of Analytical Atomic Spectrometry 26, 2373.

Zhu, Y., Itoh, A., Umemura, T., Haraguchi, H., Inagaki, K., Chiba, K., 2010. Determination of REEs in natural water by ICP-MS with the aid of an automatic column changing system. Journal of Analytical Atomic Spectrometry 25, 1253-1258.

Reviewer 23456

Score: 7.0

Comment: The overall concepts of identifying the distribution of REEs in geothermal fluids and identifying their fates in geothermal production cycles (i.e., downhole precipitation, etc.) are good. The project will expand our knowledge of REE concentrations in geothermal fluids and systems, and as such be a valuable contribution to the literature.

The work to date has been focused on improving analytic techniques and analyzing selected brines. Unfortunately, the selected brines, because of the geology of their host rocks, may not be representative of those found in US geothermal systems.

PI Response:

The slides for our talk were prepared prior to the end of our second quarter of funding and before any scheduled sampling and analysis of geothermal fluids funded by this DOE grant. We presented geochemical data on the Reykjanes geothermal system, collected prior to the start our funding, as a demonstration that we could sample wells in the field and produce high quality data from fluids that represent one of the largest analytical challenges. The near-seawater salinity of the Reykjanes fluids presents a challenge due to potential interferences from the fluid matrix. We presented these data as a demonstration that our lab is capable of producing quality data from difficult sample matrices. We never intended these data to be representative of the variation of fluid types found in US geothermal systems. The main goal of our project is to characterize fluids that are representative of US geothermal fields, and we intend to have these data available for review by the end of the first year of the project, as outlined in our proposal.

Reviewer 23526

Score: 2.0

Comment: While this project has the potential to be impactful and be a benefit to the other projects in this topical area, I have serious concerns regarding the relevancy of the results as presented at the peer review. I did not see a clear connection to DOE GTO goals and objectives. As presented, it appeared to me that the PI was using DOE funds to essentially follow their own research objectives. In fact, much of the work described and planned did not seem to be aligned with the project SOPOs provided as part of the review materials.

PI Response:

This reviewer's comment misses some key points laid out in our proposal and in the presentation. We have yet to produce or report any REE analysis from this project. The slides we presented were prepared prior to the end of our second quarter of funding, and were simply intended to demonstrate our analytical capabilities and data compilation to date. Our first quarter milestone was to compile relevant thermodynamic data and incorporate those data into existing geochemical models, and this milestone was completed on time. We are on schedule to produce and report data on US geothermal fields that are highly relevant to DOE GTO goals and objectives. Barring unforeseen delays, we will report our REE analyses by the end of our first year of funding, as stated in the milestones of our proposal.

We reiterate that the samples from Icelandic and seafloor systems were obtained at zero cost to DOE. DOE funds were not used to perform REE analysis of the Icelandic waters presented at the peer review. We are including the Icelandic and seafloor samples in our study because they come from unique geologic settings not present in currently producing US geothermal fields, but they none-the-less provide useful constraints on geological and geochemical controls on REE behavior relevant to interpretation of the data we will obtain on producing US geothermal fieldst.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23414

Score: 9.0

Comment: the experimental-geochemical modeling link between UC-Davis and Oregon is perfect

PI Response:

Reviewer 29853

Score: 3.0

Comment: The fact that this team had not done a literature search to evaluate well established procedure for pre-concentrating REE element for analysis is inexcusable. Furthermore their chosen approach is ill suited for doing ultra-trace metal analysis. There are well established procedures that detail how sampling should take place and how analysis should be conducted to avoid the real possibility of cross contamination. The researchers have a long history of conducting meaningful research yet in this study they have not shown that capability.

PI Response:

I disagree with this reviewer's criticism. Contrary to the criticism, we are well versed in the analytical procedures and we demonstrated the high quality of our approach. We presented results from our lab showing high quality analysis of REE in seawater, one of the more difficult matrixes for accurately determining REE due to low concentrations and high abundance of potentially interfering elements. Our data faithfully reproduce the REE content of IAPSO standard seawater within established error limits. We also presented data from well fluids sampled at the Reykjanes geothermal field in Iceland, which also has low concentrations of REE and seawater salinity. We stand behind the quality of our data.

The reviewer fails to provide any constructive substance in the criticism to which we can respond. Please refer to our more detailed response to this reviewer in the "Impact of Research" section of this peer review document, as it may address the concerns the reviewer is alluding to.

Reviewer 23456

Score: 8.0

Comment: The technical and scientific approach will result in better understanding of the behavior of REEs in geothermal production cycles. Thermodynamic modeling should help in analysis of REE behavior in geothermal systems. The PI, co-researchers and graduate students involved in this program have the ability to do the chemical analyses and interpretations.

PI Response:

Reviewer 23526

Score: 1.0

Comment: I have serious concerns regarding the approach being taken, and fear that the results may be irrelevant for the systems GTO is targeting, that being low temperature and co-produced fluids. The work presented to date, that being sampling high-enthalpy systems in Iceland (and the proposed sampling of MOR fluids) does not seem to support the stated goals of the project, that being to quantify REE content in hydrothermal fluids—those of importance and relevance to the United States.

PI Response:

The work presented at the review meeting was accomplished prior to our funding on the GTO project. It was presented in our proposal, and at the meeting, to demonstrate that we are capable of conducting the work we proposed to do, which is to characterize geothermal fluids in a variety of geological and geochemical settings across carefully selected geothermal fields in the US. We have yet to collect and analyze samples from US geothermal fields, as the initial phase of our study was to determine the best fields to sample such that our results can be widely applicable to other geothermal fields.

Available time and money preclude sampling of all producing US geothermal fields, so our approach, as explained in our proposal, is to find geothermal sampling opportunities where we could constrain, to the extent possible, individual variables that can influence REE behavior (including source rock, complexing ligands, pH, T, etc.). We have identified geothermal fields we hope to sample and have contacted the field operators to try to obtain samples that will meet the stated goal of project, which is to evaluate the potential of co-produced fluids for economic mineral extraction.

My presentation may have over emphasized high-enthalpy geothermal fields and I may not have adequately explained our project strategy, which includes sampling a diverse but representative set of geothermal fields. That said, I disagree with the statement that high-enthalpy geothermal systems are not of relevance to the United States. Based on our understanding of the behavior of REE chemistry, it seems likely that high-enthalpy geothermal fields, such as those in the Salton Trough or at Coso, will show the highest economic potential for mineral co-recovery. Data are not presently available to verify this supposition, but the goal of our project is to collect the data needed to make those evaluations, and we are on track to accomplish that goal. I would also point out that the United States includes protectorate territories that also have potential high enthalpy resources as well.

STRENGTHS

Reviewer 23414

Score: Not scored

Comment: combining the experimental measurements with the geochemical modeling, the new REE thermodynamic database that will be produced

PI Response:

<u>Reviewer 29853</u>

Score: Not scored

Comment: The team has established good connections with partners who have been able to provide geothermal water that is not typically available, especially water from deep sea vents. The institutions working on this project are top notch research organizations and should be capable of supporting the quality of work needed for this type of study.

PI Response:

<u>Reviewer 23456</u>

Score: Not scored

Comment: The analytic capabilities of the researchers are excellent. They have both the skills and the equipment to do the job well.

PI Response:

<u>Reviewer 23526</u>

Score: Not scored

Comment: • None noted

PI Response:

WEAKNESSES

<u>Reviewer 23414</u>

Score: Not scored

Comment: none

PI Response:

Reviewer 29853

Score: Not scored

Comment: As presented the project suffers from a number of potentially fatal weaknesses:

1. The researchers show little knowledge regarding how to do ultra-trace metal sampling

2. Concentrating on deep sea and direct ocean recharged thermal system. While interesting, these types of systems are so unique they potentially have little application to geothermal systems in the continental US

3. The data collected and the modeling approach does not appear to be capable of producing the required outcomes.

4. There was no mention of an economic evaluation, which is a major project objective listing in the provided material and on the presentation slides "Quantify the potential economic benefits of co-recovery of REE in the systems evaluated"

PI Response:

The four review points in this section are mistaken.

1. We disagree and presented data from samples collected in the field and analyzed in our labs that demonstrate that this statement is unfounded. The graduate student on this project has extensive experience planning and implementing trace metal sampling on high-profile EPA and DTSC regulated contaminated sites.

2. While I agree that my presentation may have been overly focused on high enthalpy systems, our proposal clearly indicates that we plan to sample a wide variety of carefully selected geothermal systems. Our proposal, and the associated milestones, clearly indicate that these data will be collected in Q3 and Q4 of the initial year. Our plan is to submit the data to the GDR in Q5, fulfilling Milestone 3.2.

3. The data we are collecting will produce the required outcome, which is a quantitative assessment of REE concentrations in selected geothermal fluids in actively producing US geothermal fields. These data are critically needed so that the potential economic benefits of co-recovery of REE can be evaluated. The REE thermodynamic database is a critical tool for all team members. The thermodynamic data currently available for REE at elevated temperatures (Wood et al., 1990; Haas et al., 1995) rely on theoretical extrapolations of thermodynamic data collected at 25 Celsius. Recent experimental work on REE complexes at elevated temperatures has demonstrated these extrapolations significantly underestimate the stability of REE complexes at elevated temperatures (Migdisov et al., 2009; Williams-Jones et al., 2012; Migdisov and Williams-Jones, 2014). This project will incorporate the updated REE complexation data into existing and very powerful fluid and mineral geochemical modeling software.

4. I did not adequately emphasize one of the important goals of our research project, which is an evaluation of the potential economic benefit that could result from co-recovery of REE elements in geothermal fluids in producing geothermal fields. True economic evaluation requires quantitative data on the REE concentration of geothermal fluids. These data are presently unavailable and our project is the only research project funded as part of this DOE program that is addressing this critical data gap. We do plan to evaluate the economic potential of REE in geothermal fluids from the geothermal systems we analyze, but this analysis will of necessity be completed after we have quantified REE abundances in geothermal fluids.

Haas, J.R., Shock, E.L., Sassani, D.C., 1995. Rare earth elements in hydrothermal systems: Estimates of standard partial molal thermodynamic properties of aqueous complexes of the rare earth elements at high pressures and temperatures. Geochimica et Cosmochimica Acta 59, 4329-4350.

Migdisov, A.A., Williams-Jones, A.E., Wagner, T., 2009. An experimental study of the solubility and speciation of the Rare Earth Elements (III) in fluoride- and chloride-bearing aqueous solutions at temperatures up to 300°C. Geochimica et Cosmochimica Acta 73, 7087-7109.

Migdisov, A.A., Williams-Jones, A.E., 2014. Hydrothermal transport and deposition of the rare earth elements by fluorine-bearing aqueous liquids. Mineralium Deposita 49, 987-997.

Wood, S.A., 1990. The aqueous geochemistry of the rare earth elements and Yttrium 2. Theoretical predictions of speciation in hydrothermal solutions to 350 C at saturation water vapor pressure. Chemical Geology 88, 99-125.

Williams-Jones, A.E., Migdisov, A.A., Samson, I.M., 2012. Hydrothermal mobilization of the Rare Earth Elements - a tale of "Ceria" and "Yttria". Elements 8, 355-360.

Reviewer 23456

Score: Not scored

Comment: While it is exciting to get brines from seafloor vents and Icelandic geothermal systems, it must be noted that these are basalt-hosted geothermal systems. REEs geologically are found concentrated in alkaline, not basaltic rocks. It would be much better to find examples of brines from geothermal systems hosted in alkaline rocks, in order that the analytic results and modeling are applicable to US continental geothermal systems. While it is valuable to know about REE distribution in sea water and sea water influenced geothermal systems, these results are not likely to be directly applicable to geothermal systems in Nevada and Utah, for example.

PI Response:

We intend to sample fluids from a range of geothermal systems in the US. Our site selection criteria for evaluation of REE in geothermal fluids specifically included addressing the role of source rock and we are certainly cognizant of the fact that REE behave as incompatible elements in igneous rocks. Our results from Icelandic systems and seafloor systems include data we have previously analyzed or will analyze at insignificant cost to the project. These data will provide constraints regarding the influence of fluid chemistry vs. source rock and the role flashing to steam in high enthalpy systems and will provide useful constraints on our evaluation of thermodynamic models of geothermal fluids.

Reviewer 23526

Score: Not scored

Comment: It appears that the results of the project, if it continues in its present direction, will be irrelevant. For the level of effort being put into foreign fields and wells, I suspect that dozens of domestic samples could have been collected and analyzed. I fear the PI does not have a firm grasp on the operations geothermal fields and plants.

PI Response:

Samples collected from Iceland were obtained at no cost to this project, and no project money will be spent outside of the US. Our budget for sample collection is exclusively targeted to US geothermal fields. We have proposed using analytical funds to analyze samples collected from selected non-US geothermal fields where there are opportunities to gain insight into the behavior of REE in geothermal systems. Because we have neither sufficient time nor money to sample all US geothermal fields, we have taken the approach of targeting geothermal fields where we have the best potential for understanding the relative importance of specific factors that control REE mobility. A specific example of this approach was presented to justify our decision to sample a transect of wells along a salinity gradient at the Reykjanes peninsula in Iceland. We know that REE in low SO4 and CO3 systems are predominantly complexed by the chloride ion, thereby increasing the solubility. The Reykjanes peninsula provides a unique setting where a salinity gradient, from seawater to fresh water systems, is developed in rocks of similar composition at similar T, P, pH and eH. There is nowhere in the US where we can so cleanly isolate the role of chloride in the absence of other controlling variables. That is why we have chosen to take advantage of this important natural laboratory. Other variables (for example variable source rock in geothermal systems operating at similar T, P and pH), will be best evaluated in different locations. We have been evaluating US geothermal fields that represent the best candidates for addressing as many of the potential controlling variables as we can, recognizing that perfect end-member situations where only one variable is changing in nature are rare.

IMPROVEMENTS

Reviewer 23414

Comment: I'd like to see a sneak preview of a geochemical reaction path prediction of REE movement at a geothermal well. You should be able to start linking the prediction with the field geothermal data before the thermodynamic database is done.

PI Response:

We agree and have started testing the models using published data in anticipation of modeling the data we are presently collecting.

Reviewer 29853

Comment: Perhaps the presentation was so poorly presented that this reviewer was not able to gather from it the necessary element to see this projects path to success. I believe the whole project needs to be revisited and organized "if the end results are to have broad applicability that is needed to support the GTO mineral recover program."

1. Move away from characterizing extremely unique systems

2. Reach out to researchers with experience conducting REE type geochemistry

3. Reevaluate their sampling methodology, to my knowledge it would be a rare case where an operating facility would allow geothermal fluids to flash down the borehole. Money could be better spent sampling at the surface.

4. While it is interesting to sample deep see vents, if the investigators are going to do this type of work they need to rationalize the connection between that work and how the resulting data would support the overall GTO mission.

5. It does not appear that the team is practicing ultra-trace metal sampling procedures, which is critical if the data is going to be published

PI Response:

I apologize that my presentation did not adequately convey the importance of our project in providing data that are critically needed to evaluate the economic potential of REE recovery from geothermal fluids. Our data will fill a critical data gap and will provide quantitative results needed to determine the best use of resources in any future mineral recovery programs that address REE.

1. The reviewer mistakenly believes our sampling will focus on Icelandic and seafloor samples. As outlined in our proposal, our project will focus on geothermal fluids from a range of US geological settings. We will focus on producing areas in the US that have previously not been characterized for REE. Our sampling strategy is to identify characteristic or 'type section' geothermal fields with an emphasis on understanding the role of the many competing variables that control REE behavior such that the results can be extrapolated to geothermal fields that we are not able to sample. As we have not yet sampled US fluids, the major focus of our work, we presented data from Iceland in our peer review to demonstrate our analytical capabilities.

2. We initiated our project with a compilation of existing REE data. We are aware of, and deeply appreciative of, the contributions of those who have paved the way for our study, and in particular, the pioneering work of Scott Wood and colleagues in quantifying REE in hydrothermal fluids. Scott has already been very generous in providing data to my student, Andrew Fowler. We have also been in contact with Professor Zhu, who has been very helpful with suggestions about using his method for REE determination.

3. We have never intended to intentionally induce a producing geothermal well to flash, nor are we interested in collecting down hole samples from wells where representative geothermal fluids can be obtained by sampling at the well head. Most of the producing geothermal fields in the Basin and Range province are lower enthalpy systems where standard well sampling procedures can provide representative samples of subsurface fluids. We recognize that the US geothermal industry is highly focused on these lower enthalpy systems, and we intend to do the best job we can of characterizing the REE potential of these given the funding available to us.

We also admit that our interests are biased towards high enthalpy systems. In part this is because we take a broader and more forward looking approach to supporting geothermal development as necessary component of moving our economy away from fossil fuels. The international geothermal community has clearly recognized the economic potential of high enthalpy geothermal systems. Analyses of the potential for the US to significantly increase the proportional contribution of geothermal to the US energy mix correctly identifies that it will not be accomplished by greatly increasing the number of 5-30 MW binary plants, but rather through development of a high enthalpy systems combined with EGS. Even taking the more near term view, there are important high enthalpy systems in production in the US (e.g. Coso and Salton Sea), as well as prospective systems (e.g. Medicine Lake, Hawaiian Rifts) that represent important resources for future development.

Higher temperature systems can be reasonably anticipated to have higher REE concentrations and may therefore be the best targets for the initial development of mineral co-recovery systems, so we think they are relevant to the DOE mineral recovery program. Development of mineral recovery technology is more likely to occur at the higher temperature systems, and if the technology proves to be cost effective, be improved and extended to the lower temperature systems that likely contain lower concentrations of dissolved minerals. There is a reason why Symbol built its Li recovery demonstration plant in the Salton Trough rather than the Basin and Range. While we plan characterize geothermal fluids from Basin and Range style geothermal systems, we feel that focusing exclusively on these systems is short sighted.

High enthalpy geothermal systems flash in the well bore when produced. The flashing cools the remaining fluid, and raises the pH of the liquid phase. This will affect the solubility of REE in these systems. We are trying to improve geothermal models to evaluate the consequences of phase separation on REE solubility, but we can only model equilibrium. We also need to determine what is happening in geothermal wells where partitioning of REE may not be controlled by equilibrium processes. Our approach to address this problem is sound and is proceeding on two fronts. First, we need to compare fluid sampled at the well head to fluid sampled in the bore hole at a depth below (pressure above) the level of phase separation to quantify the behavior of REE in producing high temperature geothermal fields. Second, we are using LA ICP MS to characterize the REE content of scale and alteration minerals for comparison with well fluids. Ideal samples of co-existing fluids and alteration minerals are difficult to come by as down-hole fluid sampling and recovery of drill core are uncommon in the geothermal world, due to high costs. We are never-the-less doing the best we can to address fluid-mineral partitioning of REE in geothermal systems using available scale and cuttings samples. An alternative approach to addressing high temperature fluid/mineral REE partitioning in real world geothermal systems is described below.

4. The rational for sampling deep sea hydrothermal systems, and the connection to the overall GTO program objectives, is that the deep sea vents provide the opportunity to sample high temperature geothermal fluids and coexisting mineral precipitates and determine the partitioning of REE between fluids an solid, something that has not been accomplished in an on-land geothermal system. We are particularly excited about the newly discovered Pescadero Basin hydrothermal vent field. While typical "black smoker" vents provide a good analog to the Reykjanes geothermal field, the Pescadero Basin fluids have lower T and higher pH and our initial geochemical data indicate they will provide a good analog to alkali-chloride geothermal fluids that occur in a significant portion of US geothermal. These fluids are precipitating calcite (along with anhydrite and barite), which is a common vein and scale mineral in on-land geothermal systems. The samples we have obtained allow us to quantify co-existing fluid/mineral REE contents in at T, P and fluid compositions representative of the down hole conditions in many active geothermal fields.

Analysis of a selected set of deep-sea hydrothermal fluids and minerals is an extension of what we originally proposed and is not included in our SOPO. The cost of obtaining these samples is indeed very high, but it is important to repeat that we are making them available to this project at zero cost. The only cost to the project for including these samples is the additional analytical expenses. Because we are already set up to analyze these types of samples, the incremental cost to include them with the samples we proposed to analyze is minor. We have offered to include these samples in our project with no increase in budget and no reduction in the analytical work we committed to do on on-land geothermal systems. We view this as value added change in our project that would not only advance our scientific understanding of REE behavior in geothermal systems, but would also bring positive attention to the DOE GTO program when the papers reporting the discovery of this important new vent field are published. If DOE does not want us to extend our project to analyze these samples, we will analyze them separately. If DOE is interested us expanding our project to include these samples (at no additional cost), the data will be included with the data we submit to the GDR and the DOE grant will be acknowledged in publications that include these data.

<u>Reviewer 23456</u>

Comment: Contacting US geothermal producers to get samples of domestic geothermal fluids, rather than Icelandic or sea floor fluids, will help make the results more in line with DOE programmatic goals.

What is the QA/QC program to assure accuracy and precision of analytic results?

PI Response:

We have contacted US geothermal producers and are proceeding as planned to quantify the REE abundances in US Geothermal field. I believe we have already addressed why the addition of Icelandic and seafloor geothermal fluids is relevant to the DOE programmatic goals.

QA/QC is being addressed by running many samples in duplicate, by analysis of well-characterized standard solutions, and by the collection and analysis of field, trip, and method blanks to quantify background contamination and detection limits. In addition, matrix spike samples will be used to evaluate the recovery of REE during the pre-concentration step. We are happy to provide a full outline of our QA/QC protocols on request. Our data will be reported for both technical and scientific peer review. We have no intention of presenting any data that don't meet our standards for accuracy and precision. Some reviewers have clearly expressed their opinion that we are not competent to produce quality data. All we ask is that future expression of opinions of the quality of our data are based on an actual examination of the data.

<u>Reviewer 23526</u>

Comment: FOCUS your efforts where they will do the most good for the GTO and the domestic geothermal industry, as well as the other projects in this topical area.

Concentrate on the geothermal fluids that we will have access to, that being those coming out the backside of operating powerplants.

PI Response:

I believe the comments above have already been addressed in our response to the reviewers. I acknowledge that I have no prior experience in working with DOE or the DOE program review process and some reviewers clearly found my presentation at the meeting to be inadequate. My assumption that the review panel would be familiar with the content of our research proposal was clearly in error. The value of reviewing the results of a planned two-year research project based on accomplishments of the first two quarters still eludes me. We completed all of the scheduled tasks and meet all of the milestones for the first two quarters, and we plan to complete the analyses of fluids sampled from US geothermal fields as scheduled in our proposal. In addition, we will provide data compilations and unique samples beyond the original SOPO at insignificant cost to the project. The review team has expressed many serious concerns about our project. We hope that our response to these concerns have clarified what I failed to convey my oral presentation.

One goal of the project is to determine the geochemical controls on REE concentrations in geothermal reservoir fluids, then to track their chemical behavior through the processes of boiling, cooling, and scale precipitation -- all of which occur in various geothermal energy production settings. By understanding the REE geochemistry, we will better be able to generalize about the geologic settings where economic REE recovery is optimal and about what chemical processes could be used to recover the metals. Understanding the REE behavior in relation to cooling, boiling and scale precipitation will also enable better engineering of a REE recovery system to prevent uncontrolled or pre-mature REE precipitation in scale. By examining a range of geothermal properties in high-enthalpy and low-enthalpy systems with various host rock compositions and various chemical and physical attributes (e.g. Temperature, pH, Cl- concentration), we are able to round out the science of REE geochemistry to provide the knowledge necessary to an economic evaluation of REE recovery potential. In this case, systems in Iceland, the seafloor, and elsewhere provide valuable data that is not necessarily available in in the currently producing US systems.

In summary, quantitative data on the REE composition of geothermal fluids is lacking. No one is going to invest in the technology to develop REE recovery schemes for geothermal fluids if the potential economic benefit cannot be evaluated, and that economic assessment cannot be made in the absence of real data. Nearly every presentation at the Low Temperature Mineral Recovery session referred to the critical need for quantitative data on the REE content of geothermal fluids. Our project is the only project that is designed to provide these data and to evaluate the economic potential of REE recovery from geothermal fluids. Our proposal presented a solid plan for accomplishing this goal, and the reviewers who evaluated that proposal recommended us for funding. We accomplished every goal and milestone in the first two quarters of our project and we are confident that we will be successful in completing the work we proposed on schedule. In addition to the practical value of providing critically needed quantitative data on the geothermal systems that we sample, we are excited about the potential for our research to advance the understanding of REE behavior in geothermal systems in general and feel that our results will be applicable beyond the systems that we are able to sample directly. We also feel that we will accomplish this in a highly cost effective manor and that DOE will get a large return on their investment. We look forward to proceeding with our project.

Systems Analysis, Resources Assessment, Data System Development & Population, Education Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Strategic Analysis
Principal Investigator: Augustine, Chad
Organization: NREL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 6.0

Comment: In terms of productivity, I found the project unsatisfactory. In my opinion, the main questions were answered, in spite of what the team reports. While there are reports of accomplishments, some of the responses is that the origin of the barriers were not available, so how can barriers be identified? Perhaps I misunderstood the report presented on the slides. Some of the assessment is still ongoing and I am not clear when they will be finished or delivered. I am wondering myself if the challenge of doubling the use of renewables steered the efforts to an abstract analysis without sufficient data and the team did not research the potential if nothing happens to understand if the resources are simply not viable commercially. I felt as if something was reported, but, as opposed to the team, there is not enough to support decisions (I found odd the way this was written in the summary: "… to inform decisions …").

PI Response:

Reviewer 23403

Score: 7.0

Comment: This effort attempts the tall task of projecting into the future of GT energy addressing issues like possibility doubling geothermal energy production by 2020 and also the potential targets for 2030, 2040 and 2050. With respect to 2020, the question that may arise here is that doubling is sought from which level? The investigators also want to assess the (economic) barriers posed by competing renewable energy sources and develop strategies to enable successful execution of projected deployment plans.

An analysis of geothermal projects revealed that almost half the projects were discontinued for unknown reasons. The effort has identified the major barriers slowing the deployment of geothermal projects, estimated the potential capacity of the projects that are possible candidates for deployment by 2020. In the process the geothermal supply curves were updated based on improved analysis methods and data used. In the analysis, the Casa Diablo 4 project was used as an example. In the process, the geothermal updates to ReEDUS were undertaken significantly by adding more tranches, enabling easy identification of technology and resource type deployed, and allowing different deployment assumptions, resulting in enhanced model flexibility. The out-year projections to 2050 with improved cost scenarios were undertaken. A number of activities relative to geothermal heat market remain to be undertaken. Otherwise, the progress seems to be on track.

PI Response:

Reviewer 23422

Score: 8.0

Comment: This project tries to identify the strategically important issues to the Geothermal Technologies Office (GTO) in the future. Specific study objectives include identifying the potential and barriers to double geothermal deployment by 2020; providing potential deployment targets and scenarios for years 2030, 2040 and 2050; accessing geothermal heat markets in US; and develop 3-year projection of geothermal strategic issues. An initial analysis of geothermal projects under development, status, barriers and conclusions about the project capacity was completed. The ReEDS model has been modified to increase the number of geothermal technology tranches from 2 (hydrothermal and EGS) to 5 (identified hydrothermal, undiscovered hydrothermal, near-hydrothermal field EGS, Shallow EGS, and Deep EGS). Geothermal supply curve inputs for the ReEDS model were updated. The primary impact from this project lies in identifying and conducting the studies necessary to properly inform decisions on upcoming issues likely to be important to GTO over the next several years. As some of the results are not ready for public dissemination yet, the impacts in the public domain is unknown.

PI Response:

As an update, we are working to update the analysis and publish the results of the barriers to doubling geotehraml analysis so that it is in the public domain.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 7.0

Comment: As per the 'algorithm' itself, the project followed the correct recipe in trying to mine the data and produce a form of scenario analysis, but I found it incomplete at best.

PI Response:

Reviewer 23403

Score: 7.0

Comment: For assessing the possibility of doubling GT energy deployment by 2020, existing project data were compiled; development status and project barriers including type and severity were identified and categorized, and finally identified the deployment potential by 2020.

For out-year projections, updated ReDUS for more type of GT power generation technologies; updated ReDUS to reflect most recent cost and resource data as well as GTO goals.

PI Response:

Reviewer 23422

Score: 8.0

Comment: This project compiled the project data, identified project status/barriers; categorized barrier type/severity and assessed potential for deployment. For Out-year projects, the project updated ReEDS model, geothermal supply curves inputs and assumptions. Preliminary ReEDS runs are conducted to estimate potential market deployment. Some other elements such as geothermal heat market resource potential, heating demand, technology/cost and alternative heating options are also analyzed. These technical approaches seem serving well for the goal of providing some strategic analysis.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: Not enough attention was given to the current projection to determine if the current resources can deliver a significant fraction of the desire goal, because of say technologies, market, etc. I found frustrating that no further analysis or suggestions were provided to resolve the issue on missing information. Often knowing why things happen is most of the answer. Is there a way to infer or find out reasons? I think that direct contact with stake holders might provide some suggestive data.

Reviewer 23403

Score: Not scored

Comment: No comment

PI Response:

Reviewer 23422

Score: Not scored

Comment: The lessons or feedback from the past analysis (or similar projects done in the past) may be helpful for such strategic analysis. The detailed analysis approach is not very clear, but it seems that a deeper dig in those discontinued projects may expose more insights or impacts from these projects.

PI Response:

As a quick update, we are currently "digging deeper" by contacting developers to confirm and discuss the identifeid barriers, and are planning on publishing the results.

IMPROVEMENTS

Reviewer 25420

Comment: Based on the perceived weaknesses, I would recommend the team to phrase the barriers in more tangible form. For instance, is it commercial potential? If so, what is the real underlying differentiator that would turn some projects more commercial? Perhaps the answer is already available. However, if this is a matter of incentives to deploy projects, where are the real near-future witnesses? How long does it take to generate the required power/energy? A clear admission of the limitations to complete the study would certainly be useful

PI Response:

Reviewer 23403

Comment: Include uncertainties and specify reliability of projections.

PI Response:

Reviewer 23422

Comment: For strategic analysis, a loop with positive feedback or lessons from the past/current are helpful to validate and improve the analysis. How the past data and projected future data can be used as feedback or validation for better strategy plan may be interesting to explore. More details on the barriers and rational behind the barriers may be helpful.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geothermal Resource Potential and Supply Curve Improvement
Principal Investigator: Augustine, Chad
Organization: NREL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 5.0

Comment: Given the short time frame and apparent modest research goals, the project made significant progress, before its closure. The design of the project, though, faced what actually happened to be a significant hurdle and numerous smaller objectives. It turns out there is not a good enough survey, detailed enough, of T=f(Z). It seems as if the project required some preliminary data generation, before embarking on the proposal and the project itself. The need for a supply was amply documented, but there was no clear notion of the state of the surveys available. I would judge the productivity of the project high, but it turned out too ambitious for the resources and time available. The progress reached is valuable and provides a partial answer to the objectives of the project.

PI Response:

Reviewer 23403

Score: 8.0

Comment: This is yet another effort towards incremental removal of the limitations of the capabilities of the spreadsheet based software GETEM so that better estimates of resource potential and supply curves can be made by updating the cost estimates for different hydrothermal EGS (Enhanced Geothermal System) resource types (shallow, in-field) and low-temperature EGS geothermal resources in the Eastern USA (direct-use, co-generation offsetting the use of fossil fuel).

In the case of shallow EGS resource potential studies, the findings on electricity generation potential were compared with previous MIT study and improved prediction by the present study was indicated.

In the effort on in-field EGS resource 6 publicly available data sets on existing geothermal wells in Nevada were analyzed, validated with published data for Desert Peak facility, and applied to Blue Mountain facility leading to the identification 5 potential candidate wells.

Geothermal curves were successfully updated and incorporated into ReDUS.

The low-temperature direct use resource evaluation was hampered by a lack of direct use resource potential data in the target location.

In some instances, the completion date of various tasks overshot the target by as much as 12 months. But the project seems to have been successfully completed and no further plans are reported. One publication and one presentation accrued from this project.

PI Response:

Reviewer 23422

Score: 7.0

Comment: This project studied how to improve the resource potential and supply curve estimates for key geothermal resources. The technical accomplishments include updated cost estimates for hydrothermal and EGS resource types with GETEM; improvements in shallow EGS resource potential estimates; improvements in in-field resource potential estimates; and development of an estimate for low-temperature EGS geothermal resources in the Eastern US. These are in line with the broader Geothermal Office's mission and goals. The improvement of the resource potential and supply curve estimates for key geothermal resources from this project can provide accurately assessing the potential of current and future geothermal technologies. The cost estimate and resource potential updates can aid GTO in setting program goals, strategy, and R&D priorities. The achievements largely follow the original planned milestones though the delivery of the database of geothermal wells and draft of temperature-at-depth map are a bit delayed. A couple of publications and presentations are made from this project.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 6.0

Comment: I found the approaches somewhat narrow in that the team did not provide alternatives to address the underlying problem of lack of data. I thought the project simply 'reported', almost to the point of declaring meeting milestones, but not answering the impending questions. In principle there is nothing wrong with the approach, but this is typical of following an algorithm and stopping for lack of data, instead of looking for alternatives to solve the problem. If the problem is beyond the scope, at least a declaration of limitations in a critical way would lead to the formulation of a new project or at least an extensions. The problem at hand still remains, in my view.

PI Response:

Reviewer 23403

Score: 8.0

Comment: Studies on shallow EGS resource development the temperature at depth maps were developed in collaboration with SMU Geothermal Laboratory by gathering different elements of thermal data of in the region of interest and appropriately processing to create temperature maps covering the depths of 1 to 4 km for use in the estimation of resource potential.

In the case of in-field EGS potential resource improvement studies a number of dry wells in existing hydrothermal fields were identified and maps were generated and a database containing relevant information on individual wells were created.

To estimate supply curve cost updates, GETEM was suitably modified and applied site-by-site basis to estimate costs of potential hydrothermal/EGS geothermal projects based on the currently identified situation and formatted for input into ReEDS model.

In studies on low-temperature direct use geothermal resources in the eastern USA, number and size of current installations were cataloged; converted installed capacity to fossil equivalence; demand centers were identified; and create a strategy document of potential and options.

PI Response:

Reviewer 23422

Score: 7.0

Comment: For the supply curve cost updates with GETEM, the project acquires the latest version of GETEM and runs it on site-by-site basis to estimate costs of potential hydrothermal and EGS geothermal projects. The results are then incorporated into new supply curves formatted for ReEDS. To improve shallow EGS resource potential estimates, the project analyzes several existing dry wells, develops databases of geothermal wells, and generates maps for overall in-field estimate. For the approach to estimate low-temperature EGS geothermal resources in the Eastern US, the project categorizes the number/size of installed capacity of direct-use geothermal resources; identifies demand centers for heating in the Eastern US; and develops documents on potentials/options in Eastern US. The technical approaches are straightforward and are largely executed in the project tasks based on the original plan.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: It is hard to allocate weaknesses to the project, because the team in reality made a frantic effort to provide answers to the supply curves, but the reality is that the weakness relates to the design of the project and not its execution. This is somewhat common, when gaps in previous knowledge are detected and a new project is launched to fill the gap. A second weakness of the project is the existence of too many secondary goals/objectives, in other words, the project itself became too ambitious. Although the resources allocated were not negligible, the expected rate of execution was too steep.

PI Response:

Reviewer 23403

Score: Not scored

Comment: No comments.

PI Response:

Reviewer 23422

Score: Not scored

Comment: The technical barriers lie in the acquiring data for analysis. While acquiring data may be enhanced with new data sensing/mining technologies, the analysis and technical approaches do not show many novelties. A straightforward update on the estimates and the lack of exciting insights may further weaken the technical contribution.

PI Response:

IMPROVEMENTS

Reviewer 25420

Comment: The weakness can be turned into a project to resolve the issue identified, namely the design of a survey or surveys to gather the missing information. I would encourage the team to use this ‘problem’ as a way to design a proposal that would address this problem. The team was actually working on two projects, one of which had the allocation of resources, while the underlying one, i.e. the survey, was stealing resources from the approved project.

PI Response:

Reviewer 23403

Comment: No comments.

PI Response:

Reviewer 23422

Comment: In addition to the estimates update, some analysis on the performance of the estimates may be interesting. In other words, how good or bad of the estimates can be further measured and analyzed. How to validate the estimates may also be interesting. Not only the input data can be updated for estimate update, the history, current and future prediction may be also incorporated to offer better estimates.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: The Value of Geothermal Power for Integration of Intermittent Generation
Principal Investigator: Edmunds, Thomas
Organization: LLNL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 9.0

Comment: I would like to highlight a number of very positive observations on the progress/execution of the project. First, the team has made good use of previous investments in GTO funded research activities. I found it excellent that the project team has identified challenges in the stringent requirements regarding the intermittence of renewable resources that will required geothermal generation operators to adapt in order to generate business opportunities that arise with the potential new revenue streams.

I found the project well placed in context with a clear understanding of the market drivers that derive from political decisions. The data have been exceptionally scrutinized and the team shows tremendous expertise in the execution of the project. By the same token, good productivity has been shown and the outcomes of the research have great potential impacts. The results were superbly presented. Despite being highly technical, and understanding of the final destiny of the results of the project to final users was clear.

The project accomplishments address important aspect of energy markets driven by political decisions and open the door for opportunities.

PI Response:

Reviewer 23403

Score: 8.0

Comment: Geothermal power plant operators can mitigate variability and uncertainty by operating plants in a more flexible mode depending upon the demand cycle. This study explores economic incentives and innovative reservoir management for geothermal plant operators to provide such flexibility. It is necessary to estimate additional revenues that geothermal plant operators could earn by way of frequency regulation in the State of California under a system mandating 33% renewable energy by 2020.

For the stated purpose, the investigator utilizes existing stochastic weather and production simulation models developed at LLNL leading to 30 possible daily renewable generation profiles. The cost of system operation is minimized by using LLNL's stochastic power-grid optimization model. If the local GT power grid is part of the main grid with a large-scale electric power backbone, the uncertainty of grid operations will be greatly accentuated. Consequently, this project, however, focuses on addressing the challenges of efficiency, economic planning, operation and control of a stand-alone geothermal energy source by applying stochastic weather modeling and optimization tools available at LLNL. The primary objective is to gain savings by balancing supply and demand which is typically represented by the, so-called, “duck curve”. In the case of geothermal power, flexible operation tends to extend well life as well.

The value of this research is limited isolated operation of a GT Power station which will no doubt be far from reality. The more complex problem of optimizing the operation of a local grid which is part of a main grid is a more challenging issue.

The project seems to have been completed as per the stated objectives and publications have accrued which were not accessible to the reviewer.

PI Response:

Reviewer is correct in his observation that the GT power station was evaluated as a isolated operation. The underlying assumption is that the GT plant operator is a price taker, i.e. GT plant operations do not appreciably change market prices for energy and ancillary services. This assumption is justified if GT production is not a large fraction of total generation in the western interconnet.

<u>Reviewer 23422</u>

Score: 8.0

Comment: The project attempts to estimate additional revenues that geothermal plant operators could earn by providing flexibility such as frequency regulation, load following, spinning reserve and non-spinning reserve to the system operator. A specific scenario for California 2020 is investigated. The project identifies additional revenue streams, which are expected to grow in magnitude as more intermittent renewable generators are introduced into the grid. Estimation are made on hourly prices for energy, frequency regulation, load following, spinning reserve, and non-spinning reserve services in a high-renewable-penetration market. The project seems following the proposed plan and project findings are documented in three papers and conference presentations. The primary conclusions of the project include the suggestion on considering the reward flexible operations and additional modeling/analysis needed to examine proposed higher renewable generation targets for California (40-50%) and other states.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 25420</u>

Score: 9.0

Comment: The scientific approach was impressive and rigorous. The team was well equipped to handle the challenges of the project. Moreover, initial delays were handled quite well to meet all the goals/milestones without modifications or delays. This was well executed in its entirety and the team made good use of previous developments. I found most assumptions quite reasonable and the approach of looking at historical weather data and other sources adequate.

PI Response:

Reviewer 23403

Score: 7.0

Comment: The study mostly focuses on using the LLNL software as a black box and no details regarding methods and procedures are presented. It does not seem to address the larger issue when the local grid is part of a main larger grid which may be a conglomerate of traditional (like fossil) fuel as well as alternative energy sources of different types (say, wind, solar, etc.). The results presented seem to satisfy the objectives.

PI Response:

It was not possible to describe the full detail of all the models used for the study given the time and space constraints for the paper and presention. Additional detail regarding the models is provided in our report that is currently in the publication process at the California Energy Commission. Also, see previous commetn about operation in a main larger grid.

Reviewer 23422

Score: 8.0

Comment: The project uses results from production simulation models and dispatch logic for geothermal generators. With the limited available resources, it seems that the used approach is the appropriate one. It will be interesting to identify those factors on the estimation and maybe a smooth mathematical model can also be a candidate to be developed and used to compare with the results from simulation models.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: While advanced simulation tools for weather forecast lead to the best predictions of our state of the art, reliance on those forecast might create rather biased results, because at the end of the day they are simulations. My best guess is that this was compensated by considering extreme behaviors in the 30 different forecasts used. The other aspect that is mildly concerning is the true ability of geothermal companies to respond to rapid demand peaks and still receive enough incentive to adapt to these markets. Other than that, I thought the project was well developed and should serve as an example of a highly technical and well-crafted proposal that used the expertise pool and experience of this team.

PI Response:

Reviewer 23403

Score: Not scored

Comment: No details regarding methods and procedures of the LLNL tool used. No answer is given when the local grid is part of a larger main grid. One wonders if the demand curve and price predictions have been validated by actual observations (say, for 2014 and 2015). No mention of the random variables used was made.
The scope of geothermal reservoir management with dynamic characterization was not mentioned.

PI Response:

It was not possible to describe the full detail of all the models used for the study given the time and space constraints for the paper and presention. Additional detail regarding the models is provided in our report that is currenlty in publication at the California Energy Commission. Reviewer is correct in his observation that the GT power station was evaluated as a isolated operation. The underlying assumption is that the GT plant operator is a price taker, i.e. GT plant operations do not appreciably change market prices for energy and ancillary services. This assumption is justified if GT production is not a large fraction of total generation in the western interconnet.

Reviewer 23422

Score: Not scored

Comment: The detailed estimation and simulation model is not very clear to the reviewers. The estimation does not seem very challenging, but meaningful.

PI Response:

Additional detail regarding the models is provided in our report in publication at the California Energy Commission.

IMPROVEMENTS

Reviewer 25420

Comment: The only consideration I can add is to further the analyses conducted, but in general not much can be said to compensate any perceived deficiency.

PI Response:

Reviewer 23403

Comment: Incorporate the following:

- Interaction with main power grid.
- Handling of more than one type and number of alternative energy source within the local grid.
- Try it on a pilot project.
- Address the issue of actual implementation by a GT Power operator.

PI Response:

Good suggestions.

Reviewer 23422

Comment: A detailed demand and supply engine can be incorporated into the estimation. Other impacts from technology advancing and potential cost from customer/operator sides with the flexible operation may also need consideration. Maybe a comprehensive mathematical model can be developed to 1) validate the results from the simulation model; and 2) provide another aspect or some sort of theoretical analysis that can be compared with the simulation. Some linear programming models can be good candidates for this.

PI Response:

Linear programming models used by LLNL for this study. Model validation is always a challenge for stochastic models of the performance of systems that do not exist (the power grid in the year 2020). A historical year could be modeled to provide confidence that the 2020 model is valid.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geothermal Prospector
Principal Investigator: Getman, Dan
Organization: NREL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 8.0

Comment: This highly qualified team has made us of a standardized GIS tool at NREL that provides a multi-layered presentation of attributes for the exploration of geothermal opportunities. Since the work is used on a platform that has supported other applications, there is both expertise and sufficient experience to resolve issues and enhance the Prospector further. The quality of the work is outstanding and the potential impacts large. The summary slides indicate that simplifications have been completed to enable the package use, but this remains a challenge as a few users have tried it. Extensive analysis and examples were presented. The tool can really serve as a useful backdrop to make decisions on geothermal prospects. Given the complexity of the platform, the few delays with milestones are quite acceptable and not major. I had a chance to attend a presentation on the system and thought that it would serve high-end users to conduct very detailed and multivariate analysis with this powerful visualization tool. Filters and thresholds have been refined to facilitate consistent analysis. I will provide some comments as to why I believe users have not attempted to use this tool in the weakness and suggestions criteria. Efforts have been made to share the potential of this tool.

PI Response:

Reviewer 23403

Score: 8.0

Comment: This project is concerned with adding new features to the online tool ‘Geothermal Prospector’ meant for visual exploration of geothermal resources to help in the assessment of resources, data exploration, and eventual identification of the most favorable location for new geothermal energy development, allowing easy access to best data repository such as NGDS.

In 2012, Version 1 of this GIS application was completed by the investigator and delivered to DOE. First enhancement of analysis capabilities was delivered in 2013. In 2014, newer versions with initial integration with NGDS, prototype of multivariate capability, and an upgrade to OpenCarto architecture were released.

A demonstration of the latest version of ‘Geothermal Prospector’ was highly successful performing exactly the way it is designed to do. It could display the locations of all current geothermal plants and zoom in on one of specific interest. The satellite view allowed display of the footprint of the target plant in relation to the surrounding ones. Layering ability allowed superimposition of different layers with different data attributes of the site. Apart from these and more display capabilities, it allows the user to save the analysis for other interested parties. It is, therefore, a valuable tool for all the stake holders (industry, regulators, and consumers) involved in the advancement of geothermal energy by assessing impact of various factors on economy and environment and help lowering the risk and cost of geothermal exploration. The software can be used by GTE researchers. The most powerful feature of this capability is the ability to visually explore complex datasets.

PI Response:

Reviewer 23422

Score: 9.0

Comment: This project tries to develop and enhance the Geothermal Prospector which explores the inherent cost and formatting data necessary for geothermal exploration. The Geothermal Prospector provides access to explore, query, visualize, and download data necessary for understanding the costs, risks, and potential for geothermal renewable energy. With this Geothermal Prospector, users can find the best data and analysis from the federal government; identify areas having high geothermal potential with minimum of access constraints; and share spatial datasets resulting from DOE funded research in public domain. The majority of the planed milestones have been completed as planned. The accomplishments include second phase of update in OpenCarto framework, multivariate visualization of wells data and interoperability with NGDS. Multiple presentations, demonstrations and tutorials have been delivered by this project. The information and tools from the Geothermal Prospector seems very interesting and useful to many related communities.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 9.0

Comment: The team use a solid platform to develop the tool and conducted rigorous testing. They incorporated identified improvements and continue to evolve the tool. It is at present a very impressive tool for prospecting geothermal resources. The visual multilayered system alongside the filtering techniques is a great way to lower dimensionality and provides the conjunction of data sources that are needed for decision-making. From my standpoint, there rigor in the development and team is highly technical. The approach of reusing a tested tool is commendable, because it is uses an established culture of data analysis, based on an extended tool like GIS.

PI Response:

Reviewer 23403

Score: 8.0

Comment: In the latest version of Geothermal Prospector, two of the most important features are integration with National Geothermal Data System (NGDS) and the implementation of OpenCarto framework. In the first case it allows launching of Geothermal Prospector using data listed in the NGDS catalog. In the second case, the advantage of using NREL's OpenCarto framework is to enable a superior user interface and allow other capabilities for easy data transformation, multi-scale mapping, dynamic vector and embeddable mapping. These upgrades have made the interface more user friendly, enabled significant improvement in performance, and allowed simple layer thresholding. In addition, downloading of database and accessing of metadata has been significantly simplified as well as downloading of results is possible. Users can query by point, box, polygon, or attribute. Also, a summary report of a specified region can be created. The effort is on track and ready for the next phase of possible enhancements and maintenance.

PI Response:

Reviewer 23422

Score: 8.0

Comment: The technical approaches of this project are sound and effective in delivering rich information as users needed. Particularly, the Geothermal Prospector application is built on top of OpenCarto, which was built to support web based GIS and multivariate visualization applications. OpenCarto uses open source tools and currently supports more than 18 individual applications focused on various RE technologies. Through the utilization of standards based data services, the Geothermal Prospector application is developed to be interoperable with the NGDS. The development of a multivariate visualization capability allows users to explore these data through the selection and filtering of more than one attribute. The public accessible website from this project indicates the approaches have been well executed in the project tasks.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment While I enjoyed the presentation on the project and found the demonstration compelling, I thought that the very appearance of powerful and complex is what has limited attempts to use the tools. If I recall correctly, a question regarding templates was formulated in either the demonstration session or the review session. It is clear that the intent is to enable users to conduct a free inquiry on the data available accessing the multilayers of information that serve as sieve for selection of prospects. This ‘freedom’ without sufficient guidance can be daunting. In some sense, the users has to become an expert, as it is not a trivial matter how to set up the analysis.

PI Response:

Reviewer 23403

Score: Not scored

Comment: Lack of good documentation.
Hardware platform independence!

PI Response:

Reviewer 23422

Score: Not scored

Comment: It might be helpful for the project team to get on the tables of potential users more. In other words, the lack of adoption of the Geothermal Prospector by the related communities might indicate the customer needs could be further understood or analyzed. Hence, the project may be tailored more towards what users need (instead of just what the Geothermal Prospector can provide).

PI Response:

IMPROVEMENTS

Reviewer 25420

Comment: To avoid the self-defeating power of the tool, I suggest creating simplified, pre-cooked templates that execute basic queries, in way to progressively train users as they seek out information. As I learned in a presentation years ago, we human beings are better at knowledge and wisdom, and computers do better with data and information. It might be better to guide through baby steps. They may not reveal the full extent of the possibilities, but it certainly trains users to think of the style of the graphical tool, if a few basic, but common queries are readily available. This, in a few words, is a form of self-guided workshop.

PI Response:

Reviewer 23403

Comment: Consolidate interface with NGDS.

Enable portability to different platforms.

Create a good user documentation.

Data enhancements.

Long term maintenance plans.

Start user group.

Extend capabilities to renewable energy sources.

PI Response:

Reviewer 23422

Comment: It seems the awareness of such great tool deserves some improvement. The Geothermal Prospector seems to be a complicated and very interesting tool. The impact and adopter could be more if some tutorial or college class modules can be developed and available. Inviting potential users and spreading the words can be helpful. Not only just geothermal community, but also technologies or policy-maker majors can benefit. With emerging sensing and network technologies, it will be interesting to see real-time and dynamic data feeding into the Geothermal Prospector automatically.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: GT-Mod
Principal Investigator: Lowry, Tom
Organization: SNL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 8.0

Comment: The project clearly states that it is being moved from the GTO model development phase to the analysis one. Modern statistical techniques have been incorporated to handle coupled complexities and attempts are shown in terms of promoting the use of the tool. Progress was shown during presentation time and limitations have been recognized. There is significant potential in the use of inverse Laplace transform to infer probabilities, but this is an aspect that will require better training of users to make sensible interpretations. There were questions regarding secondary uncertainties, namely associated or based on the physical model represented, that are being addressed, but need additional and careful work to be conducted. In this sense, it appears the focus has been on aspect of managing uncertainties, with considerations of the physical models adopted somewhat out of the scope of the project. This could explain why work on secondary uncertainties does not appear to be as mature as that related to managing complexity. However, the question remains as to the confidence that the complex analysis can provide. I dare say that the research has potentially significant impacts and as per design of the project, it is progressing accordingly. The results in general are satisfactory and carefully crafted in appearance.

PI Response:

Reviewer 23403

Score: 6.0

Comment: A limited amount of information on GT-Mod is available as conference publications (namely, one by Lowery et al. In 2011) and it was not possible to know the real capabilities of this software. It is not clear if all the associated aleatory and epistemic uncertainties were identified and more sensitive ones were selected based on data mined from a reliable source. In the case of epistemic uncertainties, does GT-Mod allow for updating as more data is available with the passage of time? Also, one may wonder, if the consideration of uncertainty is limited to the reservoir behavior only, or other influencing factors are considered. Very little has been stated about the software module used to simulate the physics, chemistry, advection and diffusion problems. For every added new feature, it is necessary to validate the simulation results. The supplied documents and presentation are not specific on this issue. Another important question relates to the method of quantification of risk on both individual subsystems and the overall system. One may wonder if social and national issues like economy, energy independence, security, politics, etc. along with the availability of other alternative sources of energy are part of the equation.

PI Response:

Regarding the limited amount of information: We are fully aware of there not being a fully detailed publication of the structure, governing equations, etc. of GT-Mod. Most of the publications and presentations to date have focused on the use of GT-Mod and the results of various analyses (see the peer-review presentation for a list of publications). However, this is a good comment and we agree that it is probably time to put such a paper together. This would also cover the 'software module', physics, chemistry, etc.
Regarding uncertainty: GT-Mod allows for uncertainty concerning any input parameter. There is no limitation as to how many parameters are considered as uncertain but the number of simulations necessary to produce statisically valid results will increase exponentially in relation to the number of uncertain parameters. Any of the parameters are easily updatable as new data become available.
We like the comment regarding the social and national issues like economic energy dependences, security, etc. It is a long-term goal of ours to continue to expand GT-Mod to consider some of these broader dynamics.

Reviewer 23422

Score: 8.0

Comment: This project provides DoE and related communities with a Geothermal System Analysis and Risk Assessment model to assess the risk in the system of geothermal energy production. The model developed in this project can capture the relation and interaction among multiple components and uncertainties to offer useful information for decision making. The project developed dimensionless parameter approach for reservoir performance simulation, Laplace Transform inversion for system dynamics models and a single-loop binary power plant module. The study suggests that pumping requirements for horizontal wells may be higher in low, fracture-dip formations. The results from this project are published and disseminated through over 10 publications, which should have significant impact in the community.

PI Response:

No comment.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 8.0

Comment: As explained the critiques of the previous criterion, the approach in regards to statistical techniques as well as complex system analysis appear robust and executed by a group of highly qualified experts. The physical models on which predictions are being made have not been examined further as to determine the effect of the model on the outcomes of the predicted by GTO. However, this might be something to consider. There was a question regarding the Value of Information, to which the Speaker indicated that it would be possible to do, but hasn't been conducted at present. The challenges presented seem to indicate that economic and system performance are tied to the physics-based models, but it does not address the effect of assumptions of the models, which was referred to as secondary uncertainties. One question that remains is given the complexity of the dynamical systems represented, what would actually drive risks? I felt that complexity could obscure the understanding of where major efforts should be invested. The approaches are solid in general, but analyses are being conducted without answering questions regarding the effect of different components in geothermal system. While all these questions cannot be addressed in one project, it is important to create confidence. I would recommend investing in ways to manage Value of Information exercises. If risks are to be mitigated, they are usually require capturing information or equivalently paying for tests that will provide the information.

PI Response:

Reviewer 23403

Score: 7.0

Comment: The effort essentially represents the adding of new features to the existing software framework: GT-Mod, originally developed at SNL for studying the physical and economic performance of GT power production allowing for uncertainties.

The development of ambitious software like GT-Mod with all the necessary features (bells/whistles) requires interdisciplinary effort with contributions of experts from diverse disciplines. One may wonder if the development team represents such diversity. The stated objectives are important and part of which seems to have been accomplished. The progress seemed to be sluggish, hopefully, not due to lack of capability.

PI Response:

GT-Mod has been created in a development platform called Powersim that allows for both coding and visualization in one package and that can be implemented w/o expertise in graphical programming, database management and the like. While ther are limitations to the platform, such as a relatively low ability to integrate with other codes, we feel the benefits of using Powersim far outweigh the deficits.

Reviewer 23422

Score: 8.0

Comment: It seems the project is well planned and undertaken to achieve the proposed goal. The technical approach is sound. Although, more detailed "what-if" analysis and how to evaluate the effectiveness of the developed model still remain a bit unclear, particularly, as the system consists of multiple components, and multiple uncertainties. Given a set of uncertainties, generating a targeted probability may not be difficult. However identifying the correlation among those uncertainties and identifying the major factors among those components and uncertainties might be interesting to explore. This may better highlight the direction to optimize system design and operation. Also, with emerging sensor technologies, more real-time data from the physical power and well systems can be collected and analyzed to be as valid inputs for the system, which may remove some of the uncertain inputs.

PI Response:

We fully agree with this comment. As GT-Mod continues to mature we intende to pursue this line of inquiry.

STRENGTHS

Reviewer 23422

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: In general, the project presents very few glaring weaknesses, if any. As usual, there is focus on the expertise of team members, which hardly qualifies as a weakness. Perhaps something that was mildly apparent is reliance on model system technologies, non -linear system analyses and credible statistical techniques and not so much of the physics-based modeling aspects, but to be fair, this did not appear to be the focus of the project. I would have wanted to see more testing of the system with the intent to determine modeling component that need to be improved.

PI Response:

Reviewer 23403

Score: Not scored

Comment: Lacks enough evidence of progress towards reaching the more important objectives.
Lacks highlighting of methods used and results obtained.
Lacks highlighting of the most important aspects of the progress made so far.

PI Response:

We agree with this comment. Over the span of this project, DOE has allowed a high level of latitude with regards to how and why GT-Mod is developed. This has been a benefit in that it has allowed the research team to move the development of GT-Mod in different directions as the needs of the DOE GTO change. At the same time, it has been a limitation in that it has meant that the project has not remained focused on one aspect of development or in answering specific questions.

Reviewer 23422

Score: Not scored

Comment: The major weaknesses of the project are that the validation process and performance evaluation of the developed model are not very clear. Decision making will be easier and making more senses if the developed model can generate results close to the optimal results. On the other hand, if we do not know the performance of the model, we may not know how much trust (during decision making) we should have on the results from the model.

PI Response:

Because system dynamics models are focused on the dynamics between systems, validation at the highest level is difficult if not impossible to achieve. However, the sub-models that are focused on specific physical processes are and have been validated against their various test cases. For instance, the Gringarten solution module was tested against the same

parameters given in Gringartens 1975 paper, "Theory of heat extraction from hot dry rock". The same is true for the Carslaw and Jaegar module.
Furthermore, part of the treatment of uncertainty within GT-Mod is to allow users to test scenarios across different solution methods and dynamic approaches to examine the impact of solution method and accuracy on final results.

IMPROVEMENTS

Reviewer 25420

Comment: I would recommend providing a detailed analysis of which components in the GT-MOD model can generate the largest uncertainties or equivalently serve as the main source of secondary uncertainties. I would use of the project time to address Value of Information protocols. Moreover, I would like to see what limitations are associated with models for each of the components of the geothermal system. For instance, a horizontal well or any number of them can yield predicted benefits that as indicated in the presentation could in principle reduce risks (it was not clear how this is accomplished), but to what extent this response to geological considerations? Without being aware of these aspects, it is difficult to undertake actions based on confidence in GT-MOD. Perhaps this can be framed with a list of what-if scenarios that are not well modeled in GT-MOD, despite all the complexity handling in the system.

PI Response:

Reviewer 23403

Comment: Remove the stated weaknesses.

Make verification and validation an important element of each subsystem.

Clarify how GT-Mod will characterize risk.

PI Response:

See the comment above re. verification.
Regarding the treatment of risk, GT-Mod doesn't calculate risk directly but rather risk is calculated as a post-process. Our preferred approach is to calculate risk as the product of the probability of an event occurring and the consequence of it occurring. Through the use of uncertainty, GT-Mod is used to calculate the probabilities of different events occurring (e.g., reaching a certain LCOE) but it is up to the user to decide what the consequences may be.

Reviewer 23422

Comment: As the model depends on uncertainties, finding an approach to validate and evaluate the developed model will be interesting. Otherwise, one may view the output a bit uncertain as a result of uncertainty input. One can use history data to help this and particularly large set of history data and automatic data collection/mining can be helpful.

PI Response:

We agree with this comment.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Projected Deployment of Geothermal Technologies Subject to Water Availability Constraints
Principal Investigator: Macknick, Jordan
Organization: NREL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

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IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 6.0

Comment: The project addresses an important consideration for the development of geothermal resources, particularly EGS. The project suffered from several delays, several of which appear to be well-justified. The project team managed to produce some interesting results that were presented during the review session. The delays might explain why a few to no signs of productivity in terms of articles, proceedings and presentations. I would categorize this as low productivity, though I understand some of it was not the team's responsibility. Although the finding that EGS has a higher water demand should be anticipated or even obvious the fact is that this is now documented and therefore quantified. These results attend to objective 1 in the project, but comments will be provided in the weaknesses as to the validity of the analysis. The second objective has not been addressed as thoroughly, but perhaps this requires additional pending work. The gaps filled are more semi-quantitative in nature and some of the perceived weaknesses should be addressed in this or a later project.

PI Response:

Reviewer 23403

Score: 9.0

Comment: Geothermal technologies require water for drilling and construction, cooling, make-up for water losses from the subsurface, flash steam cycle, and well field stimulation and availability of same is an important issue in the development of geothermal systems and situation may become acute, especially, in arid areas and also in the case of EGS. The primary objectives of this investigation are, first, to study if the lack of plentiful supply of freshwater can be a limiting factor in deploying geothermal systems; and, secondly, to evaluate the possibility of replacing freshwater usage with other measures including alternative or non-fresh water resources.

The issue is significant from the point of view of GT site selection as affected by local and regional planning decisions related to available water resources and the possibility of using alternative resources.

The study has led to interesting results leading to the conclusion that most geothermal processes can use alternative water resources instead of freshwater.

The investigator has successfully achieved the objectives. The outcome of this study will be of great value in GT prospecting and site selection.

Plans for the communication of results of this study are laudable and the availability of the modified version of ReDUS as part of 'Geothermal Prospector' is welcome.

PI Response:

Reviewer 23422

Score: 8.0

Comment: Geothermal technologies may require water for drilling, construction, cooling and so on. This project investigated what kind of factors are the water limitations and evaluated the tradeoffs associated with utilizing different cooling systems and alternative water resources. The study from this project can help the industry and researchers to identify exploration sites that have sufficient water resources of all types. In addition, the analytical accomplishment in the project can help improve regional and local geothermal planning decisions by incorporating a parameter of water resource. The key features of the project include unique capability of incorporating water resources as a constraint or opportunity in electricity sector and developing greater resolution of geothermal technologies.

A series of maps highlighting geothermal resource and availability of water have been developed. The ReEDS model has been extended to incorporate multiple parameters such as geothermal technology types, cooling types and supply curves. The project seems to be slightly delayed due to some reasons. This may also result in that only few publications and presentations have been disseminated.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 6.0

Comment: The team accessed the best collated sources of data available to them, which was part of the originated delays. The staff is qualified and has experience in this type of analysis in a bigger context. Some of the assumptions, such as water demand and supply, weakened the quality of the analysis in my view. I anticipated something like a Net Present Value (NPV) analysis, but I found no evidence in the material provided. While effort was placed in obtaining solid sources of data, no future projection of value of some inputs were clearly presented and hence there is a risk in taking the results at face value. I would have liked to see a broader discussion on water rights, which might have a significant impact regarding water availability and use. I also suspect that other constraints associated with reactivity or effects on EGS performance due to heat-transfer coefficient that can diminish with the use of low-quality water use.

PI Response:

Reviewer 23403

Score: 9.0

Comment: NREL's Regional Energy Deployment System (ReEDS), a deterministic optimization model of the deployment of electric power generation technologies and transmission infrastructure throughout the contiguous United States into the future was used as a vehicle for this investigation after modifying it to include the effects of costs, availability and constraints on different resources available for energy development. The modification also included greater detail on geothermal technology costs and performance characteristics. The study accounted multiple electricity scenarios to assess different levels of geothermal cost, performance, and water-use characteristics, as well as available fresh and alternative water resources. Supposedly, it will be integrated into the 'Geothermal Prospector'.

PI Response:

Reviewer 23422

Score: 8.0

Comment: The project evaluated the technical, economic and water tradeoffs associated with different types of geothermal technologies and configurations in various regions. Multiple electricity scenarios with different levels of geothermal deployment and water resources are analyzed. Regional Energy Deployment System (ReEDS) model is used for the electricity modeling analyses. The project leverages multiple prior works from NREL and Argonne National Lab. The technical approach and execution in this project are sound.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: Based on the presentation and questions formulated by the panel, I would like to summarize several perceived weaknesses:

1. The project assumes that water needs as well as water availability will be constant. This strong assumption is detrimental to confidence in the analysis presented, because as clearly presented during the review session, the geothermal resources are ubiquitous in arid regions. A more detailed analysis might be called for. 2. Water rights can play a role in water access, but this was not discussed to a sufficient degree, if at all. 3. NPV scenario analysis does not seem to be part of the project. Water costs are assumed to be constant. Water quality differences might trigger the need for water treatment or reservoir stimulation due to reactivity with rock, deposition or precipitation of organic and inorganic compounds, etc. I would anticipate significant costs that were not considered. In essence, a Net Present Value analysis might indicate that despite the desire to use lower-quality water sources, this might not be possible to a sufficient level to

make a difference. On the other hand, this is difficult to evaluate without the data. I would like to suggest using some resources to include this type of analysis within this or another project. 4. Uncertainty has not been considered, because the project is data-driven, but without considering these effects. It might be possible to consider this by using scenario analyses.

The project could integrate some of the necessary added-value analysis and fix some of the weaknesses without significant effort on the team.

PI Response:

Reviewer 23403

Score: Not scored

Comment: ReEDUS is a deterministic model.
What alternative water resources have been considered is not explicitly stated.

PI Response:

Reviewer 23422

Score: Not scored

Comment: The tradeoffs mentioned in the project seem a bit broad. It will be interesting see more details about the tradeoffs. The dissemination of the project results are a bit delayed.

PI Response:

IMPROVEMENTS

Reviewer 25420

Comment: I have included suggestions regarding weaknesses in the "Weakness" criterion.

PI Response:

Reviewer 23403

Comment: Include the effects uncertainties in input variables.

Include temporal impact over the life of the project.

Adding more capabilities to ‘Geothermal Prospector’ to account for the impact of water needs of other competing alternative energy systems coming into the fray.

PI Response:

Reviewer 23422

Comment: Water supply can be very dynamic not only just in space domain but also in time domain (maybe also in social domain). Instead of assuming the water resources as constant total or average, it may be meaningful to treat them as dynamic factors/parameters. Similarly, the cost of water supply can be dynamic. How to incorporate such dynamics and prediction into the built model might be interesting. The tradeoffs mentioned in the project seem a bit broad. It will be interesting to see more details on what kind of tradeoffs and how those tradeoffs look like.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: GETEM
Principal Investigator: Mines, Greg
Organization: INL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 7.0

Comment: The GETEM team provides the DOE-GTO with basic cost structure and inputs to estimate generation costs. There has been a concerted effort to consult industry in regards to gathered/collated data. The 2014 goal was essentially met. My understanding is that DOE and the INL team are still evaluating a change of platform to port GETEM. The original milestone was to provide a downloadable version of GETEM built in Excel, but a version not yet made downloadable has been built in Visual Basic. I am not entirely clear as to the early project risks the team is alluding, but this obviously needs to be completed to satisfaction. I am not sure what the future direction of generating a 'simple' Excel version entails and what aspects of the model will be affected by the simplification. The input data shown clearly contain uncertainties that can be masked in potential risk evaluation or even in simple generation cost evaluation. The team has identified a significant hurdle associated with drilling costs volatility and the general trends are roughly predicted within the model. This is important, if well-documented, because there will be a more adequate interpretation and use of predictions. I thought the work of student interns was not clearly explained, but seems to provide a benchmark. The overall impression is that several loose ends in the milestones are still unresolved. Overall, the research seems to be of very reasonable quality and targets are not being met yet to complete satisfaction.

PI Response:

Reviewer 23403

Score: 7.0

Comment: For a length of time GTO has been funding the development of the Excel spreadsheet-based software 'GETEM' to enable the estimation of the cost of geothermal power generation based on LCOE using user defined scenarios like exploration, well-field development, power plant, start-up, operation/maintenance costs, etc. The scenario can be for hydro-thermal or EGS resources. It can also be used to assess the impact of technological advancements on the project. This software does not account for the capital cost which can be substantial. Unfortunately, it ignores the stochastic treatment of uncertainties. Based on above, the resulting beta-version of the software was released in 2012 available online in GTO site. GETEM can, supposedly, be used in other GTP related simulation models like GT-Mod. In subsequent enhancements, early project risks were quantified in a deterministic sense. Also, some validation studies based on data provided by the industry were undertaken. Also, the Volatility of major cost drivers is to be accounted for. Since its inception, the objectives of GETEM have been useful but the software vehicle used for same has been a big setback both against portability and addition of advanced modeling schemes.

PI Response:

Reviewer 23422

Score: 7.0

Comment: The project develops a model to estimate generation costs and how technology can impact those costs. The major cost drivers for geothermal power production are identified in the model. Validation based on history data is underway. Model developed with default based on GTO resource inputs is developed. The developed models are integrated into multiple DoE market penetration models and are used to depict geothermal costs in several DoE studies. An Excel version of the simplified model is available for download from INL's website, which can be shared among public and other researchers. Furthermore, four publications from the project are listed. The results, quality and performance evaluation of the developed model, however, are not very clear.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 7.0

Comment: The scientific approach is appropriate for the straightforward objectives/goals of the project. I remain unclear as to how the decline curves were handled, but overall there appears the team was rigorous in most aspects of the technical approach. Since one of the goals is to provide a tool to assess risk and the impact of technology development, these two aspects were not entirely clear to me from the presentation. The lag in drilling costs is understandingly, but begs for a way to address its impact. I see competing issues in the design of the project as the generation costs calculations rely on some reliable default inputs even more than they do regarding the model itself. Calculations are conducted deterministically in appearance in the absence of 'bracketed' estimates that use the uncertainty of input data. However, this is still being tested to the best of my knowledge and can be addressed with relative ease. At the end, the compromise associated with the originally intended development platform appear to have constrained some of the functionalities of the system.

PI Response:

Reviewer 23403

Score: 5.0

Comment: During F14/F15 the task of making the spreadsheets more user friendly through Visual Basic implementation both in the data input phase and the outcome phase. Provided support to users and GTO researchers. Validated with Nevada Geothermal operations through student involvement. Also, provided tech support to GTO efforts to assist Energy

Information Administration. Model modification to reflect the impact of technology changes that are aligned with GTO/WBS is being undertaken. Developing user friendly Visual Basic Interface. Alternative platform use and robust model not accomplished.

PI Response:

Reviewer 23422

Score: 7.0

Comment: The model estimate seems including many elements, which depend on the input from the industry. As the model is supposed to estimate the cost of all aspects of a project development, how to effectively predict the cost elements and the impact of technologies advancing may be interesting. More history data set from more industry or societies can be used to build a machine-learning model to efficiently predict the inputs and dynamics during the whole life of a project. More intelligent statistic model can also help to further polish the model. A confidential level with the cost estimation will also be helpful to be incorporated into the model.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: First of all, the project did not meet the original milestone, but provided a solution based on Visual Basic. I find this acceptable, if a fully functional version is truly available for testing. However, there seems to exist a problem with early project risk evaluation that has not been clearly explained, not at least in the presentation I attended. Secondly, I would have liked to see a bracketed estimate based on uncertainties associated with the input values. While there is an advantage in the availability of the default values, without clear guidelines in the interpretation of the generation cost estimates, there is a potential risk in misusing these outputs. Thirdly, whenever I hear that student interns collected data, I become concerned with quality-control issues. At face value, some of the decline curves did not appear to decline, but this was not discussed or elaborated on in sufficient detail. Moreover, the issue associated with the assumption on constant brine flow rate was not addressed. I completely understand that some assumptions must be included in the model as a matter of fact. However, if one insists that prediction will go reasonably well in the exception cases in which the flow rate is constant, this leaves the door opened for devaluing the efforts committed to such a project. I gathered that this system is valuable for internal use, but as soon as this is released, confidence must be built.

I sense too many uncertainties in the future directions of the project and to me this indicates a possibility of dispersing efforts. Is this something that will lower the value of project? That remains to be seen.

PI Response:

Reviewer 23403

Score: Not scored

Comment: Lacks stochastic considerations.
Addresses a limited number of variables and scenarios and makes assumptions contrary to reality, like constant brine flow.

Portability problem: GETEM is Excel spreadsheet-based. Cannot be grafted on existing simulation software like GT-Mod.

PI Response:

Reviewer 23422

Score: Not scored

Comment: The Geothermal Electricity Technology Evaluation Model (GETEM) seems involving a lot of elements and estimation, which definitely benefit from emerging technologies in data mining or BigData. Smart prediction engine may be helpful to be incorporated into the model.

PI Response:

IMPROVEMENTS

Reviewer 25420

Comment: As I indicated in my assessment of criteria 1 and 2, as well as my statements of perceived weaknesses, I would focus efforts in unlocking further development of the software by making decisions in the following areas:

1. Incorporate a time-dependent brine flow rate, but using the data gather as guidelines. This would not necessarily demand a complete redesign of the system. One can borrow the approach use other simulation areas in which an internal 'restart' is allow in discrete time spans. This would allow to calculate cost predictions that mimic what operators due to overcome the assumption on constant brine flow rate. 2. Since calculations are simplified versions of the more complex problem in reality, I would manage uncertainties in inputs as repeated calculations that bracket the impact of the observed variability in the input data. In my view, this would allow confidence intervals to be plotted out and this is preferable to lack of confidence on the predictions. 3. I decision should be made on the development platform, even if this forces an adjustment of milestone. Otherwise, there is the risk of not completing a very usable tool, beyond the confines of DOE-GTO. 4. The casual user will need guidance on the relative importance of inputs. I strongly suggest clear documentation and help tips.

PI Response:

Reviewer 23403

Comment: Incorporate uncertainties.

Include the missing design variables.

Creating version based on higher level language like C++.

Need extensive validation with real-life data.

Add the missing features to enable universal use.

Create extensive documentation for end-user before the next release.

PI Response:

Reviewer 23422

Comment: There are really a lot of factors affecting GETEM cost estimation, from both industries and societies. And the factors are dynamically fluctuating during the time. A better prediction engine based on BigData analysis or similar techniques can be incorporated to improve the model.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005501
Project: National Geothermal Resource Assessment and Classification
Principal Investigator: Williams, Colin
Organization: U.S. Geological Survey
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 10.0

Comment: The project team did not reinvent the wheel, and they actually use several strengths to conduct the research to bring to term a successful project that met the milestones. Nothing too fancy, in view of the great expertise of the team and the project leader. The needed information, barriers, challenges, among others were produced or identified. USGS worked closely with DOE, one of the strengths in this project, to clearly communicate progress and results. The productivity in terms of work for dissemination is one of the highest I have ever seen. The focus in sedimentary basins as a way to identify unconventional geothermal resources was the right action path. The project presented balance in the use of resources to address the most impactful set of results.

PI Response:

Reviewer 23403

Score: 8.0

Comment: Work on this project has been going on since 2010 with the primary objective geothermal resource assessment and classification of USA focused on a number of tasks which included sedimentary basin resource assessment. One of the tasks was the assessment of geothermal resources from low-temperature hydrothermal systems. Another item was improving the assessment and classification methodology for EGS systems and undiscovered resources based on results from targeted filed studies and modeling.

Geo-thermometer and in-situ temperature revisions to 1982 low-temperature data were done creating an improved database. A number of interesting results accrued from the study related to shear simulation of crystalline rocks including increased accuracy of predictions based on simulations with new data. To account for variations in permeability with depth a layered approach is suggested. Also, crystalline bed rock was identified as the most promising targets for EGS development. Data from the investigation have already been incorporated in NGDS. Creation of temperature models for major sedimentary basin has been completed. The work on this project was started in 2011 and is expected to be completed by the end of December, 2015. Sedimentary basin resource assessment and comprehensive summary will have been completed.

PI Response:

Reviewer 23422

Score: 8.0

Comment: This project investigates expanding geothermal resource assessments; developing new geothermal resources classification standards; improving assessment methodologies; assisting in the NGDS establishment and enabling lower risk/cost deployment of geothermal power. These objectives are directly in support of DoE GTO goal of increasing the installed geothermal capacity in US. Multiple technical accomplishments have been shown and published in many publications and presentations, which include Geothermal Resource Classification System, Geothermal Field Studies, Hydrothermal System Life Cycle Models, Revised EGS Methodology and Low-Temperature Resource Assessment. Assessing undiscovered resources is challenging and critical factor in hydrothermal system. It seems that the project achieves the planned goals and objectives. The collaboration between USGS and NGDS seems continuously providing new values. The results are important to the project objectives and technical targets.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 9.0

Comment: The approaches were rigorous and informed. The productivity in terms of presentations and articles denote the quality of the science and the techniques provided the sought out answers. Whenever challenges arose, the team provided an assessment and a potential solution to the problem. There were loose ends in the project, despite the enormous volume of work that this represents, because data by itself cannot do the 'trick'. It requires significant work by the expert analyst, in the case members of the USGS. Great project!

PI Response:

Reviewer 23403

Score: 8.0

Comment: Under Task 1, conventional geothermal resource characterization and geological assessment is undertaken of targeted GT resources, then the low temperature resource database is updated, and finally appropriate thermal and diffusion model is exercised to investigate evolution of the hydro-thermal system. Under Task 2, EGS and non-conventional resources are considered and subjected to revision and updating of the classification system based on community feedback and collaboration with IGA Resources and Reserves committee. In areas with potential for future EGS development regional studies of relevant geological features are undertaken and an improved method for assessing potential EGS development. Task 3 focusing on sedimentary basins, necessary data on basin features like temperature, lithologies, etc. are collected to identify the regions of significant geothermal potential. Undertake focused studies on basins with high potential and identify the geologic constraints on GT development and dispense the information and consolidate it appropriately with other tasks. As part of the final task, relevant geothermal database will be publishes and incorporated into NGDS.

PI Response:

Reviewer 23422

Score: 8.0

Comment: The technical approaches involved with different tasks of this project consist of conventional geothermal resource characterization and assessment, enhanced geothermal systems, geothermal resources in sedimentary basins, USGS geothermal data and the national geothermal data system. To achieve the project objectives, the approaches adopted in the project seems solid and interesting. As the large number of publications/presentations show, it seems that these approaches have been well executed and received in the community.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: I did not see any glaring weakness with the project.

Reviewer 23403

Score: Not scored

Comment: Most prevalent rock types in most productive geothermal reservoirs granite, basalt, quartzite, etc. On the other hand, sedimentary formations are best suited oil and gas reservoirs. The investigator did not give any tangible reason for his preference sedimentary formations (basins).

PI Response:

Reviewer 23422

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

IMPROVEMENTS

Reviewer 25420

Comment: Once again, the information has been made available in a number of formats and communication was clear, even to the neophyte. I have very little to suggest.

PI Response:

Reviewer 23403

Comment: Extend studies into all types of reservoir rock formations.

Create geothermal maps based on the results of this study.

PI Response:

Reviewer 23422

Comment: The scalability concern with large number of systems may be mitigated if emerging new technologies are adopted. The process of collecting and integrating disparate data sets may be enhanced (e.g., automated) with new sensor, wireless communication and data mining technologies.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Regulatory Roadmap
Principal Investigator: Young, Katherine
Organization: NREL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25420

Score: 10.0

Comment: I had the pleasure of attending an earlier review session for this project. I continue to agree that this project is well-thought out, focused and well-executed. The how-to has not gotten in the way of meeting goals, objectives and milestones. The overall quality of the project is very high and the productivity outstanding. While not all projects can follow the paradigm presented in this project, I believe most would be enhanced in productivity and quality by literally plagiarizing style and philosophy of this project. In fact, I believe that considering the resources allocated to this project, this team has exceeded the goals and have created not just a roadmap for the geothermal regulatory analysis, but has indeed created a roadmap to address perceived barriers to development. I thought that by not reinventing the wheel, the team has 'data mined' available regulatory maps and rather than creating a collage of regulations, they have torn down inexistent barriers. I can only say good things about the project.

PI Response:

Reviewer 23403

Score: 10.0

Comment: This project is develops an user-friendly streamlined geothermal permitting process in response to the identification of its urgent need in Geothermal Technologies Program Blue Ribbon Panel Recommendations as well as the Geothermal Industry stakeholders, emphasizing its importance in eliminating potential bottlenecks resulting from the permission process and, thus, helping to reduce the cost and financial risk in a proposed geothermal power development project. The importance of this effort is guided by the fact that in the pre-survey, exploratory and trial drilling stages, project risk is very high. In subsequent stages like F/S planning, drilling multiple production and injection wells, construct power plant and transmission lines, start-up, operation and maintenance, the risk drops and the rate of cost increase eventually drops dramatically.

The effort comprises of three stages: (i) review of existing practices at state and federal level; (ii) identification of regulatory barriers, inefficiencies, and good practices; (iii) developing an optimized scheme for a streamlines permission process.

The outcome of this effort is an online system (RAPID) which will reduce permitting time leading to lower LCOE, increase the number of approved projects, and, hence, increase in the deployment of Geothermal Power. The issues addressed in the proposed regulatory process were transparency and understanding by the stakeholders, and clarity of communication by the approving agencies.

The feedback from users of the system has been highly complementary. This success was topped by news of awards, recognition, adoptions, request for expansion into other renewable sources of energy, and legislative recognition. The effort has no doubt been extraordinarily success.

PI Response:

Reviewer 23422

Score: 9.0

Comment: This project tries to understand the current process of the permitting roadmap for geothermal power projects at the federal and state level. With better understanding of the process, the project can convene industry stakeholders involved in the permitting process to identify potential regulatory barriers, inefficiencies and best practices. Analysis that can optimize and streamline the process can also be helpful for geothermal stakeholders. The progress is made as planned. Much impressive accomplishment in the work has been shown. The project developed geothermal RAPID Toolkit for 12 western states, encouraged changes, identified barriers and key game changers. In addition, the project has spurred large stakeholder momentum, which can facilitate discussions and collaboration among those who can affect change. The work also won the GEA Outstanding Achievement Award in December 2013. The impacts of different agencies, White House and legislature of this work are quite broad and impressive.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25420

Score: 9.0

Comment: I believe the secret to the technical approach in this project has been an unusual combination of creative thinking and conservative creation of guidelines and regulation. The bottom-line regarding the success of the project is to bring together stakeholders that do not normally debate or exchange ideas. Regulation at different levels tends to create roadblocks, because of the lack of consistency through the bureaucratic mesh. A brilliant use of 'lessons learned' has allow the team to produce an enormous coverage corresponding to 12 States, if memory serves.

PI Response:

Reviewer 23403

Score: 10.0

Comment: In this project, the initial preparatory effort over FY2010 and FY2011 comprised of collection of data on GT permits and creation of developer's online checklist. The cooperative effort was begun in FY12 by bringing together representatives from all the primary stakeholders (industry, regulatory agencies and NGOs) with increasing state participation to develop the framework of a regulatory roadmap, identify action items, analyze collected data on geothermal permits, and develop optimal solutions. During this period a permitting checklist of Geothermal Regulatory Roadmap (GRR) was created. This process continued up to part of FY13. During part of FY13 and in FY14 the wording of proposed draft of the permission process was developed with input from industry agencies. The remaining step is the approval of the law/policy by the legislative/executive bodies. During this period, Atlas was developed for ready access to a collection of Wiki pages to provide overviews of regulatory and requirements. During FY14, GRR and Atlas were assembled into the Regulatory and Permitting Information Desktop (RAPID) Toolkit offering one location for agencies, developers, and industry stakeholders to work together on renewable energy regulatory processes by using a wiki environment to collaborate on regulatory processes, permit guidance, regulations, contacts, and other relevant information. The approaches taken in the project could not be netter. Excellent performance.

PI Response:

Reviewer 23422

Score: 9.0

Comment: The project reviews and documents the federal and state permitting and regulatory processes required to develop geothermal power projects. The regulatory roadmap and NFPA database are integrated as a part of the Regulatory and Permitting Information Desktop (RAPID) toolkit on OPENEI. The project team met with different agencies and analyzed the process with a series of white papers and proposals to improve the processes. The approaches are sound and executed appropriately with great results.

PI Response:

STRENGTHS

WEAKNESSES

Reviewer 25420

Score: Not scored

Comment: I have no weaknesses to report, other than the need to continue funding of this type of projects. While other highly technical aspects should be researched to overcome barriers, both economic and technical, often times this type of projects can generate creative styles and solutions.

PI Response:

Reviewer 23403

Score: Not scored

Comment: None.

PI Response:

Reviewer 23422

Score: Not scored

Comment: The human factor of the process seems very interesting. A little bit further investigation on this factor can be helpful.

PI Response:

IMPROVEMENTS

Reviewer 25420

Comment: In view of the success of this project, I would generate a template of project execution that would serve needs even beyond GTO. The idea is that while many teams are conformed of very talented individuals, only a few possess the talent associated with perseverance. I am certain that leadership can be developed, but what is needed is role models. As I have indicated before, the style of this project cannot always be expanded to other very technical projects, but the experience could be 'mined' to generate workshops on project management, for instance. I would advise the team to share this even further (resources might be a limitation).

PI Response:

Reviewer 23403

Comment: The project's extraordinary success deserves further support for upgrade and continued maintenance.

It is a prime candidate for further expansion of its capabilities.

PI Response:

Reviewer 23422

Comment: The workflow management system can be very useful and deserves further investigation. And maybe a computational/mathematical model can be developed to model such complicated processes. As the first step for identifying the game changers, it may be helpful to evaluate how the suggested change can exactly improve the process, which may help move the process further in the right direction.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Resource Reporting Methodology Analysis and Development of Geothermal Resource Reporting Metric for GTO's Hydrothermal Program
Principal Investigator: Dobson, Patrick, Young, Katherine
Organization: NREL/LBNL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 24896

Score: 8.0

Comment: As a method for directing research efforts managed by GTO, the methodology developed in this project may serve program goals by establishing a reproducible set of criteria by which project impact and progress may be measured. As such, it may focus funded projects to more directly consider the established MW and electricity cost goals laid out by the project. On the other hand, there is always a danger in such methodologies of establishing too rigid of a set of criteria for conducting projects that require achieving a set of checkboxes as opposed to finding the most efficient path towards the goal of the project. While the PI's were careful to state that the reporting methodology should not be interpreted as a required set of steps for a given project, given the nature of DOE reporting requirements that may well be the manifestation. There is also the danger that the rigid resource centric approach taken in the methodology will limit innovation that falls outside of this rubric.

It appears that excellent progress has been made on this task and the team is on target to meet project goals. The FY 2016 plans do seem a bit ambitious given the pace of progress to date.

PI Response:

We recognize industry's concern that this may become a set criteria for conducting projects, but are working closely with industry and with GTO so that this becomes simply a standardize for reporting outcomes - and so t that the Protocol clearly outlines how to properly use this system.

The breadth of the metrics (covering scientific, technical, and socio-economic considerations) were designed to help DOE showcase innovationa that would typically fall outside of a traditional 1-number (MW) reporting scheme. This methodology is not meant to be the only metric that GTO uses in measuring impact. The team recognizes that no method - this one included - would be able to measure all impacts of innovation.

Reviewer 23554

Score: 8.0

Comment: The data compilation and evaluation is a very worthwhile effort.

PI Response:

Reviewer 23549

Score: 7.0

Comment: Eventual adoption and implementation will promote reporting uniformity across projects, which will therefore have relatively high impact. Importantly this will allow the program to set minima within categories for continuation and award levels should they choose to do so. In this way this project could have very high impact on DOE programs. The impact is much less in terms of science and understanding of major resources, but that is not really the point.

PI Response:

This system could have an indirect impact scientifically by targeting funding into areas of resources that are not well understood (e.g. metric combinations of high temperature, low permeability).

Reviewer 23478

Score: 8.0

Comment: It is hard to say what kind of impact this project will have on GTO or the geothermal industry. It appears to be well devised and to be producing progress towards the development of metrics with which to measure the impact that GTO funding has on acceleration of geothermal development. If the new system is successful, then GTO will have a way to quantify its accomplishments to Congress and other lay people. This could have a major effect on future GTO funding abilities. The continued availability of GTO funding through FOAs will have an impact on geothermal progress, but this progress is determined by many factors other than GTO funding. These factors include the availability of Production Tax Credits, Investment Tax Credits, the rate of permit and lease issuance, the price of petroleum, solar, wind, biomass, and other competing energy sources and the general political and economic climate in the nation. For example, if a Republican administration is elected in 2016, it is likely that enthusiasm for geothermal will be dampened in Washington with a concurrent slow-down in geothermal development.

The results of the project to date are good. A draft metric system has been created and will soon be available for critique by industry. Using multiple iterations of the system based on continuing feed-back, the system will eventually mature and appears to be one that will be objective, reproducible, and clear to technical and lay persons alike.

The project appears to be on schedule and significant progress continues to be made. It will be interesting to see, eventually, what impact this project has on the industry, in addition to the GTO.

PI Response:

We agree that many factors independent of the DOE GTO influence geothermal deployment. We hope that as this methodology is adopted by the geothermal community, continued feedback will result in an improved set of metrics.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 24896

Score: 7.0

Comment: There appears to be considerable due diligence on the PI's part to take leverages the methodologies and approaches of related efforts in other industries. They have also gone to great lengths to consider input and needs from a wide range of stakeholders. There is clearly logic in the reporting metric they are proposing, although certainly there will be different opinions about the specifics of each criterion considered.

The principle weakness of proposed metric is its rigid adherence to applying resource evaluation models. I see three distinct areas of concern here. The first is that it seems very focused on activities traditionally performed by the private sector, namely identification and establishment of a resource. To a large extent this perspective may not be congruent with the context of government-funded research. If one is going to choose this model for program evaluation, then it needs to be cognizant of concerns that would typically be encountered in such activities such as overall viability of the resource (for instance, injection capacity is not addressed) and needs to be able to address site specific concerns (for instance, the engineering and environmental consequences of different types of geothermal fluids). The main problem I see with it however is that it will be difficult to apply sensibly to projects outside of simple resource evaluations. Perhaps the Play Fairway projects may be addressed with it (though it would seem they would fare poorly in this analysis), but not resource-specific projects such as FORGE, experimental studies aimed at heuristic understanding of geothermal systems, or tool development projects do not interface well with this metric.

PI Response:

Reviewer concerns with "other issues" (e.g. injection capacity) are valid, and are planned to be addressed as part of the upcoming Technical and Socio-Economic Assessment Tools.

The reviewer's main concern of the challenge in applying this metric to different types projects is also valid. This system will not be - nor was it planned to be - the only source of metrics that GTO uses in measuring project impact. GTO will likely use additioanl metrics in measuring project impact. This system, however, can provide data to better understand the current geothermal resource and barriers to development that may be addressed with GTO funding.

Reviewer 23554

Score: 7.0

Comment: Wide range of all geothermal resources under consideration.

PI Response:

Reviewer 23549

Score: 4.0

Comment: The approach appears sound but somewhat complex. I agree that it is necessary to separate geologic from technical and economic issues in the assessment. Seems to me the geologic assessment should have been relatively straight forward, yet it has resulted in a very complex reporting protocol that took a long time to develop. I expect there will be some resistance to incorporating these protocols by investigators and operators but that remains to be seen. The geologic assessment is only the first of three to be developed and the other two assessments are still in development stage.

PI Response:

The reporting protocol captures the potential of a resource in an A to E scale while minimizing sacrifices to the scientific validity from bucketing information into standardized categories. The team has been careful to iterate to ensure that industry understands and finds these concepts acceptable. We agree that there needs to be a balance between having a system that is easy enough to use and yet have sufficient complexity to capture important distinctions between different types of geothermal systems.

<u>Reviewer 23478</u>

Score: 8.0

Comment: The technical approach is rather innovative for a government laboratory. The acquisition of feed-back and input from industry prior to the writing of a report is not often done, and in this case it appears to be an excellent methodology to follow. The iterative procedure of asking for guidance, synthesizing the responses, drafting a preliminary document, attending meetings to get new critiques of the draft, and then doing the whole thing over again seems to be working. It is not clear as to how many NREL or LBL staff are working on this project or who they are, but the results seem to be coming in a timely way, so the staff must be working diligently and effectively.

There is no data being generated, and no instruments or equipment is involved, so these parts of the criterion are invalid. All that can be said is that the draft metrics as shown in the Presentation slides appears to be novel, scientifically supportable, and may well achieve the project objectives.

PI Response:

STRENGTHS

<u>Reviewer 24896</u>

Score: Not scored

Comment: This rubric appears to be based on considerable effort by the PI's to take into account input and insight from a wide range of stakeholders and to leverage insights from similar activities in other industries. They should be commended for that. One could quibble with various aspects of their metrics for classifying the development of a given project, but they have made a valiant attempt at trying to bin disparate industry activities into a rubric based on project progress and certainty. Given the degree to which the PI's have encouraged outside input into these metrics (including holding a discussion session at this peer review) I strongly suspect that there will be continued modification to make the metric more generally applicable to the range of activities supported by GTO.

PI Response:

Reviewer 23554

Score: Not scored

Comment: Organization. Excellent effort to solicit input from academia, labs and industry.

PI Response:

We really appreciate all of the feedback that we have received from the geothermal community.

Reviewer 23549

Score: Not scored

Comment: The thoroughness with which the geologic assessment has been developed is a clear strength, but also a weakness because it results in complexity. The greatest strength of the project is the extent to which the project has requested, received and incorporated feedback during the development stage. This has been an extensive operation that has led to much well thought out detail. The level of prior input should definitely enhance, if not ensure industry adoption.

PI Response:

We hope that as the geothermal community starts to use the system, they would find it more informative than complex. This kind of feedback is an indication that we should work on simplifying our message and documents to better convey the simplicity and clarity of the system.

Reviewer 23478

Score: Not scored

Comment: The strength of this project is that it addresses a pressing need from the point of view of GTO. Without the results of this project, the value and continued funding of the GTO and other Federal geothermal agencies might well be called into question by a Congress that likes to be able to quantify the impacts of anything that they approve and fund. As part of this strength, the willingness of the NREL staff to canvass the geothermal industries for ideas prior to drafting a report should be cited. It shows that the staff realized that it did not have the experience to initiate the metrics measurement process and that it needed to talk to experienced industry representatives.

When this project is finished, the US geothermal industry will have a way to characterize the nature of its geothermal resources and accordingly, the time-related potential for development. Actually, the US system, when finalized should be more comprehensive that those of the Australians, the Canadians, and some of the European nations. The system will be distilled down to an Excel spreadsheet in which operators just have to grade the several categories A-D and guidelines will be provided to help them. After the first time, this should be fairly easy.

PI Response:

We hope that our system will be utilized (and improved) by the geothermal community.

WEAKNESSES

Reviewer 24896

Score: Not scored

Comment: The project progress component is confusing in its distinction between "Geologic and Technical" and in part with the separate distinction of the Socio-Economic component. The three dimensional progress grid further makes this confusing because it is hard to visualize non-numeric criterial in a three dimensional Cartesian space. Furthermore, the approach of these aspects is not congruent with the reality of how geothermal projects are developed. While there is overlap between the Geological, Technical, and Economic aspects of a project, there is also a sequential development between there aspects. For instance, most of the geological aspects of a project must be completed before the assessment of the economic portions are even considered (How can the feasibility be assessed before the resource is examined?).

While the metrics proposed in this rubric do make a valid attempt at presenting identifiable criteria for measuring project progress, the problem with all such rubrics is that they are by their very nature too rigid to encompass every scenario that is likely to crop up between different systems. Hopefully flexibility will be built in to address this.

It remains unclear to me how the metric described will lead to more consistent and reliable reporting of the impact of GTO funded projects. The emphasis appears to be on figuring out what the energy contribution of a given study is, but the approach advocated here does not lead to quantification.

Many of the activities that GTO sponsors (including this one), are not directed at identifying or developing specific resources. How are these to be included in this rubric?

The graphical tools developed as part of the metric are difficult to interpret on first sight (or in some cases, after considerable study). The rose diagram color and shading scheme distracts from the information content. The system size plot is very difficult to interpret…the A-E categories are not readily interpretable. If the goal is to make information accessible to both technical and non-technical audiences, then use of graphs that do not have numeric axes should be avoided lest your technical audience will be confused. I have no idea how to interpret the three dimensional progress grid.

PI Response:

This system is designed for GTO's Hydrothermal Program, which funds new resource development and new technologies. Specifically, this concept resulted from GTO's need to measure project progress from undiscovered to identified resources.

The limited time and space available for peer review did not allow us to delve too deeply into all applications of this methodology. As part of our future work on this effort, we are developing a Case Studies document and a baseline assessment of geothermal resources. Both of these planned documents will help to addres the questions of how the metric will lead to more consistent reporting (eg. right now there are no specific criteria to define the difference between an "undiscovered" resource and an "identified" resource), and how GTO might use the data and methodology in measuring impact.

Reviewer 23554

Score: Not scored

Comment: Much remaining to complete.

PI Response:

The plan is for this project to continue through FY17 to complete remaining work

Reviewer 23549

Score: Not scored

Comment: The geologic protocols are complex and might lead to resistance to report consistently. The hardest part will be developing protocols for the technical and socio/economic assessments and these have barely been begun, or at least have yet to be communicated. Can the ultimate project goals be met within the funding period?

PI Response:

The protocols for the technical and socio-economic assessments are to be developed in FY16, if funded. Thus, their completion is outside of the scope of this year's goals.

Reviewer 23478

Score: Not scored

Comment: The only weakness that should be cited is that the speed of geothermal development will not depend solely on the availability of GTO funding. The impact of the measuring system being created via this project will minimally take into account the effects of rules and regulations, permitting problems, environmental constraints like endangered species, native burial grounds, etc., tax incentives that come and go on an unpredictable schedule, the national and local political and financial climates, the prices of competing renewable and fossil fuel energy sources, and the vagaries of a two party government system that seriously affect the private and public investment sentiments. Also, risk related project aspects have not, so far, been addressed in this metric system.

Most of these factors cannot be readily quantified, and so their effects will somehow have to be "asterisked" into the end-result of metric measurements and the impacts derived therefrom. Hopefully, Congress will accept that these parameters comprise a fact of life and take them into consideration as they discuss GTO funding in the future.

PI Response:

We agree that there are many other factors that impact the speed of geothermal development. No system measures all potential impacts. This system does not plan to measure or specifically address risk.

This methodology will provide GTO a set of metrics that can be used to identify effective ways to utilize their funds to advance geothermal deployment in the US.

IMPROVEMENTS

Reviewer 24896

Comment: Specific areas of improvement include:

1) Adapt the metrics, or develop alternate ones, that properly allow evaluation of the impact and progress of projects that are not specifically related to identification and characterization of individual resources.

2) Seek further input and perhaps redesign the graphical representations of metric data.

3) Reevaluate the role of actual industrial processes in the certainty criteria in the metric. For instance, for a resource to be secured in the socio-economic metric there must be sufficient injection capacity to support production.

4) There does not appear to be an alignment of the metrics with the electricity cost goals of GTO. Perhaps that is something that could be incorporated in addressing point 1 above.

PI Response:

1. This system, when complete, will not be able to address all GTO metrics. That is not the intention of this system.
2.The graphical representation of the data has vetted in multiple workshops, apperas to be well received, and is often complimented by industry. We continually solicit and welcome all suggestions for improvements! Please feel free to share any specific suggestions you may have.
3. Great suggestion for consideration as we work to develop the criteria for the technical and socio-economic axes in FY16.
4. This is true. Other efforts (e.g. GETEM, supply curves, market penetration modeling) focus on LCOE. This model is not meant to address LCOE, though it could be used to better understand how cost requirements differ from area to area. Output from analyses using this methodology could be used to better inform inputs to LCOE analyses.

Reviewer 23554

Comment: Include some evaluation of previous resource assessments for individual areas (Circular 726, 790, heat-in-place and power density).

PI Response:

These systems, and other methodologies used by other industries, were carefully considered in the development of this protocol. Our review of these systems is documented in our Young et al. WGC (2015) paper. http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/16071.pdf?

Reviewer 23549

Comment: Seems that the geologic assessment tool is ready for implementation. Only then will real weaknesses, learning curves for industry reporting and other implications be known. Obviously a new reporting metric system will have issues, either problems with the metric protocols themselves or with reluctance to report consistently. The sooner these are known the better. The overall goal of this project is laudable. I can imagine several more years of modification to fix problems, but only after a trial implementation period. I would recommend implementing the geologic assessment tool immediately, even while development of the other two is still underway, but there might be reasons why DOE would be reluctant to do this.

PI Response:

The team agrees that testing soon is ideal, and we also recommends a trial period.

However, we recommend trialling after all three tools are drafted, to both reduce rounds of iteration and ensure that changes are carried across all sets systematically with minimal learning curves to the public.

It is clear from comments from other reviewers that confusion already exists from presenting only the Geological category information, as he felt critical pieces of data were missing from the reporting protocol (that we plan to incorporate in the Technical and Socio-Economic axis.

<u>Reviewer 23478</u>

Comment: I cannot suggest any specific improvements on the techniques that are being used to accomplish the objectives of this project. There will however be improvements to the draft metric measuring system as it evolves. Descriptions of these improvements will have await the issuance of the system documentation and the planned handbook(s)., The iterative process being followed to create the system implies the need for and accommodation of improvements, so some (or many) can be expected as the system matures.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Hydrothermal Reservoir Productivity
Principal Investigator: Mines, Greg
Organization: INL
Panel: Systems Analysis, Resources Assessment, Data System Development & Population, Education

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23480

Score: 7.0

Comment: This work describes a potentially useful means for geothermal regulators, researchers, and analysts to assess the performance of geothermal resources over long periods of time. The study has brought to light data on geothermal power plant operations, freely available to the public that has largely been ignored. When coupled with GETEM, the data can lend insights on reservoir performance and longevity.

PI Response:

Reviewer 23554

Score: 5.0

Comment: Reasonable initial evaluation of Basin and Range systems. Good reality check for GETEM assumptions.

PI Response:

Reviewer 23549

Score: 4.0

Comment: Prior to this study it was basically known that most plants decline in productivity with time. This study quantifies some of this for those plants in Nevada for which there are “publically available” data. This is a useful but certainly not transformational result. The project will certainly have a strong positive impact on the interns involved in the study. Overall the project shows what can be done with simple, publically reported, monthly data, but also the limitations of such data, which are many.

PI Response:

Reviewer 23478

Score: 6.0

Comment: The impact of this project will be modest at best. The reason for this is that data has been processed for a very small number of fields, and those only in Nevada. Additionally, it appears as if only temperature declines are being recorded as a measure of reservoir decline. To do this properly, reservoir pressure, NCG content, enthalpy, and flow rates should also be considered as should injection rates and locations.

If all the necessary parameters were considered, then this would be a very useful exercise. The results could not only be used to help validate GETEM estimates of the effects of reservoir decline on power generation, but the identification of decline mitigation effort types could benefit operators internationally.

It appears as if most of the objectives of the project have been met with respect to binary plants, but there remains to be much done to obtain valid temperatures (and other parameters) for flash plant. Funding for 2015 was not granted, so the project will limp forward with one intern and what little money is left over from 2014. Time will tell what more can be accomplished.

The results of the project should be somewhat useful to GTO in refining their power generation forecasts. They will be minimally useful to the industry as they represent such a small sample and because the raw data is not available beyond 2009 (Why??).

As stated above, progress through 2014 was adequate, but will probably slow to a crawl, if not stop entirely, in 2015 due the absence of funds.

Two young INEL interns are responsible for the project work completed to date. They were given a GEA award for their efforts and they learned a lot about the geothermal industry. These are both admirable outcomes for the project.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23480

Score: 6.0

Comment: The approach is straightforward data collection and digital formatting, limited by the reporting requirements of the Nevada Bureau of Mines and Geology (NBMG). The extent to which the data are accurate and complete is not stated. NBMG's rules and requirements for submissions are not provided; margins of error apparently cannot be determined, but these are likely within acceptable limits for meeting the objectives of this study.

PI Response:

Reviewer 23554

Score: 5.0

Comment: Compilation is complete for a limited series of Basin and Range systems.

PI Response:

Reviewer 23549

Score: 3.0

Comment: There is much emphasis on temperature, despite some issues in the reported data, and temperature must be calculated based on certain assumptions. Data presentation is mainly of these derived temperatures versus time, which clearly results in relatively high uncertainty. Only data used were those available from basic web services, but there are other data “out there” that could have been incorporated. There appears to have been no attempt to validate reported data. I am not well qualified to evaluate the modeling efforts, even though they seem fairly simple. Nevertheless, there seem to be some outstanding issues not addressed by the study even though some likely could have been by being more proactive in discussing with reporting operators. Seems like a more thorough, more hands on approach could have been undertaken. Although the study only considered data up to 2009, I don’t consider this a major problem. The time period for which data are available is less of a concern than the lack of validation of those data.

PI Response:

Reviewer 23478

Score: 6.0

Comment: The design and approach of this project was somewhat above average. The plan was to take advantage of data available from the Nevada Bureau of Mines and Geology files to create Excel files which could then be analyzed by two INEL interns. This was executed in a satisfactory way for temperature-related data, but not with respect to other reservoir characteristics that can influence power generation. Moreover, the effort staggered considerably when faced with the task of calculating temperatures in a flash power plant due to difficulties in obtaining accurate steam flow percentages.

There was no instrumentation or equipment used on this project and the staff, though relatively inexperienced initially, appear to have worked diligently and cost effectively. It is estimated that about 80% of the projects objectives were accomplished before the funding was withdrawn.

The basic premises of this project are valid and worth pursuing further. There geothermal fields with reams of data available, including The Geysers and Coso where more widely information and relationships could be explored. As geothermal fields age, their ability to maintain initial power generation levels inexorably decline. This is a fact and information concerning typical decline rates (or at least ranges of decline rates, will be helpful to budding developers as they enter into power supply contracts and sign other documents specifying performance levels over time.

PI Response:

STRENGTHS

Reviewer 23480

Score: Not scored

Comment: Compiling the data in a usable digital format for free public access is a major benefit to future analyses of plant/reservoir performance. The study demonstrates the value of data from public sources. Use of student interns offers them an excellent educational experience. In this case, they received awards for their work.

PI Response:

Reviewer 23554

Score: Not scored

Comment: A reasonable compilation for a mix of Basin and Range systems utilizing binary generation technologies.

PI Response:

Reviewer 23549

Score: Not scored

Comment: The greatest strength is the involvement of interns. The project provided some very worthwhile experience for these students. Another strength is that the project is almost finished and final analysis will be done with “carry–over” funds. The project is fairly simple; basically showing what can be gleaned from certain kinds of publically available data, as reported. This allowed calculation/quantification of temperature decline in several production facilities.

PI Response:

Reviewer 23478

Score: Not scored

Comment: The strength of this proposal is that it is a start in the right direction by obtaining, synthesizing, and analyzing resource decline data. Not only will this eventually be useful to GTO by validating some of the estimates of power generation obtained via GETEM, but it has the potential, when its scope is properly expanded to include more than reservoir temperature, to help geothermal developers that are in the early stages of their project evolution.

The fact that decline rates of binary plants of `1 to ~3% annually was recorded should suggest to GTO that their GETEM default decline value of 0.5% annually should be revised. This comprises a "truth" that can be considered to be a project strength.

PI Response:

WEAKNESSES

Reviewer 23480

Score: Not scored

Comment: There are no indications that attempts were made to contact Nevada Bureau of Mines and Geology (NBMG) to gain further insights on the adequacy/completeness of their data base. The extent to which the student interns were guided and their work verified is not discussed. Geothermal operators were not contacted to corroborate changes in production inferred from the data; causes of observed temperature/production declines and upsets were not verified.

PI Response:

Reviewer 23554

Score: Not scored

Comment: The evaluated systems are mixed and not necessarily analogous. For example, Steamboat may have voluminous available data but the system is not representative of the typical amagmatic extensional system in the Basin and Range and uses multiple production technologies to produce electricity over a range of fluid enthalpies.

PI Response:

Reviewer 23549

Score: Not scored

Comment: There are many data issues as reported and no effort was made to ensure consistency of data. Little to no contact with operators was initiated, despite that this might have provided worthwhile information or explanations for what was reported. The main cause for decline in production is assumed to be temperature, but there might be other factors involved, which were not considered. A major weakness of the study is the failure to deconvolve natural decline from operator strategies; this makes the results of the study difficult to use in future evaluations. Is this a scientific study of reservoir properties or a technical/economic study of operator behavior? As presented it is both, which limits its utility. Not much data interpretation went into the study, and essentially none for the “flash” plants.

PI Response:

Reviewer 23478

Score: Not scored

Comment: There are four primary weaknesses to this project:

1. It used only reservoir temperatures as a measure of productivity decline. Other factors including reservoir pressures, NCG content, enthalpy, gas to liquid rations, injection rates/ locations, and flow rates should also be parts of the equation in the next iteration to (hopefully) be undertaken.

2. The quantification of all the decline of all reservoir parameters needs to be improved for flash type projects. This is not at all easy, and will require the employment of field experienced geothermal professional geologists, geochemists, and power plant engineers to guide interns (if used) or to run the project.

3. When a similar project is next undertaken, funding should not be withdrawn prematurely as it appears to have been in this case.

4. There seems to be concern regarding the consistency and completeness of the data reporting, both over time and with regard to different operators' reporting habits. This should be corrected, maybe with standardized forms issued by a Federal (not State) entity.

PI Response:

IMPROVEMENTS

Reviewer 23480

Comment: The remaining available funds should be used to contact current plant operators to obtain any further information about the dataset they may wish to provide. This could be useful in assessing discontinuities or other rapid changes in the data. Provide a link to the data in the NGDS. Survey regulatory agencies in other states for comparable datasets.

PI Response:

<u>Reviewer 23554</u>

Comment: Finalize data collection

Accomplish the proposed individual analysis

Expand to systems beyond the Basin and Range

Review GETEM assumptions and revise on a regular basis

PI Response:

<u>Reviewer 23549</u>

Comment: Some level of data validation is necessary before the results can be very useful for actually understanding production facilities and the nature of the resource. At some point reservoir modeling will be required. Even if such studies were not incorporated into the present study, it is arguable whether or not the data used in this study could even be taken to the level of modeling of reservoirs.

PI Response:

<u>Reviewer 23478</u>

Comment: Please see the text of the previous section on "weaknesses" and remedy the four situations described. No further improvements can be cited at this time.

PI Response:

Enhanced Geothermal System Demonstrations Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005510
Project: Monitoring EGS Stimulation and Reservoir Dynamics with InSAR and MEQ
Principal Investigator: Davatzes, Nicholas
Organization: Temple University
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 7.0

Comment: This is an interesting concept and the work has been followed with expected critical approach. The objective of the proposal was to is to constrain the reservoir characteristics by correlating pumping parameters with resulting induced micro-seismic and surface deformation as measured by InSAR and GPS through a geomechanical model. The data sets provide a temporally and spatially constraint that exploits two distinct responses to stress change induced by pumping that depend on evolving reservoir characteristics. This appears to be showing result as expected. The work is not finalised but is certainly worth perusing.

It is clear the it will be difficult to separate the surface depression from the effect of cooling of the rock mass or reduction of the recharge of a system. An array of resistivity matrix at the surface may help to separate the two issue.

PI Response:

We appreciate their reviewer's support for both the necessity and potential benefits of this approach to reservoir characterization.

The geomechanical model in this project serves two related purposes: (1) On the one hand it is used to better elucidate the connected reservoir; and because the data spans a long time period, it also captures the temporal evolution of the system; (2) The model provides a basis to evaluate key rheologic properties of the reservoir. The approach also has the practical benefit that, the two data sets used to constrain the model are relatively inexpensive to obtain and persistently monitor the reservoir compared to other more intensive campaign style surveys.

Thus far, the combination of a solid geologic framework and pumping records with the observed MEQ and surface deformation responses has clearly defined the potential mechanisms causing the reservoir characteristics to evolve. We believe that we will be able to evaluate the relative roles of thermoelastic and poroelastic stressing on the reservoir.

In particular, this study should reveal the material properties (porosity, compliance, heat capacity, thermal conductivity, and thermal expansion coefficients) required to match the deformation behavior. This includes the sensitivity to variation in these properties and resulting uncertainties and relative importance to the geomechanical model. As a result of this analysis, the geomechanical model can be tested by gathering targeted data.

Additional external constraints will be useful once the geomechanical model clearly defines the hypothesis to be tested so that the return on an investment in gathering the data is maximized. In this way targeted campaigns can supplement this data through their increased sensitivity to poorly constrained properties.

Reviewer 23417

Score: 9.0

Comment: Current EGS research tends to ignore the complete EGS project (the classical definition) which requires a producing well and fluid flow through an artificial created reservoir. This project is one of the few that recognizes the need to monitor the reservoir once it has been created and, for that reason, this is a very important research program as it recognizes that knowledge gap. The impact that this project will have in the development of EGS reservoirs will be significant, using Brady's as a test case. The approach can be used when injection/production doublets are established at other projects locations and circulation testing begins.
Objectives for Phase 1 & 2 tasks have either been met or are in progress.

Strengths:

- A workflow diagram has been developed for Task 2.0 (Seismic Analysis) which is useful in tool in understanding the interconnection between tasks.
- Objectives are well explained with detailed task and sub tasks

Weaknesses:

- While the breakdown of project tasks into surface deformation, seismic analysis, geomechanical reservoir and rheologic modeling is a logical and well thought out approach to the problem there is no real clarity regarding how the research results will practically assist in building an EGS reservoir and tracking fluid flow through that reservoir.

PI Response:

We agree that a careful EGS characterization must include the initial state, the impact of stimulation, and the subsequent management of the EGS reservoir for a complete understanding of the technology.

The major goal of this project is to design and test a workflow that incorporates multiple constraints on the reservoir geometry and rheology and is capable of providing on-going reservoir characterization. The resulting information increases production efficiencies and lowers the levelized cost of electricity (LCOE) by: (1) Improving management of injection/production practice to more efficiently sweep heat and minimize fluid lossess; (2) Improving siting of new wells (reduced potential of failed wells) by defining the volume in communication with existing wells; (3) Assessing stimulation potential from the proximity of tight wells to the reservoir, to structures that define or bound it, and local stressing of the reservoir volume; (4) Avoiding development of short circuits and maximizing the length of injection to production flow paths for improved heat transfer; (5) Identifying volumes that do not strongly interact with established pumping wells. The project is also elucidating the relationship between pumping and induced seismicity, which can have a complicated relationship to the distribution of fluid flow and related permeability structure.

For instance, the updated seismicity catalog and surface subsidence at Brady clearly define margins to the reservoir volume and elucidate their relationship to specific faults mapped at the surface in a complexly faulted volume. The relative position and success of existing wells therefore gains necessary context. In addition, the response of the reservoir to a change in pumping practice is monitored not only by a handful of discrete wells, but by a spatially continuous response. That continuity of observation can provide important insights into small-scale structure critical to reservoir performance and management. Such definition to guide drilling is far more efficient than discovery through drilling of multiple failed wells.

These are critical issues for EGS operations on the margin of developed hydrothermal fields and the longer term management of EGS reservoirs. Thus, the characterization of the reservoir through the geomechanical model has several clear, practical benefits.

Reviewer 23625

Score: 8.0

Comment: The long term monitoring of surface movements as well as the monitoring of MEQs are highly relevant for producing geothermal fields. Firstly for safe and efficient operations and second to keep or gain public acceptance.

As critical such monitoring for the operation of geothermal fields is, it may not be so critical for the initial process of creating reservoir for EGS. For this reason I submit a score 8 only instead of a 10 score.

Subsidence in producing areas with a net withdrawal of fluids - which I assume is also the case in the Brady Field is a well known phenomenon in gas- und oil fields alike. More surprising is the observation of subsidence in areas of net fluid injection.

Like the presenter mentioned this observation requires research with the introduction of a thermo-elastic model. It can be assumed that in this particular case thermal compaction may play a role.

The scarcity of induced seismic events is remarkable. It would be worthwhile to investigate how much a net withdrawal, and therefore net pressure reduction as well as thermal contraction in geothermal fields may contribute to the reduction of induced seismicity.

PI Response:

We agree that the long-term monitoring is critical to the safety and efficient operation of both producing geothermal fields as well as those generated or enhanced by EGS. They are also critical to improving the understanding of the reservoir life cycle, including the longevity of both initial and augmented permeability.

This project will deliver both a (1) framework for on-going characterization of a geothermal reservoir and (2) a scientific improvement in understanding stimulation behavior at Brady and through application to additional sites such as the Geysers. One of the major impediments to EGS is an incomplete understanding of the process due to a lock of constraint, especially in cases of limited seismicity. As the reviewer mentions, induced seismicity is not guaranteed during or after stimulation and we submit even when present it can have a complex relationship to fluid flow. As a result, more complete evaluation of the changes in a reservoir induced by stimulation is critical to EGS technological success.

We are excited to be improving the capacity of the geomechanical model to include additional rheologies (beyond those proposed and defined in the SOPO).

Reviewer 29854

Score: 8.0

Comment: The project integrates surface deformation and seismicity data into a modeling framework for monitoring the evolution of permeability and fluid flow during stimulation and production stages. The monitoring technology can also guide the stimulation process and resource management. Modeling software tools were developed to quantify the geometry of geothermal reservoirs, pore pressure distribution and fluid flow paths. The major product is a complete workflow with data processing and modeling framework to combine InSAR data, MEQ data and reservoir modeling. Project management seems efficient: modeling tasks were added while staying under budget.

PI Response:

No comment.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 8.0

Comment: Good concept and may become a standard way of monitoring the changes in the reservoir property Needs more stations and should include resistivity network if possible.

PI Response:

We agree that additional constraints, particular expanded focal coverage of seismic stations would provide more information and additional constraints, as would monitoring fluid temperature and pressure in additional off-line wells. We point out that with the current network we are developing solid results and methodologies. We also point out that a new project, PoroTomo lead by PI Kurt Feigl (University of Wiscons) has grown out of this project and is currently working to augment monitoring.

Reviewer 23417

Score: 8.0

Comment: Technical approach to achieve project objectives has been well detailed and thorough. The only issue is that warrants more detailed technical revue seems to be how to handle EGS projects where seismicity is at very low levels. This tends to occur at a number of potential EGS sites (e.g. Raft River) and may require more detailed research.

Strengths:

- The project staffing is a highly experienced and can easily complete the work allocated to each individual researcher.

Weaknesses:

- While the PI gave a good response during the presentation the reviewer still feels that in understanding small scale ground deformation associated with individual production or injection wells that tiltmeters may have a use in understanding the orientation of fractures providing fluids to or from the well.

PI Response:

This project was in part designed in part to provide an alternative to seismic monitoring alone. Clearly, the approach works best with two strong deformation signals, but can continue to provide insight even where seismicity is absent or episodic as at Brady. With the methodology in place and tested, we agree that there are additional avenues to monitoring volume deformation such as tilt-meters. Tilt-meters can resolve smaller deformations than InSAR and can be deployed down hole (where temperatures are sufficiently low), but necessarily provide more limited spatial coverage and significant deployment cost.

Reviewer 23625

Score: 9.0

Comment: The scientific approach and the presented workflow for an integrated analysis is of highest standards.
It must be clearly distinguished between the detection and monitoring of long term effects from an ongoing production and short term effects from short term operations i.e. hydraulic stimulations.

From the presentation it was not entirely clear how interpretation of the microseismic monitoring data and interpretations of InSar monitoring are integrated into a comprehensive analysis.

PI Response:

In the current approach, surface deformations in combination with an initial geologic model and pumping records provide the initial constraints on the geomechanical model, particularly the geometry of the volume interacting with the wells. This model is then tested against additional constraints, which critically include the induced seismic response (hypocenters, focal mechanisms, and other earthquake characteristics) and tomography derived from ambient noise or inverted from the seismic catalog. We also consider both the occurrence and absence of MEQs, after augmentation of the catalog through various advanced techniques such as matched field detection. The results of this test is an iterative adjustment of the geomechanical model to provide the greatest consistency with all observations as well as to characterize sources of uncertainty in the model.

To improve this relationship, we have improved our workflow descriptions and diagrams for each relevant Task (1: Surface Deformation; 2: Seismicity; 3: Geomechanical Modeling) as well as the overall concept workflow.

Reviewer 29854

Score: 7.0

Comment: The surface deformation analysis is based on measurements by satellite radar interferometry. Reservoir geometry parameters are inferred from the response of surface deformation to injection/production stimuli. Intrinsic trade-offs between volume and depth of the deformation source seemed to be addressed by prior geological information and could be presented more explicitly. The project seeks to establish relation between pressure evolution and MEQ. In some cases the lack of MEQ could be used as information too. The matched filter detection technique mentioned (but not clear if it was implemented) in the proposal could be useful in cases with apparently low MEQ rate.

PI Response:

The Reviewer identifies an imporant issue. We explicitly incorporate any knowledge of the geologic framework into the geomechanical modeling of the surface deformation. As a necessary quality assurance step we have also tested the trade-off between the depth, geometry, and strength of the deformation source, as well as its sensitivity to rheologic properties (e.g., compliance of the medium). These tradeoffs are explicitly quantified in the inversion schemes in the InSAR and Geomechanical analyses.

To be clear we consider multiple rheological sensitivities including poroelastic fluid pressure and thermoelastic temperature sensitivities. In our investigation of Brady we have also considered the potential role of dissolution. Please refer to the response Reviewer 23625 immediately above for some additional discussion.

STRENGTHS

Reviewer 23400

Score: Not scored

Comment:

Competent in planning and incorporating the principles of the concept. Work is done according to the agreed schedule.

PI Response:

No comment.

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

N/A

Reviewer 23625

Score: Not scored

Comment: The use of existing InSar data is a novel approach. This data will certainly provide valuable information about the dynamics of producing field. The use for detection of fracture creation however is questionable.

PI Response:

The goal of this project is currently to use InSAR to constraint the geometry and bulk rheologic properties of a geothermal reservoir (whether it be natural, augmented, or purely EGS). We agree that individual fractures are below the resolution of this technique. However, (1) it is clear that InSAR is capable of reveal the correlation of discrete faults with localized or bounded surface deformation resulting from pumping and (2) this analysis is coupled to an analysis of seismicity which clearly does reveal fracture behavior.

Reviewer 29854

Score: Not scored

Comment: The project integrates surface deformation and seismicity data into a modeling framework for monitoring the evolution of permeability and fluid flow during stimulation and production stages. The monitoring technology can also guide the stimulation process and resource management. Modeling software tools were developed to quantify the geometry of geothermal reservoirs, pore pressure distribution and fluid flow paths. The major product is a complete workflow with data processing and modeling framework to combine InSAR data, MEQ data and reservoir modeling. Project management seems efficient: modeling tasks were added while staying under budget.

The surface deformation analysis is based on measurements by satellite radar interferometry. Reservoir geometry parameters are inferred from the response of surface deformation to injection/production stimuli.

PI Response:

We would like to point out that seismicity is integrated into the geomechanical characterization of the reservoir as discussed above in the response to Reviewer 23625.

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment:

Separating the effect of two effects which may the subsidence was not incorporated by this may be the effect of budget limitations.

PI Response:

This is an important challenge. For discussion of this issue lease refer to the first response to Reviewer 23400, under section: “Impact of Research, Accomplishments, Results and Progress.” We also note that team member Tabrez Ali has completed a manuscript that addresses this question.

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

No comment.

Reviewer 23625

Score: Not scored

Comment: The impact of InSAR data analysis - in contrast to microseismic data - may not be suitable for the monitoring short term operations, like hydraulic stimulation operations.

PI Response:

Please see discussion above in response to Reviewer 23417 and Reviewer 23625, under section: "Impact of Research, Accomplishments, Results and Progress."

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

No comment

IMPROVEMENTS

Reviewer 23400

Comment: Incorporate surface resistivity array to changes in the conductivity wit the depth.

PI Response:

This is a useful recommendation. Please see prior discussion Reviewer 23400, under section: "Impact of Research, Accomplishments, Results and Progress."

Reviewer 23417

Comment:

N/A

PI Response:

No comment

Reviewer 23625

Comment: Surface displacement and variations in microseismic activity should be brought into context with net fluid volume change and field pressure variations from ongoing production in the surveyed field.

This information is highly relevant for conventional hydrothermal fields, but may not be of similar importance for EGS.

PI Response:

We concur with the reviewer, and this information is being incorporated. It is an explicit part of the Workflow, which is the primary product of the current Phase of the project, and one of the related scientific investigations is also documented in a prepared manuscript.

Reviewer 29854

Comment: Intrinsic trade-offs between volume and depth of the deformation source seemed to be addressed by prior geological information and could be presented more explicitly. The project seeks to establish relation between pressure evolution and MEQ. In some cases the lack of MEQ could be used as information too. The matched filter detection technique mentioned (but not clear if it was implemented) in the proposal could be useful in cases with apparently low MEQ rate.

PI Response:

The issues raised here were previously addressed in the response to Reviewer 29854, in section "Scientific Approach."

Review: 2015 Geothermal Technologies Office Peer Review
ID: GO18200
Project: Feasibility of EGS Development at Bradys Hot Springs, Nevada
Principal Investigator: Drakos, Peter
Organization: Ormat Nevada, Inc.
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 8.0

Comment: Desert Peak was a very successful implementation of EGS technology to a hydrothermal system and it was expected that Brady will also follow the same principle but the result were disappointing and need investigating. The physics associated with it is sound but the boundary conditions needs to be looked at.

PI Response:

Reviewer 23417

Score: 7.0

Comment: This project has been primarily completed and is currently in the final evaluation phase of monitoring. Conversion of low permeability wells in producing geothermal fields into useful injectors or producers is a primary objective of the GTO. This project has successfully completed that goal by improving injectivity of a well 15-12 ST1 from 0.3gpm/psi to 1.17gpm/psi. The only decision left is a Go/No Go decision on the pipeline.
Accomplishment of all primary goals have been achieved although an objective to demonstrate the cost effectiveness of such methodologies has not been discussed.

Strengths:

- Although much of the work in the earlier phases was not reported in this presentation it is assumed that the data was presented in previous peer reviews.
- Goals have been accomplished
- Weaknesses:
- Much of the presentation appeared to be data rather than interpretation details

PI Response:

Reviewer 23625

Score: 8.0

Comment: To use an existing well with poor flow characteristics at the margin of a producing field is an ideal set up to test reservoir improvement techniques. A further advantage is a good understanding of the geological / structural system based on a vast data set.

The improvement of the well infectivity will have an immediate economic impact. It may have a lesser impact on the development of EGS at greater depth in "virgin" areas.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 8.0

Comment: One expects that there has been overconfident in implementing this proposal because of the success at Desert Peak. A review panel of experienced experts needs to be stablest to examine possible flaws in the implementation approach and any scientific gap in the know how.

PI Response:

Reviewer 23417

Score: 7.0

Comment: Technical approach to this project was very high and included all appropriate project tasks. Results of tracer injection injection during stimulation were not discussed in the presentation. The establishment of a decision tree for this type of activity was very useful (although very difficult to read in the printed materials)

Strengths:

- Extremely strong project team with many highly experienced researchers.
- Weaknesses:
- Lack of detail in some areas – tracers and costs etc

PI Response:

Reviewer 23625

Score: 7.0

Comment: There is a comprehensive data set available for the well. Unfortunately it was not disclosed at which intervals the injectivity improved most. This is critical information for the understanding of the reservoir enhancement.

Zonal isolation techniques are critical for EGS. This was not applied in this well. Open hole stimulation over the length of 900' is not a novel approach, however effective for this particular system.

PI Response:

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: It is a well established and documented site with experienced scientific group with previous experience, and in principle it should have succeeded. it is imperative to find out why it did not work.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The strength of this project is the commercial perspective of the operation. The technical approach with a three stage hydraulic stimulation with active microseismic monitoring follows comprehensive data set conforms to best practices.

PI Response:

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: Not that one can can point to.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: It was not disclosed if and which data were acquired in adjacent wells during stimulation. Although induced seismicity was reportedly low, it would be interesting to have information about the number, location and magnitude of all recorded events during and after stimulation.

PI Response:

IMPROVEMENTS

Reviewer 23400

Comment: The result obtained or the lack of result expected is a surprise and needs further investigation so that the procedure and steps developed can be implemented elsewhere.

PI Response:

Reviewer 23417

Comment: N/A

PI Response:

Reviewer 23625

Comment: There appears to be a suspended well EE-1 along the structural strike halfway to the producing field. Flow, pressure and temperature measurements in EE-1 during the stimulation phase of well 15-12 may provide valuable information about reservoir growth and area of influence of the stimulation.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006760
Project: Poroelastic Tomography by Adjoint Inverse Modeling of Data from Seismology, Geodesy, and Hydrology
Principal Investigator: Feigl, Kurt
Organization: University of Wisconsin-Madison
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 9.0

Comment:
The quality and the concept is excellent. It is recognised that this type of investigation needs precise measurement and can be seen to be slow. It is on target with its objectives.

An addition of surface resistivity methods would have been an excellent additional property for assessment/differentiation of volume charge from either cooling or depletion of a reservoir.

PI Response:

We have considered using electrical resistivity and electrical conductivity surveys to help image the structure of the reservoir and assess changes during the active pumping experiments. Two different types of imaging techniques were considered: a galvanic electrical resistivity survey and a time-domain electromagnetic survey. We conclude that neither type of survey is feasible at Brady's Hot Springs due to cultural constraints.

To fulfill the goals of the research project, we must image to a depth of 400 m within the boundaries of the Natural Laboratory. Furthermore, due to the location of the injection and production wells and the strike of the faults (SW to NE), we expect that most of the changes in material properties during fluid injection will occur along the fractures between Interstate Highway 80 (I-80) and the Frontage Road. To map these features, one should locate the electrical resistivity survey lines perpendicular to the strike of the main faults (i.e., NW to SE). In this case, the lines would have to be located between I-80 and the Frontage Road. Cables could not be deployed on top of the roads without interrupting vehicular traffic. The highway and road are separated by less than 300 m. The distance between current electrodes would also have to be less than this distance, implying that the maximum depth of the survey's penetration would be 150 m, much less than the 400 m imaging depth required for the project. Longer survey lines could be located both to the NW of the I-80 highway and on the SE side of the Frontage Road, but would not image the area of interest in the Natural Laboratory. Finally, one might consider placing the survey lines parallel to the roads. However, most of the metal pipes and barbed wire fences also run parallel to the roads. Their conductivity would interfere with an electrical resistivity survey.

An alternative to the electrical resistivity survey would be the deployment of time-domain electromagnetics. Performing a time-domain electromagnetic survey does not require deploying long cables because the technique instead uses loops of cable. The method images the distribution of electrical conductivity of a geological formation by monitoring the decaying of the induced electromagnetic field over time. This technique would induce large electromagnetic fields in the metal pipelines, fences, pumps, and well casings at Brady's. They would dominate the signal, preventing the imaging of the rock formations in the Natural Laboratory.

Reviewer 23417

Score: 8.0

Comment: This is a new project so mostly research has focused on existing data collection and interpretation. However one of the primary objectives is to characterize the physical properties of EGS sites on a scale that will allow detailed monitoring of reservoirs as they are produced. This is fundamental to the goals of the GTO and is an area of research that warrants far more attention than it has been given in recent years. Once EGS reservoirs have been established monitoring of fluid flow, temperature and pressure will be one of the most critical and challenging tasks to accomplish.

Technical accomplishments and results are limited due to the early project stage.

Strengths:

- Actually sets metrics that will be used to govern Go/No Go decisions
- The productivity of work completed so far is high considering the projects early stage

Weaknesses:

- Will the defined parameters to be measured be capable of allowing for the characterization of individual fracture networks on a fracture by fracture basis.

PI Response:

As stated in the Technical Volume submitted as part of the original proposal, “the goal of the proposed project is to assess an integrated technology for characterizing and monitoring changes in the rock mechanical properties of an EGS reservoir in three dimensions with a spatial resolution better than 50 meters. The targeted rock mechanical properties include: saturation, porosity, Young’s modulus, Poisson’s ratio, and density, all of which are “critically important” characteristics of a viable EGS reservoir (DOE GTO, 2014). Estimating these parameters and their uncertainties will contribute to the overarching objective of characterizing the reservoir in terms of its effective permeability and/or fracture transmissivity.” Using the methods planned for deployment at Brady’s Hot Springs in 2016, it should be possible to characterize a 50-m-by-50-m-by-50-m volume in terms of its effective permeability, fracture density, or “tortuosity” [*Maerten et al.*, 2000; *Molotkov*, 2002; *Morency et al.*, 2009]. However, distinguishing an individual fracture will not be feasible if it is much less than ~25 m in dimension. On the other hand, results from inverse modeling of InSAR data suggest that the deformation at Brady’s is a result of volumetric contraction in shallow units, likely associated with “damage zones” where fault segments interact mechanically [*Ali et al.*, 2015]. Such zones may be large enough to resolve in terms of material properties that vary with spatial position and/or time.

Reviewer 23625

Score: 8.0

Comment: A significant improvement in the resolution of fault and fracture pattern is highly relevant for exploration and production from geothermal fields as well in EGS.

Poro-elastic tomography requires a comprehensive data set of seismic, hydraulic, density and stress data.

The acquisition of such data sets is cost intensive. The proposed project restricts the data acquisition to the monitoring of shallow aquifers. These aquifers are considered to feed deep hot aquifers and may indirectly show a signal from pressure variations in the hot aquifers.

The acquisition experiment to monitor temporal changes in subsurface poro-elastic variations is ambitious but may open up new ways in monitoring subsurface dynamic processes.

At this stage it cannot be assessed how valuable this approach may be for the monitoring of similar processes at greater depth as it would be required in EGS.

PI Response:

As stated in the Technical Volume submitted as part of the original proposal, "***the expected outcome of Phase II is a validated small-scale prototype*** that will provide the technical specifications required to deploy the technology in a deeper, full-scale EGS field".

Reviewer 29854

Score: 8.0

Comment: The project integrates inversion tools for seismological, geodetic and hydrological data to achieve finer resolution constraints on spatial distribution of physical parameters of EGS reservoir and to monitor their temporal evolution. Achievements include advances in application of seismic ambient noise tomography in geothermal environments, demonstration of usefulness of DAS data for surface wave analysis, monitoring volume changes in Brady from InSAR data. Field experiment design and deployment at Brady are next phases. This is a vast project in its initial stages.

PI Response:

The presentation for the 2015 Peer Review in Denver was submitted at the beginning of April 2015, just after the PoroTomo project completed its second quarter.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 9.0

Comment: Excellent but needs an additional use of surface resistivity to help discriminate volume change from cooling or depletion of in-suit fluid.

PI Response:

Addressed above.

Reviewer 23417

Score: 8.0

Comment: This is an extremely well- designed project with a very well thought through approach and clear documentation. A large, but very experienced group of researchers will provide the necessary technical expertise.

Strengths:

- PERT provides excellent summary of project.

Weaknesses:

- No discussion on the ability of this approach to provide stated resolution with depth.

PI Response:

Indeed, the PoroTomo project has been designed as an experiment to evaluate the ability of the approach to provide stated resolution. As stated in the Statement of Project Objectives (SOPO) negotiated before starting the project, "***the technology performance metric for the proposed project will be resolution in meters*** of a feature in the modeled 3-D distribution of a rock mechanical property (e.g., Poisson's ratio), as determined by the dimension of a visible checkerboard pattern ***at 200 m depth*** in a test using simulated data (Table 1)." During Phase I of the project, the PoroTomo team is analyzing existing data to investigate the sensitivity of tomographic resolution to various factors, including: the number of parameters to be estimated in the inverse problem, the number of measurements, and the distribution of the sensors. For seismic data, the wavelength and distribution of the sources also play crucial roles. The results will be presented at the Stage Gate Review meeting in Reno on September 24th. At this in-person meeting, the team will evaluate if the technical criterion of 50 meter resolution in 3-D can be met. The milestone at M12 will be the Go/No-Go decision to decide if the project will proceed to Phase II.

Reviewer 23625

Score: 9.0

Comment: The selected techniques (3D and 4D reflection seismic, as well as DST and DAS) are well proven methods in the oil- and gas industry. It is commendable that such techniques are adapted to monitor dynamic hydraulic systems.

PI Response:

Thank you.

Reviewer 29854

Score: 8.0

Comment: The developments in adjoint tomography are a highlight of the project advances in geophysical data analysis. The surface deformation is interpreted via a simplified dislocation model in an elastic half-space, suggesting opportunities for more sophisticated modeling via FEM.

PI Response:

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: Very good. If this concept can be demonstrate to work as expected, it could provide reservoir property in real time during stimulation and the life of the reservoir.

PI Response:

Indeed, solving the poroelastic governing equations using the Finite Element Method (FEM) will account for and/or estimate spatial variations in material properties.

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Although the comment is correct about the potential for tomographic imaging in "real time", analyzing the data to be acquired at Brady's in March 2016 will require at least 12 months to complete.

Reviewer 23625

Score: Not scored

Comment: Solid technical approach with proven methods used in oil- and gas industry, however at smaller scale for much higher resolution.

The use of active seismic sources allows to acquire a 3D image of subsurface structures. This standard tool is not sufficiently used in the geothermal industry.

PI Response:

N/A

Reviewer 29854

Score: Not scored

Comment: The project integrates inversion tools for seismological, geodetic and hydrological data to achieve finer resolution constraints on spatial distribution of physical parameters of EGS reservoir and to monitor their temporal evolution. Achievements include advances in application of seismic ambient noise tomography in geothermal environments, demonstration of usefulness of DAS data for surface wave analysis, monitoring volume changes in Brady from InSAR data. Field experiment design and deployment at Brady are next phases. This is a vast project in its initial stages. The developments in adjoint tomography are a highlight of the project advances in geophysical data analysis.

PI Response:

N/A

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: none so far.

PI Response:

N/A

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

N/A

Reviewer 23625

Score: Not scored

Comment: The planned experiment is restricted to a shallow aquifer. The recorded data may not be of immediate relevance to EGS.

PI Response:

As stated in the Technical Volume submitted as part of the original proposal, "***the expected outcome of Phase II is a validated small-scale prototype*** that will provide the technical specifications required to deploy the technology in a deeper, full-scale EGS field". For example, extending the approach to image a geothermal reservoir at depths of 1–2 km would require extending the fiber-optic cables for Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) to at least the same depth in the vertical dimension and roughly twice the lateral extent of the reservoir in the horizontal dimension. Similarly, the ability to detect temporal changes in material properties offers several potential applications to Enhanced Geothermal Systems (EGS) for designing, monitoring, and assessing a geothermal resource during stimulation, production and injection.

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

N/A

IMPROVEMENTS

Reviewer 23400

Comment: As mentioned in previous assessments,, surface resistivity would had been an excellent thing to do.

PI Response:

Addressed above.

Reviewer 23417

Comment: N/A

PI Response:

N/A

Reviewer 23625

Comment: The quality of any spatial and temporal variation monitoring with geophysical methods depends entirely on the quality of the geological 3D model. In all geothermal projects presented I miss well documented geological 3D models based on reflection seismic data. The hydraulic topography data sampling could be complemented with density logging.

PI Response:

The Porotomo team is currently working with several 3-D geological models describing the Brady Natural Laboratory. Building on considerable field work [e.g., *Faulds and Garside*, 2003; *Faulds*, 2011], James Faulds and his colleagues at the Nevada Bureau of Mines and Geology at the University of Nevada, Reno (NBMG-UNR) have been conducting detailed analytical work relevant to understanding the dynamics of a geothermal system. The first 3-D geologic model of Brady's was done by as part of a doctoral thesis by Egbert Jolie at the GFZ in Germany in collaboration with Faulds [*Jolie et al.*, 2012]. This geological model was published by Jolie et al. [2015]. NBMG-UNR was funded by Ormat to enhance the geologic model. The resulting updated geologic model includes all of the major lithologic units. It was completed in 2013 by Drew Siler, a post-doc working at NBMG [*Siler and Faulds*, 2013]. It distinguishes the specific rock units that contain the geothermal reservoirs, as well as several of the critical fault intersections that serve as major conduits for the fluids. We were able to use this model in June 2015. Working with Nick Hinz, a Geologic Mapping Specialist at NBMG-UNR, Drew Siler (now at LBNL) and Jeff Wagoner at LLNL, we have resolved all of the technical issues with the (proprietary) EarthVision software. We have extracted the lithologic facies and fault-intersection density for each 25x25x25-meter volume element (voxel) in the mesh to be used for modeling the Brady Natural Laboratory. Illustrative slices through this 3-D model appear in the progress report for Subtask 4.9 for the 3rd Quarter, to be submitted in July 2015.

Reviewer 29854

Comment: The surface deformation is interpreted via a simplified dislocation model in an elastic half-space, suggesting opportunities for more sophisticated modeling via FEM.

PI Response:

In Subtask 4.9, we are working on mapping the lithologies from the 3-D geologic model into material properties (e.g., Young's modulus, density, Poisson's ratio and porosity). Such a functional (or look-up table) will be very important for inverse modeling and interpretation.

References

Ali, S. T., N. C. Davatzes, K. L. Feigl, H. F. Wang, W. Foxall, R. J. Mellors, J. Akerley, E. Zemach, and P. Spielman (2015), Deformation at Brady Hot Springs geothermal field measured by time series analysis of InSAR data [SGP-TR-204], paper presented at Proceedings, Fourtieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California,, January 26-28, 2015. https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2015/Ali.pdf

Faulds, J. E., and L. J. Garside (2003), Preliminary Geologic Map Of The Desert Peak - Brady Geothermal Fields, Churchill County, Nevada.

Faulds, J. E. (2011), Assessment of favorable structural settings of geothermal systems in the great basin region, western USA, paper presented at 2011 GSA Annual Meeting in Minneapolis.

Jolie, E., J. Faulds, and I. Moeck (2012), The development of a 3D structural-geological model as part of the geothermal exploration strategy - a case study from the Brady’s geothermal system, Nevada, USA. , paper presented at 37th Workshop on Geothermal Reservoir Engineering, Stanford, California.

Maerten, L., D. D. Pollard, and R. Karpuz (2000), How to Constrain 3-D Fault Continuity and Linkage Using Reflection Seismic Data: A Geomechanical Approach, *AAPG Bulletin*, *84*, 1311-1324. http://aapgbull.geoscienceworld.org/cgi/content/abstract/84/9/1311

Molotkov, L. A. (2002), On the coefficients of pore tortuosity in the effective Biot model, *J. Math. Sci.*, *108*, 752--757.

Morency, C., Y. Luo, and J. Tromp (2009), Finite-frequency kernels for wave propagation in porous media based upon adjoint methods, *Geophys. J. Int.*, *179*, 1148-1168. http://gji.oxfordjournals.org/content/179/2/1148.abstract

Siler, D. L., and J. E. Faulds (2013), Three-Dimensional Geothermal Fairway Mapping: Examples From the Western Great Basin, USA, *Geothermal Resources Council Transactions*, 327-332. http://pubs.geothermal-library.org/lib/grc/1030589.pdf

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Joint Active and Passive Seismic Imaging of EGS Reservoirs
Principal Investigator: Huang, Lianjie
Organization: LANL
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 7.0

Comment: Type or Paste Text Here
This is an ambitious project when taking into consideration the complexity of the geology and uncertainties. The work is carried out within the proposed schedule and quite remarkable. It would have been a prudent move to have tested this in a know environment first to calibrate the concept.

PI Response:

Thank you for your suggestions. We will validate our methods using a geophysical model built based on geologic features and well log data from the Raft River geothermal site, before apply our mehtods to field data.

Reviewer 23417

Score: 7.0

Comment: This is a new project (start date Oct 2014) and has little on which to report. Having better 3-D velocity models for fracture evaluation is critical so that this research has a very important role to play in evaluating geothermal projects. The increase in accuracy of the velocity models over existing techniques was not discussed.

It is also important that individual fracture systems be characterized in detail for EGS systems to be both developed and maintained. The only concern is the ability of new technique to be able define fractures in sufficient detail that would be useful for evaluating monitoring flow paths. No discussion was presented on this topic.

Strengths:

- The research has the potential to have a substantial impact on EGS development providing an appropriate level of definition can be developed.

PI Response:

Currently, microearthquake (MEQ) imaging for fracture characterization often uses a layered velocity model. Our elastic-waveform inversion of 3D VSP data will improve the accuracy of the velocity models. We have demonstated using synthetic data that our elastic-waveform inversion using sparsly acquired seismic data significantly improve velocity inversion. We expect the similar improvement for field data.

The core study showed that the fractures are nealy vertical, so the fracture zone (or the narraw zone of our Raft River geophysical model) should behaves as a horizontal transverse isotropic (HTI) medium for seismic wave propagation. We will incorporate the HTI properties in the geophysical model for our study.

Reviewer 23625

Score: 4.0

Comment: As correctly stated in the project description, the major challenge is the ability to map and characterize fluid pathways. One way to delineate fluid pathways is by locating sources of microseismic activity. One drawback is that in permeable fractures flow may take place over large distances without any seismic signal. Micro seismicity is an expression of fracture creation not of flow.

The injection tests have not resulted in major induced seismicity. The number of events as well as the magnitudes are relatively low and do not provide sufficient seismic signals for the methodology presented.

The triggered signals are sparse and of very low magnitude. It was not clear from the presentation on how many monitoring stations a full wave signal could be recorded.

PI Response:

Most MEQ imaging uses only the direct arrivals of seismic waves from the sources to the receivers. Our plan is to analyze the entire seismic waveform using elastic-waveform inversion, and therefore, we will accout for seismic waves propagating not only directly from the sources to the receivers, but also scattering within the EGS reservoir and relfections from geologic layers beneath the EGS reservoir, with a goal to image and characterize MEQs and obtain velocity changes in the reservoir. We also plan to use the improved focal mechanisms of MEQs to distinguish fluid-induced MEQs from pressure-induced MEQs. Yet, imaging fracture flow in an EGS reservoir is an unsolved, challenging problem. We will try to improve the capability using joint inversion of passive and active seismic data.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 7.0

Comment: Type or Paste Text Here
This type of concept works better when there are sharp defined foundries with sufficient impedance contrast to measure the changes. There are too many variable and uncertainties to test in this in the proposed environment. An alternative technique is to use differential method whereby the initial survey is the reference survey and the subsequent one shows the relative changes.

I suspect there are not sufficient number of sensor in the network array to make the concept effective. A synthetic model (numerical) which will allow to test the sensitivity of fine geological changes would have been helpful as the first step.

PI Response:

Thank yo for your comments. Yes, if time-lapse seismic data are available, we will be able to quantify the geophysical property changes within the EGS reservoir, which can infer the fracture flow. In fact, LANL has developed several novel elastic-waveform inversion mehtods using time-lapse differences in seismic data to quantify subsurface changes of geophysical properties. However, no enough funds are available to acquire time-lapse seismic data.

Because ther are no sufficient number of geophones required for conventional seismic imaging and inversion, we have developd a new elastic-waveform inversion method using a compressive sensing technique to effectively handle sparsely acquired seismic data, and have validated our algorithm using a 2D synthetic seismic data.

Reviewer 23417

Score: 8.0

Comment: The technical approach is innovative and novel and has the potential for assisting in EGS site characterization. It does require substantial amount of seismic data and the lack of ambient noise data may be an impediment in the future. The approach would be valid in areas where a substantial amount of data had already been collected rather than areas that are in the early stages of evaluation.

Strengths:

- Appears a well thought out set of project objectives and completion of large amount of preliminary work in relatively short time that the project has been active.
- New innovative technique

Weaknesses:

- There is no discussion on how much more detailed the results of this approach will provide as compared the techniques that currently exist e.g how more accurate will the velocity models be compared to standard approaches.

PI Response:

Thank you for your comments. We will compare our results with those obtained using existing methods.

Reviewer 23625

Score: 4.0

Comment: The scientific/technical approach to create a subsurface velocity model must be based on geological model. A robust velocity model should be based on reflection seismic data. Sparse and weak sources from microseismic events are insufficient to detect velocity variations due to variations in flow characteristics in fluid flowpathes.

Areas with increased fracturation most likely show decreased velocities. As long there are no measured data where a velocity model can be validated, modeling remains too speculative as to become a tool for decision making, in particular fluid flow path mapping.

PI Response:

Yes, we will use the vertital sesimic profiling (VSP) data to be acquired in Year 2 to invert for the velocity model in the EGS reservoir. There were surface seismic reflection data acquired by the other company but the company cannot release the data for our study.

Yes, areas with increased fracturation most likely show decreased velocities. In our geophysical model, the narraw zone is the targeted EGS reservoir and has low P- and S-wave velocities.

We will validate our new imaging and inversion algorithms using synthetic data from a Raft River geophysical model, and apply our methods to field VSP and MEQ data in Years 2 and 3 of the proejct.

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: Type or Paste Text Here
The concept has some merit but the environment to test it may be difficult. The team has good reputation and technical competence which prove me to be wrong!

PI Response:

Thank you for your comments. We will improve the imaging capability using ambient noise, MEQ, and VSP data, yet new development is needed to image fracture and flow in the EGS reservoir. As mentioned above, time-lapse data, including seismic and potential field data, may improve the reliability of flow imaging. This requires future support from GTO beyond this project.

Reviewer 23417

Score: Not scored

Comment: Type or Paste Text Here
N/A

PI Response:

N/A

Reviewer 23625

Score: Not scored

Comment: The strength of this project is the development of an elastic-waveform inversion algorithm. The algorithm however needs to be tested in an area with a rich data set and well known geological setting and well defined flow paths.

PI Response:

Thank you for your comments and we agree. We wish to apply our algorithms to data to be acquired by the EGS Field Observatory (FORGE) projects.

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: Type or Paste Text Here

I have a feeling that they have jumped at the deep end and may struggle to prove the concept because of the geological complexity and the changing properties of the properties as a function of time due to the extraction of heat energy..

I recommend an intermediate stage of synthetic model (numerical) which will allow to test the sensitivity of fine geological changes would have been helpful as the first step.

PI Response:

Thank you for your suggestion and we will test it.

Reviewer 23417

Score: Not scored

Comment: Type or Paste Text Here
N/A

PI Response:

N/A

Reviewer 23625

Score: Not scored

Comment: The developed algorithms are based on too few data. It would be advisable to test and calibrate the algorithms with data from well understood geothermal projects. It is questionable, whether the variations in fluid pathways create a detectable seismic signal. Such knowledge gaps should be closed by using areas with a well defined detailed geological model and multiple control from well data.

PI Response:

Thank you for your comments and we agree. We try to improve our imaging capbility with data currently available and data affordable to acquire. Time-lapse data would be needed to reliably image subsurface flow.

IMPROVEMENTS

Reviewer 23400

Comment: This type of concept works better when there are sharp defined foundries with sufficient impedance contrast to measure the changes. There are too many variable and uncertainties to test in this in the proposed environment. An alternative technique is to use differential method whereby the initial survey is the reference survey and the subsequent one shows the relative changes.

I suspect there are not sufficient number of sensor in the network array to make the concept effective. A synthetic model (numerical) which will allow to test the sensitivity of fine geological changes would have been helpful as the first step.

PI Response:

This comment is the same as a previous comment. Please see our responses above.

Reviewer 23417

Comment: n/a

PI Response:

N/A.

Reviewer 23625

Comment: Calibrate the algorithms with comprehensive data sets from projects with a large data base.

PI Response:

Thank you for your comment. Such a project is needed to integrate comprehensive data sets.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Archive of Fenton Hill Data; Creation and Testing of Data Sets for Simulation and Testing
Principal Investigator: Kelkar, Sharad
Organization: LANL
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 10.0

Comment: This will have an immediate impact on the development of EGS as the data will be available for potential projects in this type of environment. To classify, define its importance and and select appropriate data is exceedingly difficult, particularly if one is not familiar with very old data, which may be the case with this. The progress made is faster than one expects and hope that important data has not been
disposed off.

This project is under budgeted and needs more time and funds. The cost of experiments carried out, data collected and reports prepared would have been in terms of millions $ and it imperative that this issaved and documented for future generations.

PI Response:

We thank the rreviewer for positive comments and agreee that the budget is only a very small fraction of the original project costs, which were on the order of 180M$ in the 1990's. We agree that we should do our best to preserve for future use whatever we can archive at this time.

Reviewer 23554

Score: 8.0

Comment: Archiving relevant or at least representative data from Fenton Hill should be a priority. Losing the data would have a serious impact on applying lessons learned to future EGS efforts and a failure of purpose for much of the current emphasis on EGS as the future of geothermal energy.

PI Response:

We agree with the reviewer that it is valuable to archive what data has remained from the old project, although there has been some unavoidable loss as project personel have retired and doccuments and data have been lost.

Reviewer 23625

Score: 9.0

Comment: Still nowadays Fenton Hill is the EGS project that produced the most original and most important findings on reservoir creation in low permeability rock formations. Reservoir creation is the most critical aspect for EGS (beside affordable drilling and completion techniques).

Systematic digitizing and archiving all Fenton Hill data is probably the most cost effective way of knowledge increase and dissemination for EGS.

PI Response:

We agree with the reviewer regarding the importance of the project. The current project seeks to archive the available doccuments, mostly reports, memos and papers, in a digital form accessible electronically. While some microseismic data are availabel in an electronic form and currently being converted to a SEG-compatible format, there are practically no original paper traces/records available of other types of data.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 9.0

Comment: The approach used is commendable by bringing in those who were involved in the past to scrutinise the data but there was a suggestion that some of the paperwork was disposed off, which is not good news. It is only a marginal cost to digitise as much as possible (scan it) and retain the information in a digital form.

PI Response:

We relied on Don Brown, one of the original Hot Dry Rock program leades still available to the project at the present, to select which doccuments were important to keep.

Reviewer 23554

Score: 6.0

Comment: Objective are approached but there is still much to do particularly regarding core archival.

PI Response:

Agreed.

Reviewer 23625

Score: 8.0

Comment: Collecting boxes of old files may not sound like a highly sophisticated scientific approach. In this particular case it is probably the only way to secure old valuable data. It is most commendable that the original researchers cooperate in this project.

(There is a similar initiative in the EU to supply a central open data base open to the public with non-digited data from old geothermal projects throughout Europe.)

PI Response:

Agreed.

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: Good team and enthusiasm to do a good job. Use existing staff who are familiar with the data to scrutinise the relevance and important of the data, even though the data is over 50 years old.

PI Response:

Thank you.

Reviewer 23554

Score: Not scored

Comment: A worthwhile effort to preserve history.

PI Response:

Thank you.

Reviewer 23625

Score: Not scored

Comment: The strength of this project lies
a) in the value of the work to preserve unique data that otherwise would be lost and
b) in the fact that the former stakeholders are actively contributing to this effort.

PI Response:

Thank you.

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: The data is very old and it is important to take time to catalogue it. The budget may pose some difficulty in getting it all together in time and budget. In this case one should not destroy the data but store it for further evaluation at a later date.

PI Response:

As such, the available records were reports, memos, and papers; and not original data records; except for some micriseismic data which existed in an older format and is being converted

Reviewer 23554

Score: Not scored

Comment: Develop a final end plan and desired exit outcome.

PI Response:

Agreed - we will implement this.

Reviewer 23625

Score: Not scored

Comment: I cannot see any weakness in this small but worthwhile project.

PI Response:

Thank you.

IMPROVEMENTS

Reviewer 23400

Comment: No comments

PI Response:

Reviewer 23554

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23625

Comment: Please advertise the availability of this data, once the project is finalized. This data collection makes only sense when it is made publicly available and is used by the geothermal community.

PI Response:

Agreed. we have submitted an article to GRC Annuakl meeing and will present it in Septmeber if the project budget permits.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Bradys and Desert Peak Numerical Modeling
Principal Investigator: Kelkar, Sharad
Organization: LANL
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 6.0

Comment: The progress of the development of the code is slower than expected and may either reflect the low budget or difficult environment to model. This is a very important task and will help to scope other projects before actual stimulation is carried out.

PI Response:

We thank the reviewer for the comment. Given the available budget, we have chosen the approach to assume a relationship between the local stress changes and permeability, rather than modelign fracutre opening with a cubic law.

Reviewer 23417

Score: 7.0

Comment: This is a new project aimed at development of a model primarily used for stimulation. It will be use to evaluate the stimulation at Desert Peak well DP 27-15 and subsequently at Brady's. However the model will be useable at many other EGS sites.

Good simulators are necessary for all aspects of EGS projects if the GTO energy goals are to be met. This is one of a number of modeling research projects aimed at the EGS program and is critical that they become a part of the program. Starting with a stimulation in a known geothermal field where there is ample data for validation is a good start.

The project addresses two existing barriers to (Barriers F and L) identified by GTO.

No Strengths or Weaknesses – Project is just starting.

PI Response:

We thank the reviewer for the comment.

Reviewer 23625

Score: 6.0

Comment: Meaningful numerical modeling of flow- pressure-, permeability-, temperature-changes requires a well funded understanding of the geometry of a reservoir formation. Thickness, confining seals, fault pattern, structure and stress regime must be defined. Without the knowledge of these constraints, modeling may add little to a better understanding of the wellhead- and downhole pressure variations in a hydraulic stimulation process.

As the actual modeling has not yet been done I strongly suggest that the model must incorporate such a well defined geological model to produce meaningful results.

PI Response:

We thank the reviewer for the well though out comment. This project has a limited budget and we have chosen a limited scope to fit within the means.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 8.0

Comment: There appears to be a misunderstanding on how the in-situ process of simulation occurs. The stimulation pressure at the well-head has to significantly high to accommodate friction losses in the casing, at the borehole interface and to the far field where the shear stimulation is taking place. This required high flow and high pressures in a stepped mode for example. 40, 60, 90 l/s.or even more until seismicity occurs.

PI Response:

We agree with the view on pressure losses in the system due to friction.

Reviewer 23417

Score: 7.0

Comment: The technical approach uses existing reservoir model developed at LANL which will be modified to include rock deformation. The project has a small budget of around $100k so detail task are not identified but the description in the Desert Peak Summary document and the presentation seem to be adequate.

No Strengths or Weaknesses - Project just starting.

PI Response:

Thank you

Reviewer 23625

Score: 5.0

Comment: As the actual work has not yet been done, it is not possible to make an assessment.

PI Response:

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: A close look at what happened during the actual stimulation is essential. The data shows that low flow rate injection to create shear stimulation did not work and that larger flow rate and pressure was essential to generate seismicity and thus shear stimulation. I suspect there may be too much reliant on Mohrs stress circle rather than undemanding the observations.

PI Response:

The stimualtion at pressures below the minimum stress did creat significant injectivity imporvement - by a factor of almost 15, as discussed in outn previous work (Dempsey et al. 2014 ARMA). There was a lack of seismicity that could be detected by the existing network. This portion of the stimulation used the Mohr-Coulomb model with total effective stress including poro-elastic and thermo-elastic effects. The work intended for this project will nto relie on Mohr-Coulomb failure.

Reviewer 23417

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23625

Score: Not scored

Comment: The strength of the project is probably that there is a solid data base with real hydraulic stimulation data is available.

PI Response:

Agreed.

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: Already made this comment.

PI Response:

Reviewer 23417

Score: Not scored

Comment: Type or Paste Text Here
N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

IMPROVEMENTS

Reviewer 23400

Comment: It is imperative to understand what is actual happening during a sucessful stimulation rather than what one can generate using numerical model. Adapt the model to the actual reality and not other way around.

PI Response:

Agreed. It is not possible to include all the complexities of a real stimulation in a model, one must be selective in order to help improve our understanding.

Reviewer 23417

Comment: N/A

PI Response:

Reviewer 23625

Comment: Take a detailed geological/structual model and include all available regional stress data as the base for any poro-elastic modeling. I strongly support that the PI participates in the DOE GTO Model comparison project.

PI Response:

Thank you

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0000215
Project: Concept Testing and Development at the Raft River Geothermal Field, Idaho
Principal Investigator: Moore, Joseph
Organization: University of Utah
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 9.0

Comment: Good accomplishment and logical approach. Good track record and well done.

PI Response:

Thank you.

Reviewer 23417

Score: 8.0

Comment:
This has been a critical EGS project and has clearly been successful in substantially increasing the flow rate into RRG-9 ST1 from 20 to 540 gpm. The project has achieved most of its stated objectives with the possible exception of clearly showing the capability of tracking injected fluids on a scale that would allow identification of individual fracture systems.

The value of this type of research is critical to EGS deployment because it allows an understanding in fracture development in non-volcanic environments. A single fracture was interpreted and reported as a result of the stimulation rather than a fracture network. Monitoring and evaluation of fluid flow within this fracture is still left to be completed but it should prove to be valuable data.

A more detailed discussion of the use of propellants would have been useful.

Strengths:
- High quality researchers
- Successful attainment of project objectives

Weaknesses:
- Little discussion of time-lapse MT data. Did not show clearly how this helped monitoring of fluid flow.
- No tracer results presented.

PI Response:

We thank the review for his comments. We had hoped to present a more detailed discussion of the MT results. However, funds for the MT study were provided directly to Dr. Greg Newman at LBL by the DOE. Dr. Newman has not provided a report to DOE and the PI of the Raft River Project has no control over Dr. Newman's activities. Despite requests, the data presented at the Peer Review are the only results we have received.

I may have confused the reveiwer about the tracer testing. No tracer has been recovered; thus there are no data to present.

Propellants may have applicability in EGS projects. Lack of funds may preclude its use at Raft River.

Reviewer 23625

Score: 9.0

Comment: It is highly relevant to understand the effect of injection pressure and injection temperature to a low permeable rock formation. The high value of this project is the proof that thermal contraction is the major mechanism for permeability enhancement. This is a very encouraging finding. It explains that permeability enhancement can be achieved with low injection pressures with very little induced seismicity. These findings are relevant for many other EGS projects.

It also proves that permeability enhancement remains within pre-existing fracture zones. Unfortunately the knowledge of the geometry of the "Narrows zone" appears to be limited.

PI Response:

We concur with the reviewer. Additional information on the Narrows Zone would be useful. We have attempted to obtain the results of a 3-D seismic reflection survey conducted over the Narrows Zone by Walker Ranch/AMG, who is exploring the adjacent property but to date, they have not released any pertainent information. Gravity and magnetic data have not proven useful in evaluating the zone.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 9.0

Comment: Good approach and followed what one learnt at Desert Peak.

PI Response:

Thank you.

Reviewer 23417

Score: 7.0

Comment: Quality of the technical approach and overall direction of research is very high. Little discussion on the input from other Team members. Technical approach was well executed with apparent no major problems.

Strengths:

- Well-designed program carried out by experienced, very capable researchers

Weaknesses:

- Would have been valuable to have a greater discussion on the DTS performance

PI Response:

Thank you for the positive comments. We agree that additional discussion of the DTS surveys would be useful. Funds were provided directly to Dr. Barry Freifeld (LBL) by the DOE. Unfortunately, the PI of the Raft River project has no control over Dr. Freifeld's activities. He has not provided a report on his activities to DOE, and the Raft River PI cannot compel him to do so.

<u>Reviewer 23625</u>

Score: 9.0

Comment: The project demonstrates a systematic approach to answer key questions about the impact of hydraulic stimulation. The stepwise increase of flow rate with short intervals of 1/2 hour does not seem appropriate. The stepwise increase of flow rate after an asymptotic pressure regime has established, appears far more appropriate. This has been done and provides solid information about reservoir characteristics.

As the injection well lies in a field of ongoing production it is understandable that there are no pressure data available from adjacent wells. However it would be very important to acquire such data as well. The lack of this data has been acknowledged by the project team.

PI Response:

We agree with the reviewer's comments. Longer flow rate intervals would be beneficial. Pump tests are expensive and the overall budget is small. The decision was made to pump at high rates for as long as possible rather than extend the intervals. We believe this was the best decision. Unfortunately it is not possible to obtain the pressure data.

STRENGTHS

<u>Reviewer 23400</u>

Score: Not scored

Comment: Good technical background and systematic approach taking care of what is essential thing to do.

PI Response:

No comments.

<u>Reviewer 23417</u>

Score: Not scored

Comment: N/A

PI Response:

no comments.

Reviewer 23625

Score: Not scored

Comment: The strength of the project lies in the acquisition of real NEW data. (There is a general lack in the collection of real data). It is highly commendable to execute more scientifically monitored hydraulic injection tests like at Raft River.

PI Response:

We appreciate this reviewer's comment.

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: Could have benefited by increased the injection flow to much higher level but this may be the next step.

PI Response:

The potential befefits of increasing the flow rate have been discussed and we agree it could provide valuable informaiton. Our injection tests indicate the rate cannot be increased above 20 bpm. The cost for using the Alta Rock pump for longer term injection, the cheapest pumps we could find, exceeded $500,00 for two weeks. Our budget cannot accommodate this work.

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

No comment.

Reviewer 23625

Score: Not scored
Comment: Weaknesses of the project is the lack of detailed structural geological data. This is however not the fault of the project set up. The project team had to work with the data that was available. A reflection seismic survey over the field may provide critical information about the geological and structural setting.

PI Response:

We agree. As noted above, a seismic survey has been conducted and we have requested the data from the owner (Walker Ranch/AMG). We have been informed they will not release the data to us.

IMPROVEMENTS

Reviewer 23400

Comment: A higher injection flow is needed with a careful pressure response from adjacent wells and induced microchemistry. A long term circulation test is essential to understand a long-term gain.

PI Response:

We agree, but higher flow rates cannot be achieved without additional funding. Pressure data would be useful but cannot be obtained without drilling new wells.

Reviewer 23417

Comment: N/A

PI Response:

No response.

Reviewer 23625

Comment: The results show, that the injection program was appropriate. A further step would be to repeat the same injection operation with longer injection intervals with injection fluid at different temperatures. This would allow to quantify the effect of thermal contraction and it would also give a better indication how far into the far field this effect is present.

PI Response:

We agree and could inject at high rates for longer intervals at different temperatures with additional funding.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002777
Project: Recovery Act: Newberry Volcano EGS Demonstration
Principal Investigator: Petty, Susan
Organization: AltaRock Energy, Inc.
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 5.0

Comment: Type or Paste Text Here
The project has not fulfilled its primary objectives i.e. where to put the second well from either the enhancement of permeability or the generation of credible microseismic structure. Past projects in a caldera have been unsuccessful due to the complex nature of the stress. This is consistent with past observations in the US and Japan.

PI Response:

Reviewer 23417

Score: 8.0

Comment: Without doubt the Newberry EGS Demonstration project is the most critical of all current EGS research and development activities in that its main objective is to develop an EGS reservoir that is not in any way associated with an existing, producing, hydrothermal (conventional) geothermal system. The accomplishments of the project are substantial having overcome some of the more practical barriers such as 1) the use of diverters for multi-zone stimulation 2) the need for appropriate pumping capabilities 3) temperature limitations of downhole tools, together with project delays due to well integrity problems – all major technical barriers.

Strengths:

- Good stimulation results

Weaknesses:

- One of the Projective Objectives was to "…demonstrate economical EGS energy" There was no discussion on this topic.
- The role of the contact between volcanics and sub-intrusive and other geologic/lithologic characteristics were not discussed.

PI Response:

Reviewer 23625

Score: 9.0

Comment: Multiple fracture zone stimulation for large volume permeability enhancement is a key challenge in EGS. To find cost effective ways (e.g. without the need of a drilling rig) to stimulate a tight rock sequence is essential. The Newberry project addresses these key issues with the application of frontier technology. The use of thermally degradable zonal isolation materials is a novel approach in EGS hydraulic stimulation.
The multiple fracture stimulation has achieved some progress, but the target of a 20 kg/s flow has not been reached.

It is not clear whether frac pressure has been exceeded. As there was no excessive induced seismicity recorded I recommend running a hydraulic injection at constant pressure of about 180 bar (just below franc pressure) over a longer period of time in the open hole, without any zonal isolation to identify the flowing fractures with a simultaneously moving spinner tool. In a next step the best flowing fracture should be plugged with isolation material and the hydraulic injection resumed with the same pressure. This procedure would finally prove the functioning of TZIMs and it should also achieve an overall improvement of the injectivity of the well.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 5.0

Comment: It is well-known that caldera do have complex and very high stress levels to cope with, which makes attaining high injectivity virtually impossible as simulation pressure need to be very high and one expects the circulation pressures to be high. Production logs in the well during stimulation would have been helpful to see where the flow was leaving the well. The structure of the microcosmic clod is unconvincing and needs more work or reassessment by external organization. The criticism may be seem to be hard but this is very difficult media to deal with and may reflect in poor judgement for selecting this site.

PI Response:

Reviewer 23417

Score: 7.0

Comment: The technical approach for project completion appears to have been impacted by some of the logistical problems during early stages of the project. This appears to have resulted in the most important part of the project (production well drilling) being squeezed into the last few months. It was not clear as to how long the circulation testing would last and how the testing would be designed

Strengths:

- Value of being able of stimulate more than one zone has been clearly demonstrated

Weaknesses:

- Relying only on weighted seismic density maps for production well planning seems to be somewhat risky. Were there no data from the stimulation or fracture analyses that would have assisted in the setting the BH location.
- Drilling towards the ring fracture system seems as if it would complicate the understanding of the fracture system and specific flow paths during circulation testing.

PI Response:

Reviewer 23625

Score: 5.0

Comment: The scientific and technical approach is commendable. As the induced seismicity appears to be rather weak, additional surface and subsurface monitoring stations may improve the localization accuracy. This would allow a better understanding of the prevailing stress regime at injection level. There appears to be a lack of awareness that understanding of the stress regime is essential. It dictates the entire fracture creation process.

At the presentation two slides were shown which are not included in the slide set available to the reviewers. They showed the well track and the recorded MEQ's in their relative position to the well. This is critical information for the planning of the next well. From these slides there was no trend in the direction of the MEQ recognizable. Not only the spatial orientation of the MEQ set is critical for the second well track planning, but also the sequence when they occurred.

I do not share the view that a second well will provide a pressure and stress relieve that would improve hydraulic fracturing (shear and/or tensile) in the first well. The criteria for the positioning of the second well track were not discussed. It is mandatory to have a clear strategy to position a well in such a manner that break throughs (short circuits) between the wells are avoided and yet that the pressure impedance between the two wells would not become prohibitively high. To define such a strategy the best possible stress information is required. The MEQ pattern and its propagation away from the well bore are such critical information. A two digit million $ well can impossibly be planned without this information.

I strongly recommend not drilling a next well until more information about the prevailing tress regime and fracture system is available. This can only be achieved by further hydraulic injections over longer periods of time in the existing well. The now available data are clearly insufficient to plan the optimal track of a second well.

PI Response:

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: The organization has good and competent team but poor site section will hinder their chance of success.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The strength of the project lies in the testing of novel technology for zonal isolation. The project team cooperates with the best qualified research institutions and experts.

PI Response:

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: Selection of a site in the flank of a caldera shows poor judgement as it is well know that high temperature in a caldera is offset against very and complex stress regime.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: Weaknesses are the lack of understanding the stress regime in the area and in particular in the target formation. Reservoir creation is the key element for any EGS. It is absolutely essential to have a clear understanding of prevailing stress regime in the reservoir formation. The stress regime dictates fracture creation, fracture propagation and direction.

Unless this fundamental information is available it makes no sense to drill a second well.

Another weakness is probably funding. I have no information about the actual funding, but I would suggest that for the application of such frontier technologies funding by the industry (i.e. hydrocarbon industry) should be sought.

PI Response:

IMPROVEMENTS

Reviewer 23400

Comment: The chances of success are very limited and if at all. To create a flow of 7 l/s required around 10 MPa pressure which is exceedingly high. One expects that to create 20 l/s required flow through the system may require stimulation pressure in excess of 20 MPa. Need to look at the microseismic location and the velocity model again and rework the data. A separation of the well between the injection and production well has to be in the range of 600m and microseismic and stress data is used to target the second well. Good results in these fields are essential to locate the second well.

PI Response:

Reviewer 23417

Comment: N/A

PI Response:

Reviewer 23625

Comment: Critical Stress information must be gained even before the planning of a second well starts. Stress information can be obtained by repeated acoustic borehole imaging before and after hydraulic injection test. As I understand there was an acoustic borehole imaging tool ran before injection. I would have suggested a repeat acoustic borehole imaging run to evaluate fracture modifications and potential additional borehole deformations that have taken place in the meantime. However since the borehole is cased with a slotted liner this option is no longer available.

One option may be to perform an additional open hole injection at higher pressures and over longer period of time to create more MEQ's until a certain geometry of the seismic cloud is recognizable. Simultaneously a spinner tool should be run to identify fractures that take water.

Get oil and gas industry support. They should be equally interested in the development of zonal isolation materials.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: EGS Reservoir Stimulations and Long-Term Performance Modeling
Principal Investigator: Plummer, Mitch
Organization: INL
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 7.0

Comment: This is a worthily project and it can help the development and take up of EGS. The level of work scope is good but there are other similar codes which have not been reviewed before progressing with this one. The level of progress is satisfactory.

PI Response:

Reviewer 23417

Score: 6.0

Comment: This project is designed to support the Raft River EGS project and much of the results presented do achieve that goal. However the Summary section reports that manuscript efforts are not now being focused on the Raft River case study but on other aspects of the analysis. This was not fully discussed in the presentation and as a result the value to Raft River appeared diminished. The connection between the well geology and the pump test analysis was also not thoroughly discussed so no further detailed characterization of the reservoir appeared to have been achieved.

Strengths

- This is part of the Raft River geothermal project and, as such, is a very important area of study for the geothermal industry
- Modified project goals seem appropriate.

Weaknesses

- The stated impact “to motive industry to attempt EGS “has not really been achieved and it is probably not a realistic objective for this type of project.

PI Response:

Regarding reviewer's statement about project focus: The overall goals of this project (EGS Reservoir Stimulations and Long-term Performance Modeling) are broader than the Raft River case study. The Raft River study is being used to help guide model development by forcing us to identify processes that we can model that might explain the observed reservoir stimulation. We will make every effort to ensure that we provide meaningful interpretation and analysis for the Raft River study, while also improving INL's FALCON code as a means of performing such analyses.

Regarding reviewer's statement about the connection between well geology and pump test analysis: The pumping test analysis used geological data to estimate the orientation of the primary transmissive zones, and the relative permeability of the hydrogeologic units intercepting the well. The pumping test, however, does not provide geological information, but merely response behavior that is consistent with some hypotheses about hydrogeological conditions, but not others. We therefore use the data to indicate what models of permeability distribution can explain the observations, and how bears on interpretations of other data.
Regarding the reviewer's statement about this project's ability to motivate industry to attempt EGS: The reviewer is generally correct, except that any project that advances our understanding of how to perform reservoir stimulation gets us closer to the point where industry would be motivated to try EGS development.

<u>Reviewer 23625</u>

Score: 6.0

Comment: One of the key elements to understand fracture creation and fracture propagation is the prevailing stress regime. This aspect is entirely missing in the THM model.

The reservoir rock is treated as an isotropic fractured medium, which is certainly not the reality.

It is crucial to have a 3D geological model to define all constraints to the reservoir formation.

PI Response:

Regarding reviewer's statement about stress regime: Little information is available to infer the local stress regime, and the primary method by which the local fracturing gradient has been inferred are pumping test analysis. As such, any estimates of the local sigma 2 and sigma 3 stresses would have been guesses, and only relevant if the pressure response data could somehow be related to their relative magnitude. We are currently examining the spatiotemporal distribution of microseismicity, and its relation to hydraulic response, so may have more to say about that relationship later.
Regarding reviewer's statement about the medium not being isotropic: The
Pumping test analysis based on single well hydraulic response (no evidence of response at other wells was identified until after this peer review presentation) can not identify

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23400</u>

Score: 6.0

Comment: It would have been helpful if other similar codes were reviewed and show the pros and cons of this code and then explain why this code had more to offer. An example other similar code would be FRACSIM3D or FRIP etc.

PI Response:

There are, of course, an abundance of codes that reproduce some of the thermo-hydraulic-mechanical processes in a geothermal reservoir. The central advantage of INL's FALCON code is that these processes are coded in a package that promotes a fully coupled solution of the relevant PDEs, and that the code is developed for open-source release. While each code certainly has advantages and disadvantages, code selection isses for this project were addressed before the project start, so further attention to such comparisons should be part of another review or project.

Reviewer 23417

Score: 7.0

Comment: Other than the above comments the project has progressed within the constraints that the well stimulation has provided. It appears that the project will have some modified set of objectives and it would be useful for these to have been outlined in more detail.

Strengths:

- Valuable improvements to the FALCON code

Weaknesses:

- Not certain as to the value of transmissivity and storativity in this clearly fracture controlled environment.

PI Response:

Regarding reviewer's statement about transmissivity and storativity. Unless the individual fractures providing bulk permeability can be mapped in any detail at all, we can only make estimates of the bulk thickness x permeability of the system. In the language of hydrology, that is transmissivity. Similarly, storativity refers to bulk compressibility x thickness of the interrogated fractured system, and provides an effective means of comparison to hydrualic behavior of other fractured systems.

Reviewer 23625

Score: 6.0

Comment: All available hydraulic and temperature data seem to have been integrated in the model. The impact of long term temperature variations on the long-term evolution (decrease) of infectivity deserves special attention.

PI Response:

I agree with this comment on long-term evolution of injectivity and how it might be related to migration of the cooling front. I provided an example of what might be that relationship in my 2015 Stanford Paper but really need to sum up that work in a manuscript and in a final report on the Raft River Stimulation project.

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: Working in conjunction with an existing project and the know-how on the properties of the rock mass is great strength.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The strength of this modeling lies in the good data base from the injection operations and the use of advanced modeling code. Modeling shows consistent results with televiewer data and temperature profiles.

PI Response:

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: As mentioned before other similar codes should behave been reviewed and this code should point out its strength. Instead of relying of Raft river project as the main data comparison for the model, it would have been advisable to use the data from Rosemanowes Project in Cornwall or the Soultz project in France to assess its uniqueness for comparison.

PI Response:

As mentioned previously, a code selection is not part of this project. As for using data from other projects, we will attempt to review some of that literature to see how it bears on results at Raft River but, in general, we believe that the pumping test analyses, at least, provide insights about the reservoir that would not be altered by comparisons to other data sets.

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The weakness of the modeling lies in the poor structural data base. The geometry of the narrows zone has certainly a major impact on the direction of the pressure enhancement.

The model does not incorporate data about the stress field and assumes a reservoir formation with isotropic properties.

PI Response:

Our modeling does not necessarily assume isotropic properties and data about the stress field can be incorporated if such become available. When data about stress or anisotropy of hydraulic properties become available, it will be incorporated.

IMPROVEMENTS

Reviewer 23400

Comment: Already mentioned in the section "weakness"

PI Response:

Reviewer 23417

Comment: N/A

PI Response:

Reviewer 23625

Comment: Try to define a consistent geological 3D model for the entire geothermal field area. Incorporate regional and - if available - local stress data. Assume anisotropy in the reservoir section.

It is not clear how the reservoir is confined by low permeability formations above and below. The geometry of the narrows zone appears to play an important role for the propagation direction of permeability enhancement.

Another aspect that would be of interest is the extent of thermal contraction into the far field. With the injection of cold water or brine, the near field will be cooled most. The cooling effect, and in this case the permeability enhancement, will diminish with growing distance from the injection point. It would be of interest how far this cooling front may propagate into the garfield and come eventually to an equilibrium with the formation.

PI Response:

Reviewer is correct in that limited information in the area surrounding well RRG-9 do not adequately describe the permeability of rocks overlying and underlying the target reservoir rock, the Elba Quartzite. One interpretation of the pumping test data suggests that leakage through the fractured rocks the Elba Quartzite may explain why flow rate reaches steady state at about 1.5 days, but that there are also other possible explanations because information about hydraulic properties is based only only very few data points (wells). Regarding cooling front propagation, we have made conjectures about the rate of cooling front propagation and will include those analyses in our final report.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geysers Calpine Modeling
Principal Investigator: Rutqvist, Jonny
Organization: LBNL
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 9.0

Comment: Very good project and well thought out. Good progress and well managed.

PI Response:

The PI is very pleased with this comment and score. Overall, this is the most successful project the PI has been involved in, including the integrated modeling and field observations to understand the system and the ample field data available at the Geysers as well as the good funding and support from the DOE Geothermal Program

Reviewer 23417

Score: 8.0

Comment: This project is a companion to work reported by Calpine for EGS Demonstration in the NW Geysers. It is critical that the modeling be funded and continued because this project is non-conventional form of EGS stimulation in that it does not require high pressures. It fulfills the objectives of the GTO even though The Geysers is a non-typical system and the technology may not be applicable to many other systems in the US.

The goal of monitoring the technology has not yet been demonstrated and this needs to be a focus because specific pathways between injection and production wells have not yet been identified. Long term circulation testing needs to be demonstrated as sustainable and it I not clearly described as to how that will be achieved.

Strengths:

- Modeling to date appears to have demonstrated fairly conclusively the spatial extent of the

Weaknesses:

- While a goal is for interpretative modeling to increase the understanding of the real geologic system affecting the EGS stimulation this has not been demonstrated. Long term monitoring and further modeling are still required to most of the existing goals

PI Response:

The PI agree that it will be critical to continue to be able to model the actual production when the main (PS-31) production well is coming online. This is scheduled to happen in 2016, but the funding for the project already ended in

2014. At the moment LBNL is using carryover funding from FY2014 and try to save funds to if at all possible be able to analyze the continous injection/production once the production will be started in 2016.

Reviewer 23625

Score: 6.0

Comment: The target formation of NE Geysers EGS Demonstration project underlies the NT reservoir. In this respect the project is not an EGS project sensu stricto as e.g. defined in the FORGE criteria. It is a classical step out project from a producing field and therefore of great importance for the operator of the Geyser field. In this respect the project is comparable to the step out project at Brady, which also attempts to develop a low permeability area adjacent to a hydrothermal field.

I'm actually surprised how few reflection seismic data is available (or at least not shown) over a mature geothermal field like the Geysers. In the oil and gas industry reflection seismic data are the backbone of any geological 3D model.

The geomechanical model calculates stress changes as a result of cold water contraction. This gives valuable information about the efficiency of the fracturing process, however little information about the preferred direction of fracture propagation. This is critical information for the planning of EGS circulation systems, in particular for the planning of injector/producer well pairs.

I give a relatively low score not because of the quality of the project, but for the limited use for EGS outside known geothermal fields

PI Response:

It is true that this is an unconventional EGS to enhance the production from an existing field. This is also defined as one type of EGS by the DOE GTO. It is not a FORGE type of EGS, but the underlying processes of the stimulation of the fracture network will be similar and the monitoring techniques such as seismic tomography, pressure monitoring and surface deformations will be applicable to any fractured rock site. In this case we stimulated an existing fracture networks so it is difficult to talk about preferred fracture propoagation since we are not propagating fractures. The boundaries of the seismic cloud and the boundaries of the seismic tomography tells us is where the production/injection pair would be placed. This has been clearly established. However, in this approach we used existing wells that has been extended, and both the induced seismicty and seismic tomography shows that the well pair is within the boundaries of the stimualtion zone.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 9.0

Comment: Good technical competence and no comments.

PI Response:

The PI appreachiate the time and effort and the positive comment of the reviewer.

Reviewer 23417

Score: 6.0

Comment: Technical approach has been comprehensive with a significant amount of data available through the field operator. However there was no discussion of the production characteristics of the wells while they were being used prior to abandonment. While the field operator has many capable and experienced staff there appeared to be only one researcher from LBL working on this project. Modeling the monitoring phase of this project would seem to require more staff.

Strengths:

- Clearly the data available so far indicates a good EGS project has been demonstrated. More time is needed to confirm its operational sustainability.

Weaknesses:

- Specific pathways for fluid migration from the injection well have not really been defined. Permeability appears to be only constrained by the seismic “cloud” and by known faults.

PI Response:

I agree with the reviewer that more time and resources will be needed to confirm operational sustainability, especially once the main production well (PS-31) is taken into production. A lot will be lost if we will not be able to model and monitor the system under production. We are trying to save carry over funding to if at all possible be able to analyze the production.

There have been a total of 10 scientists at LBNL involved with the modeling and monitoring of the Geyser EGS for Phase 1 and Phase 2 of the project. The LBNL's modeling support to Calpine has been well funded by the DOE GTO; it has not been a lack of funding or resources for Phase 1 and 2 of the project. The field operator was responsible for the field work and daily monitoring of induced seismicity and also did regular injectivity tests ets. Fluid connection from the injection to the future production well has been established from pressure monioring and this was also used to accurately back-calculated permeability and porosity of the system. However, the main mechanisms of this system is not the direct flow path between the two wells, but the progressive simulation of the high termperature rock beneath the injection and production wells. This will increase the amount of steam that can be produced in the overlying production well. Again, the reviewer is right that it will be important to see how the system evolves during production, i.e. to confirm the operational sustainability. The main production well is planned to be put into production in 2016. For analyzing the production some funding would be needed.

Reviewer 23625

Score: 8.0

Comment: Modelling is not my field of expertise. I can only express what I would expect from geomechanical modeling: The prime information I'm interested in for the development of an EGS field are:

1. The optimal injection pressure to create shear fracs with the least induced micro seismicity.
2. The direction of preferred fracture propagation
3. An estimate how much thermal contraction contributes to the shearing process compared to the effect of injection pressure.
4. How deep into the formation can I expect a substantial fracturing effect by thermal contraction.

I give a high score because the project is a comprehensive approach with a large number of analytical methods applied.

PI Response:

Many of the listed 4 points are at the focus of the modeling work conducted; especially to investigate the relative contributions of pressure versus thermal effects on the stimulation of the fracture network. The current trend over the first years of stimulation indicates that the stimulation zone moves slowly downward by about 100 m per year. It will be important to follow this evolution during production, especially since the concept of this EGS is the stimulation of deep high temperature rocks for enhanced steam production.

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: Well thought out and run by staff who know what is needed. Strength in all department and discipline.

PI Response:

The PI appreachiate this comment. We have a very diverse team involving both analysis of field geophyscial data and geomechanical modeling and one of the most important factors to the success of this project has been a very good and tight collaboration between the operator (Calpine) and scientists at LBNL; it has resulted in 11 (LBNL, Calpine joint) journal papers published on the Geysers EGS project.

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The strength of the project lies in the intention to integrate data from an existing 3D geological model, from 3D tomography, from microseismic monitoring, from InSar Analysis and from geochemical analysis.

PI Response:

I agree that the strength lieas in the integrated data and modeling of the system.

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: None so far.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: From the presentation it was not clear how the different analytical steps (interpretative modeling, identification of shear-zone network, calibration of shear zone network with hydraulic properties, observed and modeled compartmentalized stimulation, elasto-plastic sheet-zone modeling and seismic tomography) were integrated in a synthesis to provide a recommendation how to further develop an EGS between the wells Prati 31 and 32.

PI Response:

I agree that much of the presentation was focused on the technical achievements related to modeling and data analyhsis to understand and defined the system. The overall development of the system in the light of the Geysers Geothermal field was provided by the field operator (Calpine) in their presentation. It will be important to analyze further development of the EGS between wells PS31 and 32, especially after well PS31 is put into production sometimes in 2016. Neverthelles, a more overreaching paper and synthesis with recommendations on how to develop this type of EGS beneath conventional steam reservoirs would be warranted. This is a good suggestion by the reviewer that is well taken.

IMPROVEMENTS

Reviewer 23400

Comment: No comment, very satisfactory project.

PI Response:

Reviewer 23417

Comment: N/A

PI Response:

Reviewer 23625

Comment: Provide a synthesis of all the findings with a clear recommendations how to further develop the Prati 31/32 EGS.

PI Response:

This is a good suggestion and recommendation; a more general synthesis is warranted.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Evaluation of Stimulation at Newberry Volcano EGS Demo Site Through Natural Isotopic Reactive Tracers and Geochemical Investigation
Principal Investigator: Sonnenthal, Eric
Organization: LBNL
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 9.0

Comment: Very well managed project with very limited budget. One of the few results from Newbury volcano project that can be taken with confidence and the data that can be relied upon.

PI Response:

Reviewer 23417

Score: 6.0

Comment: The two most valuable outcomes of this project will be i) to constrain on THMC models for Newberry, and ii) to characterize flow paths during circulation testing when the production well is drilled. A significant amount of geochemical data has been collected from flow back sampling but this data is transient in nature and while it helps to understand the results of the stimulation the data will be superseded when data from the flow through testing is completed.

The quality of the work and accomplishments are high and there are some valuable new developments but sampling at this stage of development is of limited use other than as model inputs. This is also a low cost project ($50k) so accomplishments are substantial compared to cost.

Strengths:

- Very thorough and comprehensive set of analyses
- Flow experiments on rock chips would be of great importance to understanding what may occur during flow through testing

Weaknesses:

- No discussion of the role played by rock lithologies with which these fluids are interacting and the potential for much of the geochemistry to be impacted by lithologic variations e.g. deeper rocks with less pyrite resulting in total sulfur variations

PI Response:

Reviewer 23625

Score: 6.0

Comment: It is necessary to sample and analyze the flowback. And geochemical sampling is part of comprehensive data monitoring and data acquisition. The geochemical analysis however is not critical for the project at this stage and will have little impact for decision taking for the next steps in the project. Pressure and flow rate decrease of the flowback give more critical information about the hydraulic system. Only about 5% of the approximately 3 Mio gl injected water flowed back. The fluid rock interaction at reservoir depth was minimal and the identified mineral traces found in the flow back water may not be representative.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23400

Score: 9.0

Comment: Very well done with exceptional result.

PI Response:

Reviewer 23417

Score: 7.0

Comment: Technical approach is well thought out and appears to have been competently executed.

Strengths:

- The real value of this type of analysis would be when a production well is completed. It would be a significant value to the Newberry project if this research can be extended to include flow through analysis

Weaknesses:

- There is very little discussion of the interaction between geochemical characteristics of fluids and the geologic setting.

PI Response:

Reviewer 23625

Score: 9.0

Comment: Systematic sampling and analysis of the flowback fluids is part of a thorough scientific investigation. There is no critique that this investigation was done. It was necessary. It is just not critical for this phase of the project.

PI Response:

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: good technical background and sound result.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: It is surprising, that even with a very sparse data set (less than 5% of the injected water flowed back with hardly any relevant amounts of formation water) it was possible to gain consistent formation temperature results from geothermometry.

PI Response:

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: No comments.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The presentation gave very little information about the interpretation of flowback temperatures and results of measured wellbore temperature data (DTS). DTS temperature data could provide critical information about thermal conductivity of the reservoir rock.

PI Response:

IMPROVEMENTS

Reviewer 23400

Comment: None

PI Response:

<u>Reviewer 23417</u>

Comment: N/A

PI Response:

<u>Reviewer 23625</u>

Comment: The data set may become valuable when a circulation between two wells has been achieved. The comparison between the fluid geochemistry of this initial data set and circulated water in a closed loop system may give valuable information about fluid/rock interaction over different periods of time, different pressure and temperature conditions.

Scaling and solution processes during circulation is likely to have an important impact on channeling and permeability deterioration in the reservoir formation.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: GO18201
Project: Demonstration of an Enhanced Geothermal System at the Northwest Geysers Geothermal Field, California
Principal Investigator: Walters, Mark
Organization: Calpine - Geysers Power Company LLC -
Panel: Enhanced Geothermal System Demonstrations

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23400

Score: 10.0

Comment: This is an exceptional project and worth perusing as it is an in an existing large geothermal producing zone and will help to enhance its performance. It is in a relatively new rock type zone with very high temperature but a good potential for generating huge permeability structure. The project is well planned and maintained.

PI Response:

Reviewer 23417

Score: 7.0

Comment: This is a project that has been completed and currently is in the monitoring phase although production has temporally been suspended due to well integrity problems. Thermal stimulation is the primary mechanism for creating permeability in the HTR and this has been achieved. This is a fundamental to GTO goals and has demonstrated the EGS concept in areas of peripheral low permeability on the flanks of existing geothermal systems. How this EGS projects operates over time will determine its success.

Strengths:

- Excellent summary of previous work (slide 5). In many late stage DOE project reviews the previous work completed and reviewed is not thoroughly summarized.
- In addition to EGS demonstration this project has also shown the positive impacts on NCG levels in steam. This is positive response would probably limited to The Geysers or other dry steam fields.

Weaknesses:

- The primary pathways from P32 to PS31 have not been defined in any detail so the true nature of the system has not been fully characterized.
- Many of the project results at The Geysers (successful as they may be) pertain solely to high temperature dry steam fields. Applicability to most geothermal areas is limited. An example would be the availability of large volumes of treated waste water for injection.

PI Response:

We disagree with the opinion that the primary pathways of fluid flow from P32 to PS-31 have not been detailed and the EGS system has not been fully characterized. Figure 6 of our presentation maps the two primary faults, the NW-striking Squaw Creek Fault and the NE-striking Caldwell Pines Fault, which are the major pathways of water from P32 to PS31. The parallel, NW-trending and NE-trending faults and fractures to these primary faults are mapped in detail by a careful seismic analysis conducted at LBNL. The location of these parallel fracture systems is outlined in Section 6 of the presentation Summary and is referenced to: "Jeanne, P., Rutqvist, J., Hartline, C., Garcia, J., Dobson, P., and Walters, M., 2014b, Reservoir Structure and Properties from Geomechanical Modeling and Microseismicity Analyses Associated with an Enhanced Geothermal System at The Geysers, California. Geothermics, 51:460-469".

We also disagree with the perception that "many of the project results pertain solely to high temperature dry steam fields". The primary premise of the Geysers EGS project was to show that fractures could be reactivated in high temperature areas at relatively low fluid pressures by shear reactivation. Consequently we believe that the results from the Geysers EGS project are generally relavent to geothermal resources in the vicinity of operating high temperature hydrothermal systems. Low permeability, high temperature conductive zones are present near other hydrothermal reservoirs like The Geysers including the Salton Sea, Coso, and Brady Hot Springs (as mentioned by Reviewer 23625 immediately below).

<u>Reviewer 23625</u>

Score: 7.0

Comment: The target formation of NE Geysers EGS Demonstration project underlies the NT reservoir. In this respect the project is not an EGS project sensu stricto as e.g. defined in the FORGE criteria. It is a classical step out project from a producing field and therefore of great importance for the operator of the Geyser field. The project is therefore comparable to the step out project at Brady, which also attempts to develop a low permeability area adjacent to a hydrothermal field.

I'm actually surprised how little reflection seismic data is available (or at least not shown) over a mature geothermal field. In the oil and gas industry reflection seismic data are the backbone of any geological 3D model. There is of course a rich data base of borehole data available. This does however not provide sufficient information about the structural setting and the fault pattern.

PI Response:

The high temperatures (>300 degC) of the HTR at The Geysers EGS project eliminated this area as a potential FORGE project site. Although the Northwest Geysers EGS demonstration project does not meet the maximum temperature restriction of the Forge criteria (225 degC), it is certainly an EGS project sensu stricto as defined by the DOE when this project was initiated in 2009, six years before the FORGE criteria were defined.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23400</u>

Score: 9.0

Comment: Good technical staff and equipment. Well managed and good micro-seismic network. No comments on technical and management skill.

PI Response:

Reviewer 23417

Score: 7.0

Comment: The technical approach for this project has been well designed and executed although reviewing a nearly completed project is difficult because previous research has not always been fully provided.

Strengths:

- When an operating company is the PI for a DOE research project it usually means that there are more practical solutions to problems. This is the case with this project.

Weaknesses:

- There are emissions in some of the data presented in this review presentation e.g. tracer results
- Details of the proposed monitoring program were not presented. Extended monitoring of this project is the only way to demonstrate its success

PI Response:

No tracer studies have been conducted at the NW Geysers EGS demonstration (at least in the conventional sense) because there have been only two wells, PS31 and P25 which produce injection-derived steam from water injected at P32. Instead of a conventional tracer test(s), the results of analyzing natural isotopic tracers, 18oxygen and deuterium, from the Santa Rosa Geothermal Recharge Project water injected into P32 and produced by PS31 and P25 were provided in the Peer Review.

The details of the proposed long-term monitoring program are still under consideration by the GTO and Calpine as of August 15, 2015.

Reviewer 23625

Score: 7.0

Comment: The aim of the project is to enhance fracture permeability in a low permeable formation by shearing of pre-existing closed fractures. This requires in the first place a detailed understanding of the prevailing stress regime. This critical data can be obtained from borehole deformation measurement acquired with acoustic borehole imaging (UBI). Another source of information are extended leak off tests to assess the frac pressure of the formation. The regional stress regime should be known from borehole deformation measurements in the entire Geysers area.

PI Response:

The regional stress regime in the Geysers region was defined by David Oppenheimer in 1986, "Extensional Tectonics at The Geysers Geothermal Area" and substantially confirmed in 2014 by tensor analyses of the seismic events in the EGS Demonstration by Katie Boyle and Mark Zoback, M.: "The Stress State of the Northwestern Geysers, California Geothermal Field, and Implications for Fault-controlled Fluid Flow" published in the Bulletin of the Seismological Society of America.

Acoustic borehole imaging of the very hot Geysers EGS reservoir (300 to 400 degC) is presently not possible because of the temperature limitations of imaging tools. However, there are plans for the testing of high-temperature tolerant borehole fiber-optical sensors for vertical seismic profiling (as a "first-step" with improved technology acquisition and processing). Previous, relatively shallow, VSP tests did not result in sufficient energy transfer from the source to the receivers.

STRENGTHS

Reviewer 23400

Score: Not scored

Comment: Experienced staff and well managed.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The strength of the project lies in the fact that there is ample structural data available and that there are two wells available. This makes such projects far more cost effective, than projects where new wells have to be drilled first. On the downside: Existing wells are also a constraint, as it is unlikely that the wells are placed in optimal positions to each other for circulation tests.

PI Response:

WEAKNESSES

Reviewer 23400

Score: Not scored

Comment: Perhaps a closer look at the stress regime at this depth its implication on the selection of the production and injection well.

PI Response:

Reviewer 23417

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23625

Score: Not scored

Comment: The weakness of the project is
1. The lack of a detailed 3D geological model based on 2D or 3D reflection seismic.
2. The lack of formation stress data which would allow a forecast of fracture propagation and preferential flow path directions.

PI Response:

1. The lack of 2D/3D active seismic imaging at The Geysers is due to: 1) extreme topography (seismic data is processed to either a uniform or floating datum); 2) highly variable surface coupling issues (surface varies from weathered landslide sediments to hard rock); (3)significant access issues for seismic acquisition equipment using active sources along either 2D seismic line or 3D grids; 4) complex subsurface geology with significant 3D effects and significant lateral velocity variations; and 5) cost of 2D seismic lines or a 3D seismic volume. However, a fieldwide, 3D model utilizing passive seismic imaging techniques in SKUA GoCAD software modules developed for the oil and gas industry is already underdevelopment at The Geysers. A description of this 3-D model will be presented at the GRC Annual Meeting, September 20-23, 2015 in a paper by Craig Hartline and others, "Three-dimensional Structural Model Building, Induced Seismicity Analysis, Drilling Analysis, and Reservoir Management at The Geysers Geothermal Field, Northern California."

2. There is no "lack of formation stress data" for this project (see our response related to the regional stress regime on page A-4 above) and a "forecast of fracture propogation and preferential flow path directions" is moot because several publications by LBNL (listed in the presentation Summary) do in fact describe the specific preferential NW and NE-trending flow paths for this EGS project.

IMPROVEMENTS

Reviewer 23400

Comment: Perhaps a closer look at the stress regime at this depth its implication on the selection of the production and injection well. In a normal faulting regime, the production well is above the injection well. In a strike slip regime, the production well is normally below the injection well. One may reconsider the selection of the wells.

PI Response:

The Geysers EGS project is in a transtensional, strike-slip stress regime. The hanging wall/footwall relationship of production and injection wells in a normal faulting regime is not appropriate at The Geysers.

Reviewer 23417

Comment: N/A

PI Response:

Reviewer 23625

Comment: The seismic cloud clearly indicates a downward trend of fracture propagation and a downward flow of injected water. It is also quite remarkable that it is a real 3 dimensional seismic cloud and not a sheet of seismic events defining a single conductive fracture zone. These are strong indications that there is an intricate and intense pre-existing fracture set present.

These observations could be used to the advantage of the project:

1. If technically feasible Prati 31 should be used as an injector well and Prati 32 as a producer. The injected water would flow downward to the producer, which would result in significantly reduced circulation pressure losses.

2. The "cloudy" flow path is a promising indication of an efficient heat exchanger without major channeling or short circuiting between the wells.

We were not shown any spinner log data taken during the injection phase. It would be of great interest to know which fractures in the open whole section take most of the flow. Also this would provide critical information about the stress regime in the reservoir formation.

PI Response:

Spinner data were not collected for the P32 injection. Fractures in the open whole section of P32 were identified by steam entry data collected while drilling and deepening the open-hole section of P32. These data were presented in slide 8 of the 2012 Peer Review Presentation.

In general, the limited time for the peer review presentation of this project allowed for only newly developed data and was insufficient for re-presenting supporting, albeit important information, previously submitted to the DOE.

High Temp Tools, Drilling Systems Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Elastomeric Material Evaluation and Development
Principal Investigator: Erica Redline, Sugama, Toshi
Organization: SNL/BNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 9.0

Comment: In this reviewer's experience, inappropriate choice of elastomer for o-rings has been responsible for a large fraction of in-field tool failures. This project holds promise of providing the quantitative basis to support selection of higher performance materials based on the actual fluids and environmental factors in a well. The quality of the work is high, however the presentation of results needs to be improved for most benefit to be realized.

PI Response:

For realistic beneficial results, we plan to conduct a long-term field exposure and validation tests for selected elastomeric materials at Ormat Power Plant site. This outcome will provide us with information on their life-cycle prediction and stability or degradation in real geothermal environments.

Reviewer 23433

Score: 8.0

Comment: This project aims to develop polymeric materials for seals, packers and pump components that will survive in the presence of hot, high pressure geothermal fluids. Elastomers are of widespread use and importance in geothermal applications, so improvements in these materials are of great interest. If successful, even partially so, the improvement of these materials should make a substantial improvement in the economics of geothermal production operations. The proposers' approach has been to engage the collaboration of various commercial suppliers in providing candidate materials and to execute a test program to evaluate these materials in a variety of simulated geothermal environments. The approach has been largely empirical, guided by the manufacturers' suggestions and supplemented by detailed analysis of the tested materials. This has allowed the determination of the important failure and degradation processes, leading to progressive improvements in the selected materials. This approach is systematic, and appears to be furnishing valuable results.

PI Response:

Thank you for supporting a project's progress.

Reviewer 24895

Score: 9.0

Comment: The project provides the preliminary screening data necessary for selection of elastomers for tools and equipment in various services. It includes identifying the temperature limit for materials, so lower temperature uses can use less expensive materials than higher temperature materials. Immediate use to accelerate availability of tools for geothermal. However, while the temperature limits were explored along with temperature cycling, it is not clear how much pressure or pressure cycling was done, or the resistance to movement (rotation or sliding), which may also be factors affecting the durability. Hence, this provides a screening test for the end users, but may not completely identify material they can use without further testing. Additional work is still in progress on packer type testing, which would look at sealing larger gaps than are addressed with O-rings.

PI Response:

To obtain information on integrity of rotating O-rings under high pressure and high temperature, we have a plan for the durability testing of O-rings and other elastomeric materials using high-pressure and high-temperature (HPHT) consistometer up to 20,000 psi and 200°C in a dynamic hydrothermal environment.

Reviewer 23567

Score: 8.0

Comment: The development of reliable elastomeric materials which can withstand and operate in the geothermal downhole environment ambient is a challenging task. Typical elastomeric materials cannot stand high temperatures of typical geothermal wells especially when exposed to the chemistry of geothermal fluids. If this project is successful, the introduction of novel elastomeric polymers will widen number of options and extend the maximum operating temperature range of seal components used in casing of tools and wellbores and pump systems, as well as fracturing packer components. This project evaluated several high temperature elastomeric polymers with the operating temperature as high as 327C, completed their testing at chemistry and temperature with a clear ranking of tested materials. Project looks very clearly organized with progress as planned in the original schedule. Most of tested are commercially available and anticipated time to market for those is relatively negligible.

PI Response:

Our R&D team appreciated your support for this project's success.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 9.0

Comment: The testing rubric is well-designed to simulate the variety of conditions that affect the choice of materials for an application. The results should prove very helpful in forming the basis for a handbook for field engineers. The test appears to have been well-executed and documented.

PI Response:

Thank you for your strong support.

Reviewer 23433

Score: 7.0

Comment: The technical approach can best be described as "guided empiricism". This entails the gathering of a large number of possible candidate materials, and their testing in geothermal fluid environments. Examination of the results obtained, and consultation with the manufacturers is leading to the formulation of improved materials for further testing. This appears to be a very useful practical approach, in which the testing of candidate materials is at a higher priority level than, for example, attempting to develop new molecular compounds from scratch (which is better left to the chemical companies concerned with their original synthesis). The reviewer finds this to be a very cost-effective line of approach.

PI Response:

Thank you for supporting our R&D plan and its approach to achieving our project's goal.

Reviewer 24895

Score: 9.0

Comment: The right equipment was developed to make the measurements. The equipment and the approach of using both temperature cycling as well as chemical and thermal stability provides a good range of information for the sensitivity of the materials in different applications. It could be extended to look at pressure cycling as well.

PI Response:

Regarding any pressure cycling evauations, we plan to obtain this information by using a high-pressure and high-temperature (HPHT) consistometer up to 20,000 psi and 200°C in a dynamic hydrothermal evironment.

Reviewer 23567

Score: 8.0

Comment: The approach of evaluating elastomeric materials for their stability at high temperatures and capable to withstand brine chemistry is technically sound. Experimental tests, post stress evaluation and analysis techniques are properly defined. Surface analysis techniques are well complementary theoretical investigations of degradation mechanisms, which have sound basis for evaluating chemical stability of investigated materials. Some of the materials selected are already commercially available and some were provided by material vendor as proprietary formulated engineering samples with specially added ingredients. Those specially formulated materials are especially of interest for testing as may provide advanced functionality beyond what is available “off-the-shelf”.

PI Response:

Obviously, specific additives play a pivotal role in minimizing the degradation of elastomeric polymer binders. We learned in this project that although the same polymer binder was used, the extent of its stability depended on the additive chemistries.

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: The principal strengths of this project are [a] the high quality of the laboratory work and [b] the practical matrix of thermal and chemical conditions in the test design.

PI Response:

Thank you for your comments.

Reviewer 23433

Score: Not scored

Comment: As noted above, the reviewer finds the "semi-empirical" approach to be a very effective means of converging on a practical solution to the problem in a short time with limited resources. The net for potential candidate materials has been spread widely, resulting in a broad range of possibilities. Close collaboration with the material suppliers is seen as very advantageous.

PI Response:

Your observation is appreciated.

Reviewer 24895

Score: Not scored

Comment: Good scientific approach to quantifying the performance in different chemical and temperature environments

PI Response:

Thank you for your comments.

Reviewer 23567

Score: Not scored

Comment: Well organized experimental work with clear and meaningful material ranking results.

PI Response:

Your comments are appreciated.

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: The weakest aspect of this project is the presentation of results. Although the slides were well-produced, they were ineffective in communicating the main points (and virtues) of the work. The extreme density of slide content was inappropriate for the time available, and the speaker did not speak to the slide content directly. It appeared as though the slides intended to include every detail of the report to DOE, rather than summarizing per the instructions. This reviewer did not penalize the project scoring, but counsels that a much more useful and user-friendly presentation will be needed for the work to have the impact it deserves.

PI Response:

Thank you for your advise on the style of presentation. In our effort to prepare a useful and user-friendly presentation, we will try to prepare a presentation including all your comments for a future peer review meeting.

Reviewer 23433

Score: Not scored

Comment: The reviewer wonders if possible suppliers external to the USA have been consulted. If not, it is noted that the Japanese and Germans, among others, have a very well developed chemical industry.

It is also possible that for certain applications, composite materials, such as polymers reinforced by fibers of different types can provide very useful solutions. Often the combination of two materials can provide synergism, e.g. the use of reinforcing fibers to strengthen a mechanically rather weak but chemically very resistant elastomer. This stage of the project may well follow logically after a program to select single component materials. The proposers are no doubt well aware of the use of "rope packings" for sliding seals in many applications that illustrate this approach. Work on composite seals and packing’s should start as soon as possible.

PI Response:

All samples used in this project were made in USA. No oversea products were tested. We will look into foreign products. Thank you for your suggestions regarding fiber-reinforced seals and rope packings. For the former, the evaluation of carbon fiber-reinforced FEPM composite elastomeric material as advanced packers are currently being undertaken. Regarding the latter, we will incoporate an additional task relevent to PTFE-impregnated rope and TFE-based rope packing materials into FY16 project plan.

Reviewer 24895

Score: Not scored

Comment: The conclusions need to be evaluated in practical applications, which are planned for 2016. Pressure cycling and/or non-static sealing may require advancements in the testing

PI Response:

As described in my response to the previous comment, we will conduct a pressure cycling test by using a high-pressure and high-temperature (HPHT) consistometer under a dynamic fluid condition.

Reviewer 23567

Score: Not scored

Comment: Variable pressure and temperature tests and especially thermal- and pressure- cycling testing seems to be limited to understand material stability and simulate sealing properties when used in conditions similar to what expected in the field. This will help to understand effects of thermal and pressure shock and material resistance and elasticity to repetitive deformations due to changing pressure/temperature parameters.

PI Response:

The thermal- and pressure-cycling tests will be conducted by using HPHT consistometer, which is capable of up to 20,000 psi pressure and 200°C hydrothermal temperature in a dynamic drilling- and geo-fluid.

IMPROVEMENTS

Reviewer 23401

Comment: For most utility, the results should include representative values for Nitrile O-rings, and example brand names for the advanced formulations. For example, Viton-B is named in the SOW, but is referred to only by its composition in the presentation. The average logging field engineer, for example, may not recognize "Terpolymer consisting of VDF, HFP, and tetrafluoroethylene(TFE)" if he or she is deciding whether to open a box of EPDM or Viton O-rings at a well site. Nitrile is still a standard material and its inclusion will help put the newer materials in perspective.

PI Response:

In response to reviewer's comment, Nitrile-made O-ring also will be evaluated as one of the cost-effective O-rings and benchmark. Also, the trade names of evaluated materials will be included in the presentation.

Reviewer 23433

Comment: As noted above, the proposers are encouraged to spread their net of candidate suppliers as widely as possible, to include foreign suppliers and users of possible candidate materials in other industries, for example aerospace.

Also as noted, the proposers should start work on composite formulations as soon as possible.

PI Response:

We will widely seek and investigate more candidate composite materials made by foreign manufactures.

Reviewer 24895

Comment: There needs to be testing done with pressure cycling, movement and larger gaps. Some of this is planned in the upcoming tests, but it appears there may be some gaps.

PI Response:

As mentioned earlier, HPHT consistometer will allow us to evaluate the subject material's integrity under high pressure gradient at a certain flow rate and temperatures up to 200C.

Reviewer 23567

Comment: Comparison of relative costs within tested materials has been shown; however it could be beneficial to estimate cost/performance advantages if materials used in different systems, depending on the size and volume needed to be used. Benchmarking relative to the nitrile would be very beneficial.

Include thermos-cycling testing in the future test plan.

PI Response:

When a long-term field exposure testing in our future plan is completed, we will be able to estimate roughly the material's life-cycles based upon oxidation depths and declining rate of mechanical strength as a function of exposure time. The integration of these data may provide us with information on their real time performance, and next this information will be related directly to cost of materials used in different applications. Ideally, this outcome will offer a beneficial aspect to screening the most valuable candidate materials in the different application systems. As mentioned earlier, Nitrile-based materials will be evaluated as one of the benchmarks, and also, we will investigate and educate ourselves regarding the thermo-cycling testing.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002782
Project: Recovery Act: High Temperature 300C Directional Drilling System, including drill bit, steerable motor, and drilling fluid, for Enhanced Geothermal Systems
Principal Investigator: Chatterjee, Kamalesh
Organization: Baker Hughes Oilfield Operations Incorporated
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23454

Score: 7.0

Comment: There is an anomaly in scoring the impact of this project and the associated high-temperature MWD project, in that the tools under development may meet all the GTO goals, yet may not have as great an impact on the actual market as expected. That distinction is probably beyond the scope of this review, but it is a partial explanation for score given.

The quality of the accomplishments is quite high. The company has done an excellent, even remarkable, job of design and development for the tools under consideration, but that alone does not guarantee their impact. Several major components of the system -- bit, motor, drilling fluid -- may be important and have serious market impact as stand-alone items, so the project, which is almost complete, should be deemed successful.

Achievement against the planned goals was good although several items related to mud cleaning that were included in the SOPO were not mentioned in the presentation, so it is not clear whether that work was done. It's also difficult to assess the value of the accomplishments relative to costs, since no cost data were given.

PI Response:

In phase 1 we reviewed mud cleaning options, it was decided that existing commercial technologies were adequate.

Reviewer 23527

Score: 9.0

Comment: This project addresses a critical technology gap that limits well field development options for geothermal systems in general and EGS in particular. It has been firmly established in field practice that horizontal drilling has enabled the economic development of certain types of Oil & Gas plays. There is strong reason to believe that it will be similarly important to EGS based on the need to connect permeability zones produced by hydraulic fracturing from injection wells to production wells. The focus of this project, the development of a high temperature 300 degrees C directional drilling system, is largely incremental in the sense that it involves the adaptation of existing directional drilling hardware, but it also involves enormous engineering challenges. Very promising results have been achieved to date. The project has demonstrated a seal-less directional drilling motor with performance characteristics comparable to those with elastomeric seals. Machining of the motor components was a significant challenge that appears to have been successfully addressed. The long term reliability of the developed hardware falls short of the low temperature state of the art, but the developed PDM is nonetheless a significant step towards a commercial option for directional drilling in a 300 degrees C environment. The high temperature test stand that has been developed as part of the project is a critical testing capability that will be required to screen stator and rotor coating options. It states in the project summary that this test stand is suitable for testing up to 260 degrees C. Clarification should be provided as to why it is not 300 degrees C capable. This concern similarly applies to the aging test performed for the drilling fluid. The adaptation of tricone and hybrid cutting structure bit designs has been systematically addressed and the modifications appear to be reasonable. The field tests performed to date are also encouraging with reasonable ROPs and build-up-rates achieved in granitic rock. The demonstrated build-up-rate of 6 degrees per 100 ft is less than what can be achieved in commercial practice. It would be useful to know why this BUR was chosen and what the estimated maximum is for granite at EGS relevant depths.

In general this project has advanced the DOE GTO mission and goals. It focuses on an important technology gap and has made good progress towards developing fieldable hardware. The knowledge gained from this project should also advance the state of the art of high temperature drilling hardware design.

PI Response:

At present motor testing is done at room temperature, from this even 260C testing is a big leap. We faced numerous technical difficulties and safety concerns in operating the test stand at high temperature and opted for 260C testing as a representative for high temperature testing. We expect the drilling system to operate at 300C.

For high temperature motors 6 degrees BUR is quite good. Moreover, this angle was tried to demonstrate directional capability, there is no limitation and the system can achieve commercial angles.

Reviewer 23537

Score: 9.0

Comment: This project proposes to develop a high T (300 degree C) directional drilling system that will also be effective at great depths/pressures. An objective is that high T, directional drilling systems would enable "horizontal drilling", among other results. Horizontal drilling for geothermal systems, including EGS, is (still) a solution in search of a problem, unfortunately. Nevertheless, the project outlines technical barriers and then goes about overcoming these barriers at least at the testing stage. It was unclear why 50 hrs. was the time threshold for this system, however.

Quality: The approach and the testing results (rocks, temperatures, and drill bit development) to date appear to be in synch with project objectives. I would rate the quality of this work to date as high.

Productivity: The types and results of tests conducted to date vs. the project plans and objective seems to be on track.

PI Response:

Reviewer 23553

Score: 8.0

Comment: The challenges associated with developing a high-temperature directional drilling system are substantial. Baker Hughes has built and assembled several working prototypes of the final tool. They have successfully tested the built tool and drilled at standard conditions. They have found coatings and lubrication that works under the expected operating conditions. They devised inventive plans to validate and verify the tool performance. The technical challenges have been approached in a systematic fashion, showing measured progress along the way. The lessons learned from the development appear as though they could be applied to other areas of tool development. The quality of the accomplishments and work is commendable. The results from the project will help to expand the tools available for geothermal exploration which can help to bring down the overall costs.

Based on the present results, it appears the tasks outlined in the statement of work have been addressed. The productivity and project management are appropriate for the tasks being performed. The team has met the design goals and is near completion and delivery of the 6.5" tool.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23454

Score: 10.0

Comment: This project was apparently tightly organized and executed, with a sound technical approach embedded in very well-equipped facilities and an excellent staff. Development followed a logically consistent sequence. Very few companies or entities in the world have the facilities and staff to have done this work.

Having said that, however, this reviewer must comment that it is difficult to truly assess the technical approach when coming into the review process in the fourth year of a five-year project, with no previous exposure to this work, and with limited information available.

PI Response:

Reviewer 23527

Score: 9.0

Comment: This project has systematically approached the adaptation of a conventional directional drilling technology for 300 degree C operation. Component level considerations including seals, lubricants and high temperature performance of materials have been thoroughly addressed. The testing systems developed as part of this project and tests performed to date are also appropriate and essential to the development effort. The staff involved in the project appears to be highly qualified with the relevant expertise to perform the work needed to successfully execute the project. The field and technology experience of the company performing the work is also extremely beneficial. Development of commercial technology is often a combination of rigorous engineering and incorporation of 'best design practice' acquired from experience and knowledge of hardware performance. The latter is especially true in harsh environment applications. Field testing is especially important for the development of technologies to be used in challenging applications. It is encouraging that this project was able to perform field trials of the developed technology in at least a partially representative environment (hard rock). The span of time that was required to reach this point seems excessive. It might be worth reviewing the history of the project with the performer to better understand why it has taken 5 years to get to field trials. This would be a useful data point for the program if it is typical for technologies of this type.

PI Response:

We first note that BETA test was carried out in December 2013, 18 months ago. At BHI such projects typically take 2-5 years depending on complexity, budget, risk, personnel etc. Considering the novelty of the project; the first 300C drilling system, we think the time span is appropriate.

Reviewer 23537

Score: 8.0

Comment: Notwithstanding one of the objectives of this work, the technical approach seems rigorous and appropriate for the desired outcomes. The BETA site and the tools available there and at allied labs (e.g., in Germany) also appear to be more than adequate to test and potentially achieve the desired results.

It is unclear how and where field testing may ultimately be achieved especially as there are no EGS "operators" anywhere yet. Successful field testing is an expectation in this project and will be the biggest obstacle.

PI Response:

Reviewer 23553

Score: 8.0

Comment: The rigor and approach used to address the technical challenges is appropriate for the required tasks. Several barriers had to be overcome in order to arrive at the current status. Based on the results to date, it appears the team has been able to define the challenges and take the necessary action to meet those challenges. The approach to testing and validation of performance is very good.

PI Response:

STRENGTHS

Reviewer 23454

Score: Not scored

Comment: As noted earlier, the principal strength of this project is the development of a high-temperature drilling system with unique capabilities. It's also important that the three major system components - bit, motor, drilling fluid - can be used as stand-alone technologies in many scenarios. This development was facilitated in large part by the great depth of the resource base and experienced personnel available to the contractor, and this is a primary aspect of the project's strength.

PI Response:

Reviewer 23527

Score: Not scored

Comment: The project performer has deep expertise and experience in the relevant drilling technology. Development of the technology has also been systematic and thorough. Perhaps the greatest strength of the project is that it has been focused on field deployment of the technology and has gathered valuable knowledge related to directional drilling in granitic rock. Directional drilling experience in this type of lithology is limited so any field experience is important for understanding potential limitations of the technique. The build-up-rates and ROPs obtained in the project are very reasonable indicating promise for future adoption of the technology for geothermal use if the high temperature barriers are overcome.

PI Response:

Reviewer 23537

Score: Not scored

Comment: The team, the approach, the equipment and the labs at their disposal are all strong.

PI Response:

Reviewer 23553

Score: Not scored

Comment: The directional drilling tool development has shown Baker's strength in tool development. They demonstrated they have the knowledge, resources, and ability to overcome the barriers associated with developing a high-temperature directional drilling tool. The resulting tool appears to be robust and functional for the environment in which it was designed.

PI Response:

WEAKNESSES

Reviewer 23454

Score: Not scored

Comment: Although technical development is impressive, it appears that this system will be very expensive to build and operate. It's difficult to evaluate this, since no cost numbers were given in the presentation or background material, but the complexity of the machining and assembly lead to that conclusion (e.g., motor cannot be rebuilt in the field or perhaps even in the country.) Because of the metal-to-metal contact in the motor, there will also need to be extremely good fluid cleaning. This was mentioned in the SOPO, but no results were included in the presentation.

There is also a durability question, in spite of one successful field test. It's true that an impressive interval was drilled in granite, but there is no information as to whether the granite was heavily fractured, which is quite common in geothermal reservoirs and is one of the primary factors causing bit and motor failure. The field test was done at low temperature, and it is unclear what effect realistic geothermal temperatures would have on longevity.

Finally, the system to be delivered is for drilling 8.5" hole, which may not be adequate for some EGS applications. It is not clear that the motor is scalable to larger sizes, or whether it is powerful enough for larger bits. Either way, larger holes will exacerbate the cost problem.

All in all, a lot of good work has been done in this project, but it is not yet clear that it will be technically and economically viable for extensive EGS drilling.

PI Response:

Reviewer 23527

Score: Not scored

Comment: No glaring or obvious weaknesses are note. It has taken quite a bit of time to get to the point of time of field trials and high temperature testing of system hardware has still not been completed. 5 plus year projects are not typical for DOE GTO. As mentioned in other sections, it would be worth revisiting the period of performance for this project and understanding why it has spanned such a long period of time

PI Response:

Reviewer 23537

Score: Not scored

Comment: Line any such endeavor, the proof is in the pudding. Absent drilling funds, it may be a while before this group can field test whatever final product is developed. There are an abundant number of hydrothermal sites where this could be tested. Whether an operator would allow this innovative drilling system to be implemented in one of their drilling programs, however, remains to be seen.

PI Response:

Reviewer 23553

Score: Not scored

Comment: Although the tool has been used to drill demonstration holes, it has not been tested at 300C.

PI Response:

IMPROVEMENTS

Reviewer 23454

Comment: Steps to address the "weaknesses" described previously should be considered.

If fluid-cleaning requirements have not been established, they should be, and those requirements should be documented.

If it has not already been done, some analysis should indicate what portion of EGS holes can be 8.5" diameter, and whether the existing system can be scaled up or whether it can drive a larger diameter bit.

More field tests should establish typical system life, and should help to develop a business model for how this system can be marketed so that it will be an asset to the EGS industry.

PI Response:

Reviewer 23527

Comment: Expedite time-line if possible.

PI Response:

Reviewer 23537

Comment: If field testing this becomes an insurmountable obstacle, perhaps the drilling system ultimately developed could ultimately be integrated into FORGE drilling (killing two birds with one stone).

PI Response:

Reviewer 23553

Comment: Testing the tool at high-temperature.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005505
Project: Directional Measurement-While-Drilling System for Geothermal Applications
Principal Investigator: Chatterjee, Kamalesh
Organization: Baker Hughes Oilfield Operations Incorporated
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23454

Score: 6.0

Comment: There is an anomaly in scoring the impact of this project and the associated high-temperature drilling-system project, in that the tools under development may meet all the GTO goals, yet may not have as great an impact on the actual market as expected. That distinction is probably beyond the scope of this review, but it is a partial explanation for score given.

The quality of accomplishments and progress toward goals is high -- the contractor has done an excellent job in choosing among various technologies and prototype designs to date seem reasonable. Significant challenges still lie ahead -- many of the components of the system have never existed before, and some are not yet even at prototype stage. This is a very complex system with no redundancy; that is, all the components must be successful for the system to function. Not to say that this is impossible, but it illustrates the difficulty of the project.

The "productivity" part of this criterion calls for consideration of accomplishments compared to costs, but no cost data are given. Based on the schedule presented, work seems to have been performed in a timely way, and the schedule for completion of the project appears within reach.

PI Response:

Reviewer 23527

Score: 8.0

Comment: -

PI Response:

Reviewer 23537

Score: 8.0

Comment: This project endeavors to develop a system for acquiring data and navigating the bit in a high T/high P. Like its companion project, threshold operating conditions are 300 degrees C and 10,000 ft depths.

Like its companion project, the barriers to success have been well thought out and the potential solutions appear reasonable.

Quality: the results thus far appear to track with the plans and goals.

It seems, however, that the success of the project hinges on the efficacy of the insulating dewar flask system.

Productivity: with the exception of a functional dewar flask that is robust enough to persist at the T's and P's anticipated, as well as the drilling vibrations, the accomplishments to date are rigorous and track with the project goals.

PI Response:

Reviewer 23553

Score: 7.0

Comment: The team has evaluated options for developing the MWD tool for high-temperature. They have come up with an active cooling design for keeping the electronic components cool for 50 hours at 300C. This is a commendable feat and shows promise for the rest of the project. Other challenges including testing and durability still need to be addressed.

The project plan was divided into five primary tasks. Nearly three years into the project, they are only onto task 2. It appears the team has performed a few tests and come up with some basic concepts for meeting the design challenges. Although they are starting with a known design, there is still quite a bit of work to be done. Based on the current schedule, they may have difficulty having everything done by December 2016.

PI Response:

Yes, it is a tight schedule we hope to keep. In 2014 there was 9 month delay by DOE to give approval for Phase 2. This in part explains the project delay.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23454

Score: 9.0

Comment: The technical approach to this project has been adequately planned and thorough. Performance requirements, although possibly unrealistic, were broad enough that the contractor could have considered many design alternatives, and they have performed well in choosing among them. Since this is the third year of the project, no information is provided on how the original technical approach was devised, but project performance to date seems to have followed a rational course, so the implication is that the project design was adequate. Again, no data on resources was given, but there is no indication that the project would be further advanced had more resources been available, so one must conclude that the technical approach was a good fit for the resources.

Personnel and equipment were outstanding -- few companies or entities in the world have the resources to have carried this project to the point it has achieved. The plan for one field test is not enough of course to validate the technology, but given the nature of the proposal, it's probably all this was possible within the framework of the funding for the project.

PI Response:

Reviewer 23527

Score: 9.0

Comment: -

PI Response:

Reviewer 23537

Score: 7.0

Comment: The concept, the technical approach and the decisions made to date are very sound given the nature of the problem to be solved. The solution to this problem, however, is far from straight forward and, as admitted by the PI, is high risk. The solution for housing these tools in a high T, vibration-resistant flask may be insurmountable given the timeline and funds available. It wasn't apparent from the presentation that the PI is confident that this will be achieved, either.

PI Response:

We admitted to the high risk nature of the problem, but we are confident that MWD robust flask could be achieved.

Reviewer 23553

Score: 7.0

Comment: Baker has evaluated options for developing the MWD tool for high-temperature. Based on limited options for high-temperature electronics, they down-selected to an actively cooled system. This solution appears to appropriate based on the information at hand. The trade-off between the uncertainties of having 300C capable components available vs having to actively cool the system with a dewar is a difficult decision.

They have shown efficiency in leveraging resources within Baker and previous work in developing a dewared measurement tool. Their initial design looks promising, but there is still much detail to consider.

PI Response:

STRENGTHS

Reviewer 23454

Score: Not scored

Comment: The principal strength of the project is the extensive background work and analysis that has gone into selecting each of the system components. This is a complex, but well-integrated project and there are few companies with the resources to have carried out this design effort to the point that prototypes or advanced designs exist for all the major components of this system, and to continue support of the development through completion. This capability is enhanced by Baker-Hughes' ability to test all prototype components and the full MWD system in their own facilities.

Several concepts in the proposed prototype system are highly innovative, and it is possible that successful development of some of the components will have stand-alone value outside the full MWD system.

PI Response:

Reviewer 23527

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23537

Score: Not scored

Comment: The team and the approach are solid. They have access to solid testing equipment and have a wealth of drilling experience.

PI Response:

Reviewer 23553

Score: Not scored

Comment: The team has evaluated options for developing the MWD tool for high-temperature. They have come up with an active cooling design for keeping the electronic components cool for 50 hours at 300C. This is a commendable feat and shows promise for the rest of the project. Other challenges including testing and durability still need to be addressed.

They have leveraged previous work in developing MWD tools for high temperature.

PI Response:

WEAKNESSES

Reviewer 23454

Score: Not scored

Comment: The difficulty and complexity of what's being attempted may not be considered "weaknesses" of the project, per se, but from the perspective that anything diminishing the chances of success is a weakness, then those factors qualify. In the same way, operational success of several crucial components of the system remains to be demonstrated. It is too early to characterize these as weaknesses, but the fact is that there is a long way to go before this system is shown to be a useful element of geothermal technology.

On a separate issue, it is disappointing that no data have yet been entered into the Geothermal Data Repository. Surely, with the great amount of background design, construction, and preliminary testing that has taken place, much of this would be of interest to the geothermal community. As a specific example, all of the material supporting the Go/No-Go decision at the end of Phase I would surely be relevant.

PI Response:

In phase 1 of the project the review testing and preliminary design all pertains to drilling tool development and we believe this is not relevant to the geothermal community. In addition, tool design and development data is proprietary to BHI. We are committed to and will release any field testing data whenever we acquire it.

Reviewer 23527

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23537

Score: Not scored

Comment: Like the companion project, this is partially a solution in search of a problem. Another weakness may be that the scope of the project may be larger than can be reasonably expected given the time and available funding.

PI Response:

Reviewer 23553

Score: Not scored

Comment: The project plan was divided into five primary tasks. Nearly three years into the project, they are only onto task 2. It appears the team has performed a few tests and come up with some basic concepts for meeting the design challenges. Although they are starting with a known design, there is still quite a bit of work to be done. Based on the current schedule, they may have difficulty having everything done by December 2016.

The use of a dewar in the BHA may prove tool be challenging when designing for the drilling loads and vibration environment.

It also appears there has been some change in staffing for the project. This may also set the project back from a scheduling perspective.

PI Response:

IMPROVEMENTS

Reviewer 23454

Comment: All objectives described in the SOPO have been addressed to this point in the project, so with the limited information available, it is difficult to define any specific improvements. All aspects of the project appear to be well-organized from a programmatic perspective, so the path to improvement simply means getting on with the work.

As noted earlier, interim data in the Geothermal Data Repository would be welcome.

PI Response:

Reviewer 23527

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23537

Comment: I don't have any suggested improvements.

PI Response:

Reviewer 23553

Comment: The most obvious area for improvement is in the project management and progress. There are still many challenges to address by December 2016.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: High Temperature Chemical Sensing Tool for Distributed Mapping of Fracture Flow in EGS
Principal Investigator: Cieslewski, Grzegorz
Organization: SNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 6.0

Comment: The achievement of a downhole sensor specific to iodide ion is a substantial achievement indicating a high level of technical accomplishment. Whether this technical feat will have significant impact depends on two factors: can the degree of electrode poisoning be quantitatively accounted for in real time, and will iodide become a tracer of choice in EGS. Neither of these issues was adequately addressed in the presentation or the review literature.

PI Response:

Thank you for your comments. We agree that the electrode poisoning could be the problem and will attempt to address the problem as the project continues.

Reviewer 23433

Score: 8.0

Comment: The overall objective of this project is to be able to detect the different levels in a borehole where inflows of geothermal liquids occur. This is to be achieved by injecting particular trace materials and then detecting their return flow by the use of various sensors. Such measurements should provide valuable information concerning the flow paths in the reservoir. To date, at least two possible tracer materials (naphthalene sulphonate and iodide ions) have been evaluated, and the iodide solution selected. Some work was also done to evaluate the use of gas chromatography. Additional work has been accomplished on pH sensors, a reference electrode and the associated hardware and instrumentation necessary to incorporate the sensors in a downhole tool. This work has progressed in an orderly and systematic way, and results obtained so far seem valuable. It is probably too early at this stage to determine the ultimate value of the technique in real field operations.

PI Response:

Thank you.

Reviewer 24895

Score: 8.0

Comment: Downhole measurement of ions and pH is certainly a stretch project that would contribute a much better understanding of the flow paths from the injector to the producer. Getting a usable tool downhole with the ability to measure iodine and pH will be a great accomplishment. The successful development of the pH and ion tool will require an electronic system for deployment, which part of the principal investigator's portfolio, so there is a good deal of synergy between this and the other electronic projects. The temperature limit of 225C is a bit low for the normal EGS target reservoirs, but may still be valuable.

PI Response:

Thank you for your comments. We agree that the current maximum operating temperature of 225 C does limit the number of reservoirs that could be studied with this tool. Our thought was that if we can solve the materials chemistry and engineering challenges at 225 C and the community finds the eventual field data useful then we would work towards increasing the temperature limit in a future project.

<u>Reviewer 23567</u>

Score: 7.0

Comment: The development of tracer detection tools capable to go to depth is an important task for successful implementation of EGS. Such tools would allow fracture mapping and will provide information on the distribution and flows. It is true that currently used methods for manual sample collection and laboratory analysis are a slow and not very accurate and real time measurements will provide significant advantages. This project has demonstrated lab scale testing and calibration of three electrode electro chemical sensor approach with test temperatures up to 225C. There have not been mentioned on the stability of tested sensors as well as possible solutions on how to correct drift if found to be significant. The consumption of the electrodes is expected to accelerate at the higher end of operating range temperatures and early stability/reliability testing may become essential for practical implementation.

PI Response:

Thank you for your comments. We agree that as the stability and lifetimes of these electrodes will decrease at the upper end at our operating range. Lab scale testing in the last quarter of this project will explore this issue on our pH, reference, and iodide ion selective electrodes.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23401</u>

Score: 5.0

Comment: The redefinition of project objectives to detecting a very limited group of tracers that are not very commonly used may be based on a careful consideration of EGS tracer use. If so, that fact was not discussed in the presentation. If not, this approach may consign the tool to the category of a technical novelty that is unable to gain wide acceptance.

A second concern is that probe stability (i.e., poisoning) is not accorded a sufficiently high priority to get the completed tool accepted in the field. The example of thermistor use in logging tools shows how difficult it is to introduce tools with frequent recalibration requirements.

The quality of the program execution is excellent, as evidenced by its accomplishment.

PI Response:

Thank you for your comments. We should have better addressed the reasons for choosing the family of ionic tracers as targets during our review. The choice was made during informal discussion with scientist in the field at the 2013 DOE GTO Peer Review and the 2013 GRC meeting. The primary tradeoff was that the new knowledge gained by collecting this data downhole would outweigh the disadvantages of going back to using ionic tracers versus the more recently used sulfonates.

Reviewer 23433

Score: 7.0

Comment: The scientific approach seems well founded, and the plan of work logical and systematic. The reviewer feels that some attention should be applied to snags that might crop up in real field operations. An example would be to investigate how the behavior of the different sensors might be affected by the occurrence in the well of various possible (expected, possible, unlikely) contaminants that could upset the performance of the sensors. The proposers suggest that they will build on existing PTS tool designs which seems logical and a good way of capitalizing on previous work.

PI Response:

Thank you for your comments. We intend to move to more realistic testing and the introduction of more complicated intereferents in our autoclave testing now that the overall structural design of our electrodes has been set. During our last quarter we intend to measure and report on selectivity coefficients for the most likely intereferents.

Reviewer 24895

Score: 9.0

Comment: The electrode response was quantified and corrections determined. Technical obstacles were overcome with the reference electrode in particular. While there is a lot more that needs to be accomplished and field tested, good progress has been made.

PI Response:

Thank you for your comments.

Reviewer 23567

Score: 7.0

Comment: The approach for integrating ion selective electrode, pH and reference electrodes into the existing Sandia high temperature PTS tool is rational and efficient to take advantage of already developed sensor tool platform. It is not clear if developed electrode sensor technology has limitations to go higher in temperatures and could be in future enhanced for higher temperature capability. Although technical approach is solid for electrochemical sensing it would be beneficial to compare overall capabilities and sensitivity range as well as implementation complexity with other tracer sensor technologies, beyond ion selective membranes. The testing of the sensors is done correctly using simulated brine solution and the target sensitivity level of 10-25ppm is ok.

PI Response:

Thank you for your comments. There are certainly some challenges in moving towards higher operating temperatures though it should be possible to raise the limit. The membrane used for the iodide electrode is stable to at least 300 C and the materials used in the pH electrode are capable of going higher as well. The biggest challenges are finding adequate sealing materials and dealing the different thermal expansion coefficients of all the parts. We did look at other non-electrochemical technologies and agree that other completely different approaches to the problem are possible.

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: The technical capacity of the team is demonstrated by the probe already developed.

PI Response:

Thank you for your comment.

Reviewer 23433

Score: Not scored

Comment: The project appears well focused on an area in which the proposers have strong capabilities. The overall objective, to determine the exact locations in the wellbore where the return flows of geothermal fluids occur is clearly desirable, and an advance on current detection methods, that only determine total returns. Progress has been steady so far with the selection of a promising approach and the elimination of at least a couple of unsatisfactory alternatives.

PI Response:

Thank you for your comments.

Reviewer 24895

Score: Not scored

Comment: Good scientific approach to measurement and resolution of the technical problems as well as having a stretch goal aid in quantifying the fluid flow paths through the reservoir.

PI Response:

Thank you for your comments.

Reviewer 23567

Score: Not scored

Comment: For the specified operating temperature range the solution has solid readout electronics technology with the access to high temperature casing and packaging. The approach of using existing PTS tool is an inexpensive way to realize developed sensors.

PI Response:

Thank you for your comments.

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: There is insufficient linkage to potential users of the tools being developed to be confident that they address the correct problems.

PI Response:

Thank you for your comments. We agree that more conversations with potential end users would be useful and will address this in the next quarter.

Reviewer 23433

Score: Not scored

Comment: One possible weakness could be that the currently-preferred approach, that of measuring iodide ion concentration could be upset in a particular well by the presence of some undesirable contaminant. Some attention should therefore be given to considering whether there are substances that could upset the measurements.

PI Response:

Thank you for your comments. We agree and will be quantifying the response of our electrodes in a wide range of intereferents in the next quarter.

Reviewer 24895

Score: Not scored

Comment: Temperature is limited to 225C, which will limit the applicability in higher temperature reservoirs. Most of the target EGS reservoirs will have production temperatures greater than 225C, but some of the demonstration projects will be in that range use of the tool would allow a better understanding of flow path creation in those reservoirs. The high limit of detection for the iodide will either have to be improved, or the field tests will have to use higher concentrations of iodide in the injection slug, which may not be a big problem.

PI Response:

Thank you for your comments. Given the significant chemistry, materials, and engineering challenges that needed to be overcome to make the first prototype chemical tool we settled on 225 as the limit though we would like to see that number raised in the future. We agree that ideally we would be able to improve the iodide detection limit so that the least amount of tracer possible can be used and are working on addressing this issue currently.

Reviewer 23567

Score: Not scored

Comment: Tool under development maximum operating temperature capability seems to be limited to 225C. In some deeper and hotter EGS systems the developed technology may not be practical as higher temperatures will be encountered. Although it seems that most of the domestic wells may be focusing on the lower end of 200-300C temperature range, the enhanced temperature capability will improve overall reliability and versatility of technology.

PI Response:

Thank you for your comments. We agree that increasing the temperature limit of the tool would be valuable and we believe possible.

IMPROVEMENTS

Reviewer 23401

Comment: Bringing in a user group or an operator willing to commit to a field test to rigorously debate the final tool specifications could ensure further funding well directed.

PI Response:

Thank you for your comment. We agree and are interested in talking with potential operators and end users.

Reviewer 23433

Comment: Some thought should be devoted to considering what might go wrong in transferring the technology from lab to field. As noted above, it may be that some particular contaminant in a particular well may upset the measurement in question. Other possibilities may occur to the proposers.

PI Response:

Thank you for your comments. We agree that intereferents can pose significant challenges. While we are testing our tool against common intereferents one of the steps we feel would be necessary before use in a particular well would be to use samples of the fluid in at least quick lab based tests to ensure adequate calibration and understanding of sensor response.

Reviewer 24895

Comment: Needs to be demonstrated in the field and more than one tracer is needed, but both are part of the ongoing work.

PI Response:

Thank you for your comments. We would welcome future opportunities for field testing.

Reviewer 23567

Comment: Continue sensors laboratory validation and move on to the field testing as soon as possible. Secure field testing partner.

PI Response:

Thank you for your comments. We would welcome future opportunities for field testing.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Enhanced High Temperature/High Speed Data Link for Logging Cables
Principal Investigator: Cieslewski, Grzegorz
Organization: SNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 8.0

Comment: The project objectives represent a substantial opportunity to improve the value of logging, even at "ordinary" temperatures. The impact of higher data rates on single conductor lines will be felt in better resolution, self-diagnostics, drift correction, etc. as companies learn to take advantage of the technology. The quality of both the work and the presentation are very good. The SOW was not provided to this reviewer so no opinion can be offered relative to productivity.

PI Response:

Thank you.

Reviewer 23433

Score: 5.0

Comment: The proposed work is a continuation of a project aimed at increasing the data transmission rate capability of a single wireline conductor. This is achieved by sophisticated data encoding, which will require the development or acquisition of a digital signal processor, a custom designed DAC and a custom-designed line driver. Each of these will have to be capable of operating in the down-hole high temperature, high pressure environment. At present, it is intended to develop these items only to a temperature capability of 210 C. This seems rather low for current ambitions in the geothermal industry. It appears from the section on "Challenges to date" that difficulties in obtaining the necessary hardware have slowed the development of the software. The reviewer wonders whether the two parts of the project should therefore have been formulated as separate projects. However, useful progress has been made on the software side and with some of the high temperature components.

PI Response:

The two problematic components (ADC and the line driver) should be formulated as a separate project. However, due to funding limitations they cannot be. The primary temperature limitation is the DSP. The functionally of the DSP could be implemented in HT ASIC which would increase the operational temperature significantly.

Reviewer 24895

Score: 8.0

Comment: More data intensive applications have been a problem, because high temperature well wirelines are normally single conductor cables, which have serious bandwidth constraints. Fiber optic cables have a higher band width, but LED's for 300C don't exist to transmit the data from downhole and modulators would have to be developed to input the data into fiber optic cable with the LED's at the surface, which is also a challenge. In addition, there are existing high temperature cables in existence that would benefit from this improvement.
The project was unable to meet the goal with the first attempt (achieved 400k with a target of 1M, but returned with an entirely new approach, which overcame the limitations of the first phase and have meet the goal in laboratory testing. In particular, the new approach, OFDM, provides self-correction as the cable properties change with temperature and the amount of cable down hole compared to on the spool.
There is currently a 210C temperature limit compared to the 300C temperature limit of the wireline, which degrades the system capability. This may be overcome with better electronics, but the 210C limit would require thermal protection (dewar) to get 300C capability.

PI Response:

Agreed.

Reviewer 23567

Score: 7.0

Comment: The improvement of the data transmission of a single wire copper line by implementing advanced signal processing algorithm and hardware seems to be potentially cost saving approach for an existing cable solution. Improved transmission system may provide capabilities to operate some data intense downhole tools currently not feasible to deploy due to the lack of communication link solution. This is definitely a step forward and should allow the use of existing cabling solutions which may take long time to replace as they carry large capital expenses. Project progress is solid, however it is desirable to have demonstration or testing completed at high temperatures.

PI Response:

Thank you.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 8.0

Comment: The technical approach has been effective in meeting the principal objective of >1Mbps over 5,000 ft of cable. The presentation did a good job of explaining how the challenges were overcome and what solutions found. The successful test of the complete system at 210 C is a noteworthy milestone. Without the SOW it is difficult to rate the effectiveness of the approach in terms of equipment or staffing.

PI Response:

Agreed.

Reviewer 23433

Score: 5.0

Comment: The technical approach to the problem of obtaining high data transmission rate from downhole to surface via a single electrical conductor seems to be workable. However, several specialized electronic assemblies will have to be developed. Although versions of the necessary electronics that operate at room temperature are widely available, such equipment is not often available for high temperature applications. It appears that the work effort will have to be divided between devising the software that will be required to handle the required signal processing and developing the hardware to enable this processing to be carried out down hole. The reviewer wonders whether in future data transmission will continue to be done by single wireline in view of the likely introduction of fiber-optic transmission lines. It therefore seems possible that although the technical solution to the problem of high speed data transmission by single wireline may be found using the present approach, it may turn out to be bypassed by rival developments elsewhere.

PI Response:

I agree that the fiber optic solution could eclipse this project. However there are comparably very few wirelines with fiber currently deployed and they are expensive to make. I believe that fiber optic solution will be developed and used for specific applications standard single conductor wireline will continue to be most commonly used.

Reviewer 24895

Score: 9.0

Comment: Good progress to date with circuit design and overcoming the limitations with available high temperature components. Still some way to go to have a field test ready system available. Needs testing with the cable at temperature as well as the components to assure cable changes with temperature are really self-compensating.

PI Response:

Agreed.

Reviewer 23567

Score: 8.0

Comment: The approach of using frequency division multiplexing is great example of adapting existing telecom sophisticated techniques for improving communication link bandwidth. It seems however a high level of complexity is involved in building electronic hardware and implementation is not trivial sometimes due to absence of parametric component models. As currently high temperature electronics still in development, the maximum operating temperature will not be that easy to extend. But overall the approach of this project is very compelling. Besides increasing the number of communication channels by implementing orthogonal frequency multiplexing, the approach is enabling real time transfer function characterization to optimize signal processing filters and improve reliability of the link. Such capability makes the system immune to the possible interference and form factor of the cable not dependent on the shape and state of the spool.

PI Response:

Agreed.

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: Willingness to abandon a technical dead-end approach (Phase 1) in time to move forward with a new approach (Phase 2) must count as a primary strength of the project. A corollary strength is the availability of the technical skill on staff to implement the new approach.

PI Response:

Thank you.

Reviewer 23433

Score: Not scored

Comment: The proposed work should provide a way of substantially increasing the data transmission rate along a single wireline cable. The reviewer wonders whether in future, high data rate transmission will be carried out mostly by fiber-optic cable, and that therefore the present approach will become redundant. However, this result is not guaranteed, and so the present, alternative line of approach may turn out to be valuable. Further, even if the required electronic components cannot be obtained with the desired high-temperature capability, the high speed data transmission techniques being developed may find application at ambient temperatures.

PI Response:

I agree.

Reviewer 24895

Score: Not scored

Comment: Built on new telecom protocols, leveraging the new technology in the telecommunications area, Meeting the challenge of adapting the circuitry to available high temperature components

PI Response:

Reviewer 23567

Score: Not scored

Comment: An effective solution was found to increase transmission bandwidth at 5000feet distance to more than 1MBps.Lab scale setup confirmed transmission in experiments.

PI Response:

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: The review materials were not prepared according to directions: the SOW is missing entirely and the Project Summary is a draft with revision marks still evident.

PI Response:

I am sorry that the SOW was not provided.

Reviewer 23433

Score: Not scored

Comment: A potential global weakness of the project may be if transmission of data by single wireline becomes obsolete in view of the development of transmission by fiber optic means. This is, however, not yet certain. The close connection between the hardware and software sides of the project appears to weaken the project, insofar as testing of the software in the down-hole environment has to wait for the development of the necessary high temperature hardware. The current temperature limit of 210 C may not be sufficient for many geothermal wells.

PI Response:

Agreed. Where the 210C is relatively low goal, if proven successful the system can be adapted to higher temperatures.

Reviewer 24895

Score: Not scored

Comment: The system, including the wire line, needs high temperature laboratory verification and then field verification. If possible, the lab tests should include varying the temperature of the cable. Field verification is planned in the next steps. The 210C limitation will pose a problem in high temperature wells and limit the usefulness to 210C, which is lower than the 300C limit of the high temperature wire lines. This can be overcome with thermal insulation (dewar), but reduces the running time for the tools.

PI Response:

Reviewer 23567

Score: Not scored

Comment: Maximum temperature limit is likely to be limited and system may have limited use to Geothermal Industry.

PI Response:

Agreed. Where the 210C is relatively low goal, if proven successful the system can be adapted to higher temperatures.

IMPROVEMENTS

Reviewer 23401

Comment: As the project moves forward to address the "Future Directions" and approaches commercialization, more attention to management details will facilitate a credible presentation to industry partners. A field test demonstration in a DOE project well should be sought.

PI Response:

Agreed. Fuding dependant.

Reviewer 23433

Comment: Ways should be investigated to increase the temperature capability of the system beyond the current limit of 210 C.

PI Response:

Agreed. Where the 210C is relatively low goal, if proven successful the system can be adapted to higher temperatures.

Reviewer 24895

Comment: Higher temperature or look at dewar alternatives for short time usages (acoustic logging) and limit the depth for long time usages (seismic).

PI Response:

Agreed.

Reviewer 23567

Comment: Complete tests at high temperatures as soon as possible and explore options for industrial non-government funding to work with geothermal and oil and gas developers. Electronics flasking seems to be the solution for extending the usable temperature range to 300C, so maybe early feasibility investigation will have significant impact for future work.

PI Response:

Agreed.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Deployment of Integrated Wide Bandgap Sensor, HT Packaging, and Data Communication System
Principal Investigator: Cieslewski, Grzegorz
Organization: SNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 8.0

Comment: The potential impact is large for very high temperature tools that are rugged enough to operate in the hottest wells. The contracting issues and consequent delays require a slight downgrading of the project score, but overall this is a project at the core of what DOE can do best to advance its geothermal objectives.

PI Response:

Thank you.

Reviewer 23433

Score: 4.0

Comment: The proposed work is to develop a system of wide band gap sensors to measure down hole temperature and pressure in a producing geothermal well. This activity will combine sensors developed in Professor Pisano's group at UC San Diego / Berkeley with expertise from Sandia on readout and calibration systems and the use of a high temperature logging cable. The project did not start until q 2 of 2014, and shortly thereafter Professor Pisano moved from Berkeley to San Diego. Progress has therefore been slow because of the move and resulting disruption in the funding stream. It is thus difficult for the reviewer to evaluate what progress has been achieved, and the quality of the work. However, the objective itself has merit, and it is hoped that substantial progress will be achieved in the near future. Work done so far has demonstrated the fabrication and testing of a pressure sensor, a temperature sensor and a simulated differential pressure sensor, all of which are based on silicon carbide. Since silicon carbide has much greater thermal stability than silicon, any work to further the use of this material will be of great value to the geothermal industry.

PI Response:

We are actively working with UCSD to speed up the process.

Reviewer 24895

Score: 7.0

Comment: Early in the project, but there has been good progress in conceptualizing the options and the initial construction of SiC components for testing. There have been some difficulties with the sensor manufacture that will need to be resolved. The objective is long term electronic measurement at high temperature. SOI components have a drift with time and the SiC is a possible remedy to that. Currently, long term pressure measurements are made using nitrogen filled cap tubing with a chamber on the bottom. I am not sure long term electronic measurement of pressure offers a significant advantage over the current system, which is inexpensive and robust. Long term temperature measurement may be possible with fiber optic cable instead of a downhole electronic solution, so there should be an advantage offered by an electronic system, but it was not clear what that was.

PI Response:

While the fiber solutions are very attractive, it is still not clear if they can be used to measure pressure at HTHP. The advantage to this system will be a pressure measuring apparatus which leverages current MEMS technology and its application to SiC. The SiC sensors should have superior longevity and chemical resistance.

Reviewer 23567

Score: 5.0

Comment: It is recognized that a low drift, chemically stable and inert pressure and temperature sensors are needed for constructing geothermal tools. SiC does offer significant material advantages to impact geothermal industry, but provided that there is a direct commercialization of the technology planned and research is aiming at generating results which will be practical. SiC technology needs improvement of fabrication quality and manufacturing robustness to enable transfer of technology and enable sellable SiC-based electronics and products at fair costs directly to the user or in the form of new logging or drilling tools used by the geothermal industry.

It is not clear at all how mature the technology for making SiC pressure sensors and project has clearly failed to deliver on any working parts and especially to demonstrate viable packaging technology which will be practical to implement in the high temperature tool design. There is no preview for this work resulting in a commercially available sensor for use by the geothermal industry as a component or as a logging tool.
Development of the pressure sensor brings the most value to this project, while the development of a SiC temperature sensor does not seem to carry significant benefit /commercial value or transformation impact as there is already a number of low cost temperature sensor solutions available on the market. Temperature sensor part of the project likely may not be providing critical path for moving forward alone without the unique pressure sensor approach.

PI Response:

I agree with this assessment. The temperature sensor is a complementary component to the primary pressure sensor. This project is focused on proving that the SiC is viable for geothermal deployment. I recognize the difficulties with commercializing this technology at this early stage.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 9.0

Comment: The novel approach taken to creating rugged designs for high temperature merits high marks. The execution within the constraints of manpower limitations is also commendable. The only noteworthy fault to be found is with the problems with the subawardee whose institutions ought to have been able to keep the project on track. The resulting tool appears to address all the necessary requirements for success in the field.

PI Response:

I hope we have resolved all contracting issues. The project should proceed on delayed track..

Reviewer 23433

Score: 4.0

Comment: The major scientific ambition of the proposed project is to demonstrate the development of pressure, temperature and differential pressure sensors based on silicon carbide rather than silicon. The former material has much greater thermal stability, possibly allowing operation to 300 C and 5,000 psi. This is clearly of interest to the geothermal industry. Due to external difficulties noted above, execution of the project has been delayed, so it is difficult to evaluate the quality of the project management. Engagement of Sandia's expertise in the recovery and interpretation of the data (high temperature wireline and surface data processing) has not yet been engaged.

PI Response:

I hope we have resolved all contracting issues. The project should proceed on delayed track.

Reviewer 24895

Score: 8.0

Comment: Project is contributing to the early development of SiC measurement of P and T for long duration at high T, which may blossom into other sensors and components. Plan for future testing appears well thought out. Good opportunity for collaborative work between a university and a national laboratory.

PI Response:

Thank you.

Reviewer 23567

Score: 6.0

Comment: The integrated approach for combining temperature and pressure sensor is quite premature as most of the risks and performance evaluation has not been completed on both sensors. Miniaturization is of course of interest, but doesn’t seem leading to a meaningful value as it is not economical at this stage of technology development. There seems to be a disconnection between the project plan and achievable goals to produce a usable high temperature tool.

Project portion related to the pressure sensor has shown significant delays due to unavailable parts and only two dead-on-arrival sensors available for Sandia. It is not logical why PI has decided to wait for replacement pressure sensor parts and not continuing the work on readout electronics solution for the sensor system using just the temperature sensor components first.

PI Response:

I have decided to wait for the replacement pressure sensors as the pressure sensor is the primary goal of this project.

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: High order of technical competence demonstrated in both the Sandia and UCSD areas of responsibility. Presumably the Golden office and Sandia deserve kudos for their work with UC to keep the project going.

PI Response:

Thank you.

Reviewer 23433

Score: Not scored

Comment: The project is strengthened by the combination of the expertise of Professor Pisano's group in San Diego with the capabilities of the personnel in Sandia in terms of data transmission (the high temperature wireline and the interrogation /interpretation system uphole). This combination should allow Professor Pisano's group to concentrate on the development of the sensors.

PI Response:

Agreed.

Reviewer 24895

Score: Not scored

Comment: Collaboration of two groups with different expertise to solve the problem of long term high temperature measurement of pressure and temperature will increase the chances of a good outcome.

PI Response:

Thank you.

Reviewer 23567

Score: Not scored

Comment: This project is experimenting with wide-bandgap SiC technology and continuing to drive unique solutions based on novel semiconductor technology.

PI Response:

Agreed.

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23433

Score: Not scored

Comment: Delay in funding and the dislocation resulting from the movement of Professor Pisano's group from Berkeley to San Diego has not helped the project. However, it may not be fair to cite this as a weakness of the project either in concept or execution. Apart from that, progress appears to have been adequate on development of the sensors. However, it is not evident that any thought has been given as to how to include the new sensors into a down hole tool, nor to the high temperature wireline that will be needed. Is this the responsibility of San Diego or Sandia?

PI Response:

Sandia is responsible for integrating the sensors in the tool.

Reviewer 24895

Score: Not scored

Comment: Too early to identify weaknesses, other than that the competition from cap tube measurement of pressure and fiber optic measurement of temperature may limit the commercial space for these two sensors.

PI Response:

Reviewer 23567

Score: Not scored

Comment: The selected approach for utilizing SiC pressure sensor seems to be significantly delayed and dependent on parts availability from Professor Pisano’s group. As his Berkley lab is currently in the process of moving, there is no clear view on when and how the availability of pressure sensor parts may happen. This critical dependency is significantly holding the project back.

There is a lot of uncertainty in the quality of pressure sensors and potential for reliable operation needed to moving this project in the deployment stage as originally proposed. It seems that a lot of effort will be needed to improve SiC pressure sensor fabrication.

PI Response:

Agreed

IMPROVEMENTS

Reviewer 23401

Comment: A field test partner would help prepare for a seamless proof of concept demonstration. The NW Geysers or Salton Sea would be the most obvious venues for a credible demonstration.

PI Response:

Agreed, however the due to limited funds the field test will probably not occur.

Reviewer 23433

Comment: There is little evidence so far of active collaboration between Sandia and Professor Pisano's group. Perhaps it is of lower importance until some actual sensors have been developed and are ready to be installed. However, it is never too early to start activities to coordinate the work, and so it is recommended that the two groups soon start discussions as to how the new sensors are to be included into a down-hole tool. In particular, some attention should be devoted to the question of how the sensors will be incorporated in the down-hole tool. Does the tool already exist, and is it just a matter of swapping in a new sensor, or is a major development required? The same question may be raised concerning the high-temperature wireline.

PI Response:

Agreed. We will improve the cooperation between the two groups and address the questions posed.

Reviewer 24895

Comment: No suggestions

PI Response:

Reviewer 23567

Comment: PI has mentioned of using SiC JFET-based electronics in the future to design and fabricate readout electronics. There are several other groups working in the field of SiC devices and materials development which are worth contacting and evaluating potential for collaboration. Some work which has been already done dates back to more than 15 years ago and PI may want to look at prior art and publications from groups and authors such as Phil Nuedec (NASA), GE, KTH and potentially others.

PI Response:

Thank you for the suggestions. I will look into it.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Evaluation of High Temperature Components for Use in Geothermal Tools
Principal Investigator: Cashion, Avery
Organization: SNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 7.0

Comment: The objectives of the project are well stated to support the goals of the Geothermal Program. The small number of industry respondents and the statistically insignificant number of devices that can be tested raise questions about effectiveness of the project at its present scale. The statement of work identifies an increasing number of candidate components coming to market due to Oil industry demand, but this is not reflected in either industry collaboration or numbers of candidate devices.

PI Response:

While the number of high temperature components coming to market for the Oil and Gas (O&G) and automotive industries is increasing rapidly, the number that are rated for extreme geothermal temperatures remains low.

Reviewer 23433

Score: 5.0

Comment: This program aims to evaluate electronic components and assemblies for geothermal down-hole applications by subjecting them to endurance tests involving high temperatures (260 to 300 C). Evaluating such materials is time-consuming and difficult, with the result that it is often not done for the particular conditions of an industry with relatively restricted market for those components. Hence the starting of a program to carry out such tests for the geothermal industry's particular demands may be seen as a desirable objective. So far, some useful progress has been achieved in setting up test facilities and standard protocols for the testing of specific items. However, as is further discussed below, it is not clear to the reviewer that the components tested are of the greatest importance to the geothermal industry. Furthermore, since to objective is to test existing components rather than to develop new ones, it is unlikely that there will be important new developments in the range of components available

PI Response:

Please see response to Reviewer 23433 below.

Reviewer 24895

Score: 8.0

Comment: Testing has identified the temperature/time limits of commercial components, enabling the development of high temperature tools. In the process, the tools can be used to test new commercially available components of the same type, to provide comparisons, as was the case for capacitors. Immediate use to accelerate availability of tools for geothermal. Some questions about the ability to get or entice participation by the component manufacturers, relative to project GTP150022, which seemed to have more success at getting vendors to supply or develop test electronics.

PI Response:

Please see responses to Reviewers 23433 and 23401 below.

Reviewer 23567

Score: 7.0

Comment: High temperature components are typically not the primary focus of manufacturers as there is no significant need for volume of these; and high temperature electronics (>225C) field is not capable to drive volumes by itself. As a result, most of high temperature rated components are poorly characterized and reliability along with associated failure mechanisms is poorly understood. In this respect, the independent evaluation of components suggested for use at high temperatures does make sense as testing usually not straightforward, involves complicated test setups and likely to serve as a path finding effort which can help improving existing parts from big manufacturers as well as help efforts of small players who is just starting up with the unique technology. This project although providing valuable test data doesn’t seem to produce disruptive effects on the supply chain or significantly accelerate learnings and innovation in the field of high temperature tools.

PI Response:

This project is relatively young and many of its data has only recently become public. Direct proof of disruptive effects on supply chain is always difficult and is not the primary goal of this project. Knowledge of the absolute limitations of the existing foundation of available components is critical to advance the state-of-the-art in tool design.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 5.0

Comment: The SOW describes this work as late-stage R&D which suggests the application of accepted test procedures to significant quantities of devices for commercialization. This project did not attract participation from any of the manufacturers which are likely to have their own high-temperature testing facilities. As a result, there appears to have been little application of prior knowledge to the design of test equipment and much of the effort went to learning to test rather than into testing. The technical approach should perhaps have been reconsidered when only three US manufacturers expressed interest.

PI Response:

The intent of the open solicitation was to help find manufacturers of new components that show promise for operation in geothermal environments that Sandia researchers were perhaps unaware of. The aim is to assist these developers who are producing important parts for a small target market. There are few manufacturers that operate in the described space. Manufacturers can provide samples if they choose but most components evaluated in this program are purchased. The manufacturers that supply samples for 3rd party testing are generally enthusiastic participants because they are benefitted by the evaluations performed in this program.

Reviewer 23433

Score: 4.0

Comment: The justification for carrying out long term tests on electronic components for the geothermal industry is understood. However, the reviewer did not find a clear explanation as to why the components that are being tested are of the most importance to the geothermal industry. Are other components equally, more or less deserving? Are some of the components of sufficient interest to, for example, the military or aerospace industries that they will be tested elsewhere? Otherwise, the test program itself appears well thought out, and capable of giving useful results. However, as noted above, the maximum result that is likely to be achieved is the certification of some components to a particular time at temperature and/or pressure. Components with novel performance will not be developed

PI Response:

The reviewer makes an important point that is reflected in other comments as well. Identification of which components are most critical to enhance development of more robust high-temperature tools for subsurface accesss and monitoring is paramount for maximizing the impact of this project. This reasoning is why the early stage of this project had significant focus on communication with component and tool developers and on the development of test facilities for evaluating component families that have been identified. Exact component needs are of course dependent on the specifics of the system being designed but there are consistent barriers to development on which the next year of this project will focus. Key limitations for extreme temperature downhole instrumentation packages include computation devices (FPGAs, microcontrollers, DSP), memory devices (RAM, Flash, etc.), power electronics (converters, regulators), and signal conditioning devices (ADCs, amplifiers, capacitors). While this program is not funded at a level commensurate with testing all devices that fall in these categories, the extreme temperature component industry is small enough that this program can evaluate a significant subset. Part of the difficulty for geothermal tool designers is that the market is so small that component manufacturers often do not target geothermal temperatures. The manufacturers often decide to underrate their components to improve reliability for O&G or automotive industry applications even if the part they developed is capable of operation in more extreme environments. The reviewer is correct that the goals of this project do not include direct development of new components. Developers of new components that are designed for operation at extreme geothermal temperatures and that fall into the identified needed component categories are assisted by this program through independent evaluation and exposure.

Reviewer 24895

Score: 9.0

Comment: The test methods allow comparing multiple vendors' products for thermal reliability, allowing reliability versus cost comparisons. Protocols have been developed that will allow testing of new products when they are developed.

PI Response:

Reviewer 23567

Score: 6.0

Comment: This project has a direct approach for down-selecting several components, testing them at different temperatures up to 300C and evaluating their temperature stability and reliability. Components list first narrowed down and then tested at temperature. It is understood that availability of parts is not extensive as only few of them can be qualified as high temperature, however it is not clear what metrics PI suggests to use as a success criteria. The down-selection of vendors and parts type is also not clearly justified.

PI Response:

Please see responses to Reviewer 23433 and Reviewer 23401 comments above.

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: The researchers are clearly talented and diligent, and their results are well-described in their report.

PI Response:

Reviewer 23433

Score: Not scored

Comment: The proposed scheme of work appears well thought out, and capable of giving useful results.

PI Response:

Reviewer 24895

Score: Not scored

Comment: The test methods provide immediate benefit to the industry as an enabling technology for development of needed electronic tools that can survive higher temperatures. If nothing meets the needs in a particular component, that could be used to focus DOE research on fundamental, but unavailable high temperature components or seed fund commercial development in that area.

PI Response:

Reviewer 23567

Score: Not scored

Comment: Few types of capacitors are compared and tested at high temperature – this helps to compare some capacitor technologies and identify most robust one.

PI Response:

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: The small size of the testing facility and the possible reinvention of testing equipment prevented the team from achieving results on a statistically or commercially significant scale.

PI Response:

It is true that not all components can be tested in large quantities. With this necessary limitation in this program, the scope must focus enhancing development of new components and maintaining statistical significance in evaluations of commercial components where relevant and possible..

Reviewer 23433

Score: Not scored

Comment: The selection of components to be tested arose as the result of advertising the intention of Sandia to start the testing program, and candidates were apparently selected based on the responses of various suppliers. No doubt the proposers evaluated the items proposed to be tested, but it is not clear to what extent the selected components represent the most critical items for the future development of geothermal instrumentation. In short, was the selection based on determining those components most needing improvement, or was it based on the range of items proposed by the suppliers? The reviewer is unable to decide whether the range of items selected corresponds to those that are most critical to the geothermal industry

PI Response:

Please see the above responses to Reviewer 23433 and Reviewer 23401.
Reviewer 24895

Score: Not scored

Comment: The project depends on the manufacturer's willingness to supply their equipment for 3rd party testing.

PI Response:

Please see the above response to reviewer 23401.

Reviewer 23567

Score: Not scored

Comment: Only few components have selected for testing, it would be great to see a larger selection. Solid metrics for ranking components and recommendations may be useful to implement unless project has the goal to generating the data in the extended temperature range to complement manufacturer's datasheets.

PI Response:

Please see the response to Reviewer 23433.

IMPROVEMENTS

Reviewer 23401

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23433

Comment: The proposal would benefit from a clear statement of why the particular items selected for test are the most critical to the development of the geothermal industry. They should be justified in terms of the number of components likely to be used, or, for example, by allowing an increase in the temperature capability of a component that is particularly sensitive to high temperature and/or vibration. The evaluation and certification to higher performance of one component that is currently deficient and that thereby denies the use of a complete system would be of particular interest.

PI Response:

This is useful feedback. For further expansion, please see the above response to Reviewer 23433.

Reviewer 24895

Comment: May need a more focused way of interfacing with manufactures that may have components worth testing

PI Response:

This is a good suggestion. Please see above responses.

Reviewer 23567

Comment: Increase number of samples per tested component type. It is understood that the project has limitation on how many parts can be tested and doesn't have the goal for full statistical approach or complete qualification, but some data on the frequency of failures and potential failure mechanisms would help implementing screening or burn-in methods if possible.

PI Response:

This is a good suggestion. Resources dictate the number of samples that can be evaluated.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Testing and Calibration of HT Wide-bandwidth Seismic Sensors for EGS Applications and Collaboration with IPGT Program
Principal Investigator: Majer, Ernest L.
Organization: LBNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 6.0

Comment: The work described consists principally of gathering public information from a variety of industry sources. The reporting seems to consist mostly of general remarks by the PI on the qualitative merits of the different systems. While the eminence of the PI gives value to his opinions, more quantitative rigor is required to make the information actionable.

PI Response:

Yes, I agree, but due to the fact that no proprietary data were allowed we could not get into the details

Reviewer 23433

Score: 8.0

Comment: This is a very interesting project, with a very wide ranging objective. In short, it is to survey all available and potential wide bandwidth seismic sensors with a view to selecting those that may be suitable for geothermal applications. As the proposers point out, however, there are many different applications for such sensors in the geothermal field, depending on required frequency range, temperature capability and so on. It is thus a major task to identify and classify what sensors are available, not only in terms of their seismic performance, but also in terms of resistance to temperature and pressure, availability and their history of success in the field. To do this is clearly a desirable activity as it will guide current and future research and field application. The project is of fairly modest scope, and so far it has been barely possible to sketch out the range of the enquiry. However, the results presented so far indicate that this activity is off to a good start. It should also be noted that the results of the survey may well have applications in fields other than geothermal, including, for example, studies of natural and induced earthquakes.

PI Response:

Reviewer 24895

Score: 6.0

Comment: Project was to compare electronic systems (conventional geophones), with the possibility of leveraging Japanese technology (electronic), but concluded that fiber optic systems were better, so no leveraging was possible.

Others in the US had reached similar conclusions (Project GTP150023, but that project was driven by someone selling the system while this review was from the standpoint of a user.

PI Response:

Reviewer 23567

Score: 6.0

Comment: This project is comparing several seismic sensor array technologies and identifies fiber optics based technology as most promising for use in geothermal systems. The outcome in the form of summary identifying fiber optic system as most viable candidate is not a surprise and rather a usual suspect as fiber based technology has most of attributes to meet complex requirements and temperature capability to operate in geothermal wells. It is quite expected that the rest of technologies fail by much compare to fiber optics due to limitations of electronic components.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 5.0

Comment: The PI's presentation did not address many of the specific activities promised in the SOW provided to the reviewers. For example, this reviewer did not see the Japanese contributions to analysis, or any comparative testing. It appeared that all the data in the presentation came from papers by others at the SEG annual meeting. It was unclear why the Bench Testing and Field Testing tasks in the SOW were not reported or underway.

PI Response:

Yes that is true, due to the limited budget of this project (50 K total) we had to rely on other to test. WE did do some bench testing on the Lumedyne and USSI sensors, however, the proof is the field testing. The Conoco –Phillips test was a multimillion test and provided valuable data and it was not biased by any manufacturer.

Reviewer 23433

Score: 7.0

Comment: The approach so far is to cast as wide a net as possible over all available technologies to get a first look at as broad a range as possible. This seems to be a sound approach since the project is of limited scope and is not at a point where large resources can be devoted to evaluating one particular technique in depth. As the proposers state, "an effective seismic imaging and monitoring program cannot be described by 'one size fits all' ." Collaboration with the Japanese is noted as an advantage since they have expertise in electronic devices and data transmission whilst the DOE is more concentrated on fiber optics. As time goes on, it may be expected that a further development of the project will be able to select those approaches that are best suited to particular applications.

PI Response:

Reviewer 24895

Score: 5.0

Comment: Unclear if/how temperature evaluations or comparisons are being made. It is unclear how the performance is being assessed and compared. It appears to rely on manufacturer's data rather than independent testing at time and temperature, but it does provide verification or confirmation from someone who is a user rather than a vendor.

PI Response:

At the time of the presentation these data were not available , but now they are for the USSI system and it performed as advertised , the other systems have not been tested yet, but hopefully they will be in the near future (the limited budget of this project (50k) does not allow independent testing of many different systems

Reviewer 23567

Score: 7.0

Comment: The approach focuses on outlining key attributes and technical needs for recording and monitoring seismic data. The strength of the project is in the angle at which seismic sensors evaluation was conducted – this was done from the point of view of the system user rather than promoting technology or having a goal for tool development. Such an independent approach generates fair comparison and outlook at what is realistically available for deployment now and potentially can become a near term solution.

PI Response:

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: PI is clearly well versed in the technologies available and the vendors offering them.

PI Response:

<u>Reviewer 23433</u>

Score: Not scored

Comment: A particular strength of the project is that, from an early stage, a very wide net has been spread to bring in evaluations of as many techniques as possible. These include, importantly, information from the oil and gas sector, where, although high temperature capability is not yet well developed, there have been extensive advances in data processing and the understanding of underground features.

PI Response:

<u>Reviewer 24895</u>

Score: Not scored

Comment: Good team, with the possibility of leveraging Japanese technology

PI Response:

<u>Reviewer 23567</u>

Score: Not scored

Comment: Project does generate a good understanding of what could be applied for use in FORGE project, which is calling for a temperature range at the lower end of EGS systems – 175-220C.

PI Response:

WEAKNESSES

<u>Reviewer 23401</u>

Score: Not scored

Comment: The title of the project seems to be a misnomer, as neither testing nor calibration were reported. There was a vague reference to testing at The Geysers later in 2015, but no specifics and the summary indicates no funding set aside for it.

PI Response:

<u>Reviewer 23433</u>

Score: Not scored

Comment: A possible weakness in the proposal is that, faced with an avalanche of information on different types of sensor and interpretation method, it will not be possible to see the wood for the trees. it is possible also that the proposers will be faced with continuously advancing developments in the different fields, so that the correct identification of desirable technologies will become a moving target, with the optimum choice of data acquisition and interpretation methods changing on a frequent basis. The proposers do, however, have a long history of involvement in the field, so they can probably be relied on to maintain a balanced view.

PI Response:

Reviewer 24895

Score: Not scored

Comment: Project success probably depended on leveraging Japanese technology. When the project decided the Japanese technology should not be used, as fiber optic technology was better, the project investigated capabilities of the fiber optic technology and other alternatives, but did not seem to be very well constrained or focused.

PI Response:

Reviewer 23567

Score: Not scored

Comment: It is not clear if a feedback from the test was provided to actively stimulate tested tool designers/manufacturers with the goal to improve designs and expand operating temperature range. It is clear that most tested tools are not capable to operate even at the lower end of EGS temperature range

PI Response:

IMPROVEMENTS

Reviewer 23401

Comment: The testing and calibration described in the SOW are needed and should be a priority for completion.

PI Response:

Reviewer 23433

Comment: In view of what has been written above, it may be desirable to have early reports on progress. A particular objective would be to get an overview of the different industry sectors and their possible areas of contribution, and to have that overview contrasted with an appraisal of the requirements in different styles of geothermal well. The objective here would then be to see if there is a match between capabilities being developed in a particular industry and the requirements of a particular type of geothermal well.

PI Response:

Reviewer 24895

Comment: It may have been better to start over with a cleaner definition of goals and objectives when the fiber optic systems proved to be superior and the joint work with the Japanese was no longer the target.

PI Response:

Reviewer 23567

Comment: There is a discussion started by the PI on the key attributes and technical needs required for seismic sensor high temperature instrumentation and affordability mentioned as one of them. As there are only few systems actually exist which can potentially go to temperatures above 200C, the affordability by geothermal budgets is likely to be most important attribute for successful deployment. The back-of-the-envelope estimates and initial costs discussion would benefit complete understanding to map the available technologies and complete gaps analysis. What would be most likely scenarios for using sensor seismic systems in geothermal applications? What are the estimates for typical associated costs, margins and how much of the geothermal budget will be needed to guarantee technology effectiveness and feasibility of acquiring meaningful data? It seems that low cost options will not deliver required performance and reliability, so does more expensive option is a viable alternative?

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: GO18185
Project: Well Monitoring Systems for EGS
Principal Investigator: Norman, Randy
Organization: Perma Works
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 9.0

Comment: The accomplishment of 290 C capability for real time monitoring of downhole conditions is substantial and highly significant. Getting the results out of the shop into the market is also an unusual and highly commendable accomplishment.

PI Response:

Reviewer 23433

Score: 7.0

Comment: This project has many threads, some of which have been more successful than others. The overall objective, to develop a 300 C, 40 Kpsi logging tool was not successful, but a tool with reduced pressure capability, to 30 Kpsi was successful and has been released commercially. The reduction in pressure capability does not appear to be a significant disadvantage, so this may be counted as a success. Other threads in the project, for example, the development of a high temperature solder, and a sodium - sulfur battery were not successful. Work on the solder continues, but no further work is planned for the sodium-sulfur battery. It is not clear how these setbacks will impact the overall development of the project. How all the various threads come together is not entirely clear. The proposers state that they have a good solution for the solder problem to 290 C and some ideas for a 300 C solder. Does this affect the performance of the claimed 300 C 30 Kpsi logging tool? The reviewer is pleased to note progress in many of the threads in the program, but is not clear how they affect the overall success of the entire project

PI Response:

Reviewer 24895

Score: 10.0

Comment: There were a few setbacks, such as the batteries, but mostly great progress producing tools that met the goals, with additional capability identified, such as the 300C cable. Solid state flow sensor is a great addition, but would benefit from getting the temperature up to 300C. Making the developments available to all should decrease the cycle time to getting tools into the field, which will improve the performance of both EGS and conventional geothermal. Field testing will hopefully confirm the performance, so it would be good to see more field test data.

PI Response:

Reviewer 23567

Score: 10.0

Comment: EGS well monitoring during stimulation and production phases is very important and crucial for geothermal industry. This project addresses down selection of existing high temperature capable solutions and components suitable for building high temperature measurement system. It also provides solution for integrating these components and high temperature electronics into a usable and practical downhole tool. This project is a good example where a methodical search and evaluation of cutting edge high temperature electronics drives additional innovation. PI carries valuable activity for stimulating supply chain as well as subcontracting for a promising research to enable novel technologies and extend their operating temperatures to be more relevant for use in geothermal systems. Major goals and operating temperature capability up to 250C – 300C were demonstrated for most components.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 8.0

Comment: The technical approach was successful in accomplishing a high percentage of the program goals, the only notable exception being the battery component. The strongest evidence of a satisfactory approach with adequate rigor is the commercialization of several resulting products.

PI Response:

Reviewer 23433

Score: 5.0

Comment: The scientific / technical approach is complicated as it is not entirely clear how the various threads of the program come together, and how important it is if one or other is successful or fails. Evidently, numerous aspects of technology have to be solved in order to build a high temperature well monitoring system, but it is not clear which are more critical than others. Perhaps the project proposal and/or progress report should indicate how the various threads come together and the relative importance of each element. For example, the failure to develop a high temperature sodium-sulfur battery does not appear to have prevented the deployment of the 300 C 30 kpsi monitoring tool. Does this represent one level of success in a range of possible desirable outcomes? Overall, some aspects of the program have clearly been very successful, for example the development of crystal clocks capable of operating at 300 C, while others, for example, the development of a high temperature solder, have been less so. The reviewer finds it difficult then to assign an overall level of success to the project and to the quality of the planning, execution and management.

PI Response:

Reviewer 24895

Score: 8.0

Comment: This project used an interesting approach of incentivizing existing manufactures to produce tools for geothermal. It appears the methodology has been very successful in incentivizing the development of higher temperature capabilities.

PI Response:

Reviewer 23567

Score: 9.0

Comment: The technical approach selected by PI is very sound and aimed at achieving measureable and realistic results. As many selected component selected already exist, it is aimed and delivering the final result. In the outcome many little things were taken into account with a great level of detail for demonstrating complex technology. The scope of the project is well thought though and goals are verified in collaboration with geothermal developers.

PI Response:

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: The project objectives correctly identified high-impact targets for R&D and the execution of the project maintained focus on those objectives.
"...an engineering project, not a science one..." is a good description.

The magnetic flowmeter, in particular, addresses a problem that has plagued field testing for a century. The project brought development to a level upon which follow-up development can be based with low risk.

PI Response:

Reviewer 23433

Score: Not scored

Comment: The strength of the project appears to reside in a multi - thread approach to the problem, insofar as developments in one thread may contribute to the overall success of the project, and success in any of these areas may also contribute to other projects outside the scope of the present project. Further, failure of a particular aspect is not necessarily fatal to the project as a whole.

PI Response:

Reviewer 24895

Score: Not scored

Comment: Leveraged the existing technology to produce tools for geothermal temperatures

PI Response:

Reviewer 23567

Score: Not scored

Comment: Very goal and deliverable oriented projects with high potential to produce practical and usable high temperature downhole tool technology. Current working prototype of the developed high temperature system is now available from Permaworks. A large number of high temperature components are being addressed as building blocks integrated into a high temperature platform, which can be redesigned in the future and improved when updated components available.

PI Response:

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: The project seems to have suffered from lack of test sites that could have been provided by geothermal operators. A stronger outreach effort facilitated by some sponsor matchmaking might be necessary to alleviate this weakness in the future.

The lack of commercial interest in the flowmeter is unfortunate, most likely due to a lack of understanding. Mechanical flowmeters have a high failure rate and poor resolution in the field, so the magmeter should represent a major advance. Somehow that wasn't adequately conveyed, or fell on deaf ears.

PI Response:

Reviewer 23433

Score: Not scored

Comment: A weakness in the project, that may or may not be real, is that it is not clear to the reviewer how the different elements are interlinked. Clearly the development of high pressure, high temperature tools depend on the development of a number of technical solutions (cables, solder, batteries, sensors ...), but it is not clear how important each element is. The reviewer would find it useful to learn how important each aspect is, and whether progress has been made in the most critical areas. Without this assessment, the reviewer tends to see the project as a shotgun approach to solving several problems that may or may not be critically linked.

PI Response:

Reviewer 24895

Score: Not scored

Comment: Unclear how the temperature performance has been verified. Field testing at temperatures approaching the limits will be necessary to vet the claims.

PI Response:

Reviewer 23567

Score: Not scored

Comment: Battery and LED output technologies were no clearly stated to be usable at 250C - 300C range and were indicated as need to be explored further.

PI Response:

IMPROVEMENTS

Reviewer 23401

Comment: Field demonstration of the prototype flowmeter was a step too far for this project's time and budget. Accomplishment of that would have been a crowning achievement and remains a highly desirable objective.

PI Response:

Reviewer 23433

Comment: The most useful addition to this project would be a clear statement of how the various project elements are linked. To be desired would be some sort of flow chart that shows how each development affects the probability of success of the other elements. Evidently partial successes would lead to useful innovations, even though the most ambitious objectives are not achieved. This would lead to a much clearer evaluation of what has been achieved, and what more could be done in the future.

PI Response:

Reviewer 24895

Comment: No comment

PI Response:

Reviewer 23567

Comment: Incorporate other sensors beyond temperature, pressure and flow to continue increasing tool complexity and continue on building overall value to a higher level.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005509
Project: Development of a 300°C, 200 level, 3C Fiber Optic Downhole Seismic Receiver Array for Surveying and Monitoring of Geothermal Reservoirs
Principal Investigator: Paulsson, Dr. Bjorn
Organization: Paulsson, Inc.
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23401

Score: 9.0

Comment: The 3-component seismic array is one of the few tools to emerge from R&D that is capable of revolutionizing our understanding of reservoir structures. The mathematics of analysis has not yet progressed to exploit this tool's potential, and is beyond the scope of this project. When someone with access to a supercomputer does advance the processing technology, this system has the potential to replace most of the present geophysical tools for in-field reservoir visualization.

Field testing will resolve questions about sensor cable life and present a fresh set of R&D problems.

PI Response:

Reviewer 23433

Score: 9.0

Comment: The ability to develop a detailed view of the subsurface of a geothermal reservoir is clearly of great importance. Of particular interest is to be able to detect seismic events that result from hydraulic fracturing or other stimulation methods. Seismic imaging offers the possibility of doing this, in three dimensions and in real time. The project under review is one that has had a long history of development; it is now at a stage where most of the technical problems appear to have been solved, and the next, and critical, step is to carry out a field test. The proposers state that the various components of their array - in particular the sensors and the fiber-optic cable - have been tested extensively under conditions of high temperature and high pressure. The probability of success in the field test must therefore be considered to be high. The reviewer therefore considers that the project has considerable merit, since it should not take much more effort to see if the system operates correctly in a field environment.

PI Response:

Reviewer 24895

Score: 9.0

Comment: The fiber optic system has been completed, tested and is ready for field testing. Timing has been delayed, but having a system ready for field test is a great accomplishment. The plan is to test at the Geysers, which will provide a seismically active test. The field test will show if the system can meet the goals in a real life situation.

PI Response:

Reviewer 23567

Score: 9.0

Comment: The ability to detect seismic events at conditions of a geothermal well is a critical capability. The project team has made significant advances in the design, fabrication and deployment for test of the optical fiber seismic system. 16 level 3C system completed in Q1 2015 and basic capability/feasibility demonstrated. Some tests completed at temperatures up to 350C. Future commercialization plan and approach for moving this system to market is clear as Paulsson will continue development and improvements of the tool with interest to offer 300C rated borehole seismic measurement services.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23401

Score: 10.0

Comment: Commendable approach resulted in three critical elements: [a] manageable tool diameter, [b] a working 4.5 km test array, [c] a field test agreement.

PI Response:

Reviewer 23433

Score: 8.0

Comment: The proposal has considerable technical merit. The use of seismic techniques for imaging the subsurface has advanced enormously over the last few years, as witnessed by the progress that has been made in the petroleum industry. It is therefore appropriate to try to extend their use into the geothermal area. Once the seismic data have been obtained, all the techniques that are currently available to the petroleum industry should be applicable to geothermal reservoirs. The only question is that of obtaining the required seismic data. The problem is that the current range of sensors in not capable of operating in the high temperature high pressure environment of a geothermal well. The proposers have now developed the sensors and transmission system that appears capable of doing this job. If their system can be demonstrated to work in the geothermal environment, then it will be possible immediately to bring to the geothermal industry the advanced seismic techniques that have been developed in the petroleum sector. This would represent a very large advance and the possibility to transfer a large quantity of capability to the industry without additional development work being required.

PI Response:

Reviewer 24895

Score: 9.0

Comment: Components were developed and laboratory tested and then low temperature tested in a well for performance. The field test at moderate temperature (Geysers) is pending.

PI Response:

Reviewer 23567

Score: 9.0

Comment: Darkening of optical fibers in hydrogen is correctly addressed by PI, seismic sensing system approach is utilizing Ge doped fiber to slow down unwanted effects as well as pure Si core fibers are also on the list for investigating trade-offs for cost/performance. Fiber optic sensing technology seems to offer superior temperature capability and extend operating temperature range by at least 100 degrees over currently available electronic based solutions. Such extended capability has a lot of promise for realizing ultra-long borehole receiver arrays for use in deep geothermal wells. The approach overall is correct and all aspects of mechanical and packaging system components are well addressed. Although the cost of fabricating fiber-bragg gratings is not low, the system price will be comparable to the cost of a high end system.

PI Response:

STRENGTHS

Reviewer 23401

Score: Not scored

Comment: Potential impact of the tool on useful data acquisition is high. Construction of a test tool makes further progress likely.

PI Response:

Reviewer 23433

Score: Not scored

Comment: The major strength of this proposal is that it appears that the bulk of the development work has been done. All that appears to be necessary is to carry out the critical field test of the complete system. Work carried out so far seems to indicate that the required development of the different components has been achieved successfully. Further, the new type of sensor to be used appears about a hundred times more sensitive than the geophones used at present. This would appear to indicate a high probability of success.

PI Response:

Reviewer 24895

Score: Not scored

Comment: Persevered to get the system completed

PI Response:

Reviewer 23567

Score: Not scored

Comment: Correct choice of fiber optic technology for high temperature downhole seismic measurements and multiple options for clamping the sensor array inside the well will make the tool available and useful in many seismic sensing applications.

PI Response:

WEAKNESSES

Reviewer 23401

Score: Not scored

Comment: Presentation slides were entirely too text-intensive for effective communication.
It is unclear whether fiber darkening will limit sensor life to the point of being a major economic factor.

PI Response:

Reviewer 23433

Score: Not scored

Comment: No weaknesses noted

PI Response:

Reviewer 24895

Score: Not scored

Comment: Yet to be determined

PI Response:

Reviewer 23567

Score: Not scored

Comment: One potential weakness could be in the final cost of the developed tool services and affordability for use in geothermal wells. It may not be clear at the moment, but will have to be addressed in the future to identify optimal tool construction tailored to be most efficient for geothermal use.

PI Response:

IMPROVEMENTS

Reviewer 23401

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23433

Comment: None noted

PI Response:

Reviewer 24895

Comment: Look for a field test at 300C in a liquid dominated reservoir to fully test the capability of the system (Geysers is ~230C and low pressure)

PI Response:

Reviewer 23567

Comment: The report on the project discusses results of the lab-scale tap test and seismic data recorded in the field test in comparison with the standard geophone. It would be important to expand testing to evaluate fiber optic seismic sensor technology reliability and stability in the long term tests. These experiments should address potential gaps of the technology, identify challenges to overcome and provide solutions to extend operational time and temperature range further. The additional goal of this test may be also aimed at evaluating fiber optic cable system and connections reliability.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: High Temperature Downhole Motor
Principal Investigator: Raymond, David
Organization: SNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23465

Score: 7.0

Comment: Overall this is a reasonably good project with a strong likelihood of success and completion at the demonstration scale. It is too early to tell if the geothermal drilling industry will benefit and adopt this type of drilling motor. Intuitively, it appears that there are too many moving parts and those only increases the probability of failure. It may be that this type of high temperature motor may not get past the demonstration stage but further demonstrations, testing and refinements will be needed at an actual geothermal field site to determine market worthiness. That said, it is this Peer Reviewer's opinion that it is a concept that is worth continued DOE funding.

If the development of this type of high temperature linear motor is successful, it may provide an alternative to present day use of positive displacement motors (PDM). It is way too early to tell if these types of motors can compete with PDMs on a performance basis including torque and cost. While the PI asserts that concept modeling designs indicate competitive performance against PDMs, this Reviewer will maintain a neutral position until actual field data is provided.

The purpose of this project is to develop a high temperature downhole linear piston motor that can operate on drilling fluid or compressed air for drilling in high temperature and with the ability to perform in high strength formations. The critical component, at least for FY15, is the development and demonstration of a prototype power section. Other actions involve water-based drilling fluid testing and testing the power section on a dynamometer.

The presentation itself identified the projected accomplishments, results and progress. The project appears to be on track in achieving the technical goals/targets and objectives. The level of productivity with respect to the accomplishments is on schedule. Given the project's track record of meeting target development goals on time it is reasonable to assume that the accomplishments in comparison to costs are attainable. The achievements against planned goals and objectives, technical targets have been met.

PI Response:

PI concurs that this is a project worthy of DOE funding to explore candidacy of the concept for geothermal drilling. The concept does not have a great deal of moving parts - only the rotor and pistons. The piston motor concept offers significant advantages over conventional motors that make it worthy of evaluation.

Reviewer 23527

Score: 7.0

Comment: The focus of this project, the development of a high temperature downhole motor, is important to the mission of the Geothermal office. The use of directional drilling has enabled the economical development of unconventional oil & gas plays such as shale gas and heavy oil and is likely to be crucial to the development of EGS. There are some commercial drilling technologies able to operate at temperatures below 300 degrees C. For example, Halliburton advertises a 300 degree C "Sperry Turbopower" turbine drilling motor. However these motors are typically only suitable for impreg bits because of their high rotational speed. These motor/bit combinations have also been extensively utilized and they do not appear to meet the Geothermal Office's drilling goals. As another example, Schlumberger has published a case study of a directional turbodrill/impreg bit combination in granite with an average ROP of only 6.9 ft/hr. There are numerous other published 'records' of impreg bit performance in hard formations with ROPs in the 10 - 15 ft/hr range. These are low indicating a need for better technologies.

Concerning progress to date, this project has achieved reasonably good results. The detailed analysis of drilling requirements is excellent and critical for understanding the performance basis for the developed technology. The PI has excellent understanding of drilling mechanics. The project team is also building on prior experience to develop the adaptations required for high temperature operations. The rotating metal on metal interfaces are of particular concern to the reviewer. Details of the rotor assembly were not provided, but it does state in the presentation that there is 'alternating pressure on piston lands for reciprocation'. This is generally not desirable and there should be effort made early in the project to evaluate wear rate of coatings replacing lubricants in representative conditions to confirm that this is a viable approach. The modeling and initial characterization work performed to date has been useful. The test stand in particular should provide a necessary platform for evaluating component performance.

PI Response:

Conventional turbine motor product offerings do not meet geothermal drilling requirements and a new high temperature solution may provide a pathway to access geothermal reserves more effectively. The project plan calls for addressing the direct metal component part interfaces via selective coatings and evaluating their performance under representative operating conditions. The test fixtures developed to date will enable these evaluations.

Reviewer 23537

Score: 9.0

Comment: Project appears to be tracking reasonably well per proposed time lines. A functional prototype motor concept was developed including designs/concepts for hydraulic fluids and high pressure/high T compounds.

Drilling is an extremely costly and therefore limiting factor in the exploration for and ongoing development of geothermal systems. If/when EGS technology becomes technically and economically sustainable, high T mud motors will serve a valuable tool because of the possible need for multiple, deviated laterals drilled in hot rock.

Quality: Designs as outlined in the provided text and presentation material appeared rigorous and take into account the conditions that limit existing directional drive motors.

Productivity: Again, the project appears to be tracking with proposed timelines and interim goals.

PI Response:

High temperature mud motors will be a valuable tool to enable geothermal directional drilling. The piston motor concept under development will address the limitations of existing motor technologies.

Reviewer 23433

Score: 10.0

Comment: The development of a down-hole motor for geothermal applications is an extremely important task. Until the present, no down-hole motor has been available. Turbine motors cannot operate at the required low speeds, and PDM motors (relying on polymer-lined stator sections) cannot stand the high temperatures of geothermal wells. The new approach, based on a swashplate type motor concept, is novel and appears to have considerable promise, in particular as it represents a new departure in downhole motor design. Current work on the design concept builds on existing swashplate motor and pump designs. This is good, as there is much information and experience available. Critical issues concern the selection of suitable materials for the motor components, in particular concerning the abrasion resistance of sliding components (pistons and cylinders) under high temperatures in more-or-less abrasive drilling muds. The proposers are clearly aware of the issues involved and note that they are paying close attention to existing designs of, for example, mud pumps. The reviewer believes that the development of a low-temperature swashplate motor is fairly certain, although geometrical constraints of packing the motor into a restricted diameter may prove tricky. High temperature operation, mainly governed by the correct selection of suitable materials, looks likely. Good and logical progress has been made in design, materials selection and the building of a suitable test loop, although tests are still to be carried out. A further objective of the program is for the motor to be able to function in gas-driven mode. Little progress has been made in this area so far (priority having been given to the mud driven option, which is as it should be). This appears to be a more risky task, in view of the higher sealing tolerances required. However, even if this task is not successful, the development of a mud-driven swashplate motor is a very desirable result in any case.

PI Response:

PI concurs that presently available downhole motors are limited and a new approach can offer considerable promise. The piston motor concept is building upon lessons learned with industrial swashplate type motors. Proof of concept demonstration is initially focused upon a functional demonstration using hydraulic fluids in the geometric form factor limitations of a downhole tool. Critical issues concerning the selection of appropriate materials to demonstrate functionality on representative geothermal drilling fluids are concurrently being addressed within the prototype developments.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23465

Score: 7.0

Comment: The technical approach taken by the researchers is appropriate. They employed a reasonable and logical methodology to understand and attempt to address significant technical challenges that would be expected in designing critical power components for geothermal application. The technical tasks and deployment of those tasks are being executed in a practical manner. The procedures engaged are suitable for this type of product development.

PI Response:

Concur.

Reviewer 23527

Score: 7.0

Comment: The technical approach is well defined, logical and generally sequenced appropriately. The early definition of drilling performance requirements was thorough and forms a rational basis for ensuing tasks. Similarly, the conceptual design of a high temperature directional drilling motor was appropriate and seems to have been reasonably performed. Not much detail was given on the conceptual design task. There appears to have been some review and down-selection during this phase, but little information was provided to the reviewers. It would be interesting to know how many competing concepts the project considered and the criteria used in the down-selection. Modeling and analysis tasks are also appropriate. The general analysis of the dynamics of the motor performance is necessary to ensure that designs meet performance requirements. However, there does not appear to be analysis focus on stress based failure analysis at this point in the project. This would seem to be appropriate given that the proposed technology is adapted from conventional hydraulic pumping technology that does not typically operate in an environment where the support structure experiences significant dynamic loading, such as will be the case for a motor attached to a drill string with a drill bit. It is recommended that some basic stress based failure analysis be performed for the motor assembly. This may have already been done as it is noted in the challenges to date section of the project summary that there is a stress concentration in the harmonic drive. Any such effects will be exacerbated in a drilling environment.

The dynamometer test station under development is also needed for successful completion of the project. Performing testing in representative pressure and temperature conditions is critical for the development of the proposed technology. This appears to be on track and the companion flow system has been adequately specified. In general, the reviewer believes that the technical approach is sound. It is recommended that some small scale laboratory testing of proposed solutions that involve adaptation to high temperature be performed. For example, as mentioned in the first review section, concerns associated with low friction coating survivability in a high temperature environment could be mitigated with some basic experiments.

PI Response:

Motor concept evaluation and down-select are not addressed in the present work. The subject concept was presented to the DOE Geothermal Technologies Program as a viable alternative to current motor technologies.

Modeling and analysis is performed concurrent with motor development activities. Stress analysis is addressed concurrent with design activities to ensure prototype developments are competent for the anticipated operating conditions. PI concurs that operational drilling environment will be more severe; present developments relate to a proof of concept demonstration and critical function evaluation within the laboratory - details of stress analysis were not included in the Peer Review presentation.

Reviewer 23537

Score: 9.0

Comment: Development of high T motors for directional drilling, especially in high T/high P environments found in geothermal or EGS systems, is an appropriate and necessary R&D undertaking. Sandia has identified the problems and potential solutions required to fully realize the development of high T motors for these systems. The presentation and text provided to reviewers suggests that the protocols in place for the design, development and testing of such a motor has been well thought out.

PI Response:

Concur.

Reviewer 23433

Score: 9.0

Comment: The approach is well thought out. The reviewer particularly likes the fact that the proposers are paying good attention to what has been done previously in related fields. This includes the design and execution of high-pressure mud pumps and other devices, and the selection of suitable materials for high temperature operation in abrasive fluids. The reviewer also likes the combination of theoretical studies and the building of a suitable flow loop test facility. So far, it is too early to tell how well the project will develop in practice, but progress so far appears good. Current issues concerning the geometrical arrangement of the motor seem to be mostly related to the problems inherent in packing the required components into the restricted space of a down-hole motor. However, these problems do not appear insurmountable. In the worst case, they might be solved by reducing the desired output power of the motor.

PI Response:

Concept development is building upon success realized in related industries. Development is complemented by theoretical and experimental evaluations included in the technical approach. PI acknowledges challenges associated with developing a piston motor within geometrical constraints of a downhole tool. Design requirements have been established to ensure developments have reasonable performance to remain viable options for the geothermal drilling industry.

STRENGTHS

Reviewer 23465

Score: Not scored

Comment: Solid technical team credentials.

PI Response:

Thank you.

Reviewer 23527

Score: Not scored

Comment: The project team has deep expertise in drilling mechanics and equipment development. It also has experience with a variety of drilling technologies. It has also been claimed that the team is leveraging prior work as part of this effort. This knowledge base should help with a priori identification of many of the challenges associated with developing the proposed technology and mitigate some of risk.

PI Response:

Concur.

Reviewer 23537

Score: Not scored

Comment: Strong PI. Sandia has a history of providing strong project results in this area. Project has a long enough time line such that positive results can be expected.

PI Response:

While the project has had a long project time line, continued project funding must be sufficient to allow challenges associated with drilling tool development to be appropriately addressed.

Reviewer 23433

Score: Not scored

Comment: The project has two important strengths:

1. It offers the possibility of developing a new, third category of down-hole motor. viz. a swashplate motor to add to existing turbine and polymer stator positive displacement motors.

2. The approach leans heavily on the idea of learning from existing swashplate pump and motor designs. The proposers have well understood the particular additional requirements in the present case, i.e. resistance to abrasive muds and high temperature operation.

The reviewer also likes the combined theoretical and experimental testing program.

PI Response:

Concur.

WEAKNESSES

Reviewer 23465

Score: Not scored

Comment: The project information and presentation lacked specifics on how the power section functions. It is understandable that the PI wanted to keep this information vague and has pending patent applications. Just because someone has patent pending applications is not reason enough to, at minimum, provide a conceptual discussion on the mechanics of how the linear piston would work, specifically how the mechanical power transfer would occur. A reference was made that the linear pistons would work similar to a swash plate axial piston but no discussion or diagrams were provided to explain just how the mechanism would work. No problem in understanding that, this Reviewer is very familiar with axial piston motors, however, the PI should have provided additional information to make the connection. This type of information withholding precludes the opportunity to conduct a more precise technical review.

Perhaps this Reviewer should have asked more questions, but time was limited and there were other Reviewers that needed to ask other questions. In a short discussion, this Review had with the PI and another Peer Reviewer, the PI repeated what he had already presented and did not explain how the power section would operate.

Another important operational function that was not addressed by the project material or the PI is how would this linear motor operate in reverse if it stalls. Will the motor maintain its torque?

Compared to PDMs the proposed linear motor has many more moving parts, and as already mentioned, the higher probability of a component to fail.

For the FY15 scope of work objective no significant weakness can be readily determined, however this is not suggest any unforeseen events such as equipment failure or poor dynamometer test results. The later seems more unlikely given the well-defined technical approach and past project performance in meeting the scheduled milestones.

Looking into to future there are areas in which it is very likely where this project will have practical engineering limits. Below is a list of potential issues that may have been discussed but will need further consideration or explanation for the next phase of development:
1) Vibrations. This is real problem, especially in the development stage.
2) Stress concentrations. The PI mentioned this topic in the presentation but did not provide a discussion regarding the minimization of stress concentrations on key interfacing surfaces.
3) Misalignment. This is serious challenge that was mentioned in the Work Statement and will limit power section performance and cyclic life. Misalignments caused during the assembly or installation process will compromise overall system operations. Imbalances of equipment components during the manufacturing process or within the stator housing will result in uneven wear in load bearing components and limit cyclic life.
4) Number of linear piston subsections. The practical limit of the number of piston subsections will depend on minimizing misalignments, vibrations and natural harmonics caused by the sliding pistons and rotational forces.
5) Temperature. High temperatures in a geothermal well will affect the physical properties of the mechanical components.

PI Response:

PI acknowledges that the issues highlighted by the reviewer are valid concerns. These issues will be addressed in detail during the course of the project plan.

Reviewer 23527

Score: Not scored

Comment: The primary weakness of the project is not a weakness, per se, but difficulties related to the proposed technology. It appears to be mechanically complicated in comparison to other drilling technologies. This mechanical complexity introduces many challenges.

PI Response:

The concept is not necessarily more complex than competing downhole motor technologies. For example, predicting the operational performance of a multi-lobed PDM motor is complicated; manufacturing the rotor of a PDM requires precision machining equipment. Likewise, a mud turbine is a complex device that must be appropriately designed for operational performance. The subject piston motor concept is fundamentally simple in operation, yet requires thorough effort in design, development and testing to meet stated performance objectives. This complexity validates its consideration, evaluation and development by a National Laboratory.

<u>Reviewer 23537</u>

Score: Not scored

Comment: No obvious weakness on this project or with the team; however, reviewers are reliant on only data provided by PI in presentation and a few pages of text describing results. This is a weakness of the process.

PI Response:

No comment.

<u>Reviewer 23433</u>

Score: Not scored

Comment: A potential weakness is the possibility that the gas-driven option will not work. This is because of the much tighter tolerances that are required in a gas-driven motor. This issue has not yet been addressed so success or failure is not yet determined. However, the reviewer finds that even if this part of the project turns out to be unsuccessful, there is still strong merit in supporting the development of the mud motor.

There is a risk that friction and wear problems may arise with the sliding surfaces of the swashplate/piston contact areas. The project team are aware of this problem, but it remains to be seen whether it will be solved successfully.

PI Response:

The mud-driven motor option is the primary option to be beneficial to geothermal drilling and is given preferential treatment in expenditure of project resources for development. PI concurs that friction and wear are potential problems on contact surfaces; the project plan will rely upon operational testing using representative drilling fluids to evaluate these concerns.

IMPROVEMENTS

<u>Reviewer 23465</u>

Comment: Provide at a minimum a schematic diagram with an explanation on how the linear piston motor will transmit power to the rotational drill bit including directional fluid flows.

Identify the major motor manufacturing entity.

Identify subcontractors, and who is building what components.

PI Response:

The schematic diagram referenced by the reviewer exists yet was not included in the presentation. The project has not advanced to the field testing stage so a major motor manufacturing entity, or subcontractors to manufacturer the prototype, have not yet been identified.

Reviewer 23527

Comment: Perform high temperature component level testing earlier in project prior to prototype motor development.

PI Response:

As outlined in the project plan, the concept must first be validated as a low temperature downhole rotation solution. The challenge of this is evident as there are only two motor-types available to produce downhole rotation. A high temperature demonstration will follow once the concept it proven as a viable solution. Component material options exist to address high temperature operation. Motor performance may be downgraded at high temperature, but the principal challenge presently is in demonstrating functionality; migration to high temperature may compromise the motor performance envelope, but is not expected to invalidate operation as is the case with PDM motors. High temperature component material identification and testing will commence once the operational performance is better defined and understood.

Reviewer 23537

Comment: None.

Unfortunately I am not technically qualified enough to offer substantial improvements.

PI Response:

No comment.

Reviewer 23433

Comment: Some scoping work could be started to make a preliminary assessment of the problems and chances of success for the gas-driven option.

PI Response:

Referenced scoping work is underway.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Drilling Technologies Evaluation
Principal Investigator: Blankenship, Douglas
Organization: SNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 9.0

Comment: If the use of Mechanical Specific Energy (MSE) monitoring can be spread across the geothermal drilling industry, and if the 10% increased ROP is commonly achieved, this project will have had strong impact on the geothermal industry and on the long term GTO objective of lowering drilling costs. One cannot really call this work research, but rather adoption of a technique that has been used for quite some time in the petroleum industry. The beauty of this "innovation" (for the geothermal business) is that little new hardware or software is required. It is available from the petroleum industry and needs little or no modification to work in geothermal wells.

What is needed, and what has been available to SNL is collaboration with MSE-experienced drilling engineers who can teach willing geothermal testers just how to interpret the downhole measurements of ROP, rotation speed, WOB, and deviation so as to understand whether the parameter changes observed are due to whirl, drag, or a need to change out a BHA.

SNL had the full cooperation of Ormat and drilling engineers from Texas A&M University as well as the chief drilling engineer (retired) from Exxon so as to field test the monitoring of MSE. The results speak for themselves: at least 10% increased ROP when the signals received by the MSE monitored were recognized and the appropriate changes in procedures were made.

The positive results of this project do not mean that technological innovations in bits, muds, cements, etc. should not be attempted. It just shows that changes in learning and procedures can be very effective cost reducers!

PI Response:

Agreed with comments, but I point out that while the data was limited the increase in ROP was closer to 85% versus the 10% noted by the reviewer

Reviewer 23480

Score: 7.0

Comment: Project demonstrated substantial increase in ROP using MSE monitoring. MSE governs the drilling process in real-time, allowing for quick decisions to optimize the drilling process. In addition to real time response, MSE results should allow for learning curve improvements in the same geothermal field. MSE has made a difference in the oil patch, and should serve well in geothermal fields.

PI Response:

Agreed, however active monitoring of the drilling process through MSE management or other means should not necessarily be confused with the development of leaning curves. The basis behind the monitoring in this effort was to relate a measurement of performance (MSE) to the physics of what was occurring in real time and was not based on the history of a prior well.

Reviewer 25041

Score: 10.0

Comment: The PI identified that they were too focused on the evaluation of "gadgets" in the beginning but realized that improved "processes" were as important factor as improved mechanical devices. They gave a clear recommendation to the geothermal industry to actively monitor " Mechanical Specific Energy: MSE" and conducted the monitoring with a major company ORMAT. They showed a series data that indicate positive improvement on drilling efficiency because of that.

This project is probably one of the best executed projects among the ones I reviewed this time.

PI Response:

Thank you

Reviewer 23537

Score: 9.0

Comment: The objective of this work, to evaluate MSEs and other techniques used in allied extractive industries to improve technology transfer to the geothermal industry, has been accomplished to date. The presentation and text associated with it outlined the concept of MSE's and how assessing these real time drilling data against drilling rates (ROPs) could be an extremely valuable, drilling efficiency protocol.

Quality: Presentation of accomplishments was clear and suggests that project is progressing on track and on budget.

Productivity: As one of highest cost components of geothermal exploration and development is drilling, the implementation of MSEs as outlined in this presentation should help the GTO and therefore this industry achieve goals of lower production costs.

PI Response:

Agreed and thank you

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 9.0

Comment: This is not really a scientific project. It is a technical one and a very good and successful one at that. This approach used in this project included studies of various activities utilized in the petroleum, mining, and construction drilling businesses to identify one system that appeared to have a measurable positive effect on drilling progress and therefor on costs. The proponents were able to convince Ormat, the leading driller of geothermal wells in the USA (currently) to partner with them in order to quantify the effects of MSE monitoring. To do so, both SNL and Ormat personnel had to learn from MSE users in the petroleum business and they were able to do so by acquiring the expertise of drilling engineers at Texas A&M University and Exxon.

SNL was able to use MSE monitoring equipment obtained from current petroleum industry drillers and they installed it on an Ormat rig. This allowed both SNL and Ormat staff to learn how to interpret the readouts and to make adjustments in WOB, RPM, the BHA, stabilizers, etc. to optimize the ROP and minimize the MSE.

The whole project has been implemented remarkably well. Accordingly, Ormat now plans to use MSE monitoring on all rigs drilling for them internationally. The spread of the use of MSE in the US is likely to be slow because there are so few geothermal wells now being drilled here, but when enthusiasm returns, surely the use of MSE monitoring will become almost universally accepted.

PI Response:

Agreed and thank you

Reviewer 23480

Score: 7.0

Comment: Approach builds on experience from oil/gas drilling with demonstrations in real geothermal wells. MSE incorporates the major variables controlling the drilling process: WOB, rotation rate, and ROP. The intent is to minimize MSE while maximizing ROP. Project benefits from having a proactive industry partner (Ormat) and a team member from the oil industry.

PI Response:

Agreed

Reviewer 25041

Score: 9.0

Comment: Identifying MSE as something to be monitored by several geothermal projects by credible drilling companies and show the positive changes by actual data is a very good approach. The MSE monitoring allows the drillers to take a look at device efficiency as well as the efficiency of the processes.

Nicely done.

PI Response:

Agreed and thank you

Reviewer 23537

Score: 9.0

Comment: While the concept of MSEs as applied in O&G has apparently been in use for decades, the consideration of these drilling efficiency protocols for geothermal systems is highly appropriate.

Teaming with Ormat and then integrating these protocols into 2 Ormat wells drilled at McGinnis Hills was the most important part of this project as it took these MSE efficiency protocols and applied them to real drilling. Although reviewers are required to base all comments on the limited data presented, it appears that this relatively simple process may have significant applications to any other geothermal drilling program.

PI Response:

Agreed

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: The strength in this project is in the fact that nothing new had to be invented. Significant (~10%) ROP increases and cost reductions have been achieved at minimal expense and remarkably fast. Very capable SNL and partner staff worked on the project so further smooths the implementation of MSE monitoring in the field. Though there was and will continue to be a learning curve attached to the optimal use of MSE in wells of differing lithologies, temperature ranges, and deviation requirements, there is no new equipment to fail and require re-engineering or back-tracking to re-think a new concept. This is definitely a project strength.

It can only be hoped that the industry partner, Ormat will be open with the positive results of their work with MSE and attempt to convey this to other geothermal operators. It is recognized that ROP is not the only metric for decreasing drilling costs, but is an important one and the word about MSE should be spread ASAP.

PI Response:

Agreed and thank you. As noted above the reported ROP increase was about 85%, not the 10% noted (albeit the data is limited). I will again comment that while this may be an issue of terminology, making physics based decision from drilling measurements is not necessarily the same as the development of learning curves. Ormat from the beginning has committed to be open with the results from this work.

Reviewer 23480

Score: Not scored

Comment: The project includes the partnership of Ormat, a major geothermal developer/operator, and involvement of a senior research executive from Exxon-Mobil. Sandia has a 40+ year record of performance in geothermal drilling R&D. MSE has been shown to work in the oil patch. Changes in the downhole drilling environment tend to be amplified by MSE, making those changes more obvious to drilling personnel and thus correctable more quickly.

PI Response:

Agreed, but not sure I understand the last sentence.

Reviewer 25041

Score: Not scored

Comment: Clearly identified way to improve the drilling efficiency and they are proving that what they propose is working.
Self-contained and manageable execution of the project.

Very strong project.

PI Response:

Agreed and thank you.

Reviewer 23537

Score: Not scored

Comment: Strong PI. Strong teaming partners with Exxon's drilling expert as well as Ormat, which provided project beta test site. (It is also very encouraging to see that Ormat and DOE chose to make results of this publicly funded project completely transparent!) Relatively low cost operation that can add significantly to GTO's mission of decreasing production costs.

PI Response:

Agreed

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The only reason that this project was not scored a "10" was that there needs to be further field use of MSE with different bits, muds, and BHA combinations so as to develop comprehensive knowledge to pass on to prospective new MSE users in the future. Such further experiments are being planned by SNL and should definitely be funded if and when applications are made.

I cannot currently cite any other weaknesses in this project.

PI Response:

Agreed, implementation of advanced technologies (e.g., bits) is planned for this project if funded in the future.

Reviewer 23480

Score: Not scored

Comment: MSE is not a cure-all, which the PI points out. There remain many other issues affecting drilling costs which have to be investigated. The project is totally focused on MSE, and future work in other areas (e.g., casing) is not addressed. Too much emphasis seems to be placed on bit development/testing, a significant Sandia strength, but not likely the road to major cost reductions. The role of MSE vis a vis other active monitoring systems is not presented. Not clear how experience from the oil industry was collected or factored into this study. Beyond MSE, there isn't much evidence that experience from other industries in cost reductions has been incorporated. The project is scheduled to run until 2020; an overall development plan for the next five years is not presented.

PI Response:

I agree that MSE monitoring is not the "cure-all" but during discussions with our group we found this to be not only the low hanging fruit but the foundation for future implementation of advanced drilling technologies. While the reviewer correctly notes that the next steps will include advanced rock reduction systems I would argue that improvements in the “hole making” portion of well construction will result in major cost reductions – it is not the only area that needs to be addressed but it is one of the important areas to address if cost reductions are to be realized. Improvements in the drilling process can not only result in higher ROPs but can also result in superior well conditions and provide secondary benefits. For example, by controlling downhole vibrations one can drill wells that are closer to gage – gage wells not only reduce the cost of cementing but the mitigate issues associated with running casing. As the project progresses, issues of well construction beyond drilling (e.g., lost circulation, casing, …) will certainly be investigated.

Reviewer 25041

Score: Not scored

Comment: They know that adoption of new practices is difficult and requires commitment from the stakeholders.
The next big hurdle is to understand how to use what they learned from MSE to educate the stakeholders to improve the drilling efficiency at the industry scale.
This maybe beyond a scope of this project but they should be given an opportunity to work with somebody who can help them on this issue in the future so that their recommendation will have a true impact.

PI Response:

Agreed

Reviewer 23537

Score: Not scored

Comment: Although it may not be relevant, I do not recall hearing or reading about the consideration any drilling techniques or drilling efficiency measures from any other industries such as mining. Perhaps this was considered and not mentioned or perhaps I missed it when it was discussed.

PI Response:

We will be investigating options that are largely derived from mining. Plans exist to filed test down-the-hole-hammers, an area DOE has already made investments to harden for use in goethermal environments. This should have been conveyed during the presentation.

IMPROVEMENTS

Reviewer 23478

Comment: See text in the previous section "Weaknesses". I cannot now suggest any other improvements!

PI Response:

Noted

Reviewer 23480

Comment: Try to recruit other geothermal developers; contact other agencies and companies from industries with drilling interests. The next five years offers an opportunity to assemble a broad consortium of organizations with interests in reducing drilling costs. The intent should be to focus research resources on issues likely to produce the most benefit in the shortest time.

PI Response:

Agreed

Reviewer 25041

Comment: Maybe provide a list of what geothermal industry can borrow from oil/gas and mining and prioritize them if they can.

PI Response:

Good thought

Reviewer 23537

Comment: Ideally, I'd like to see these protocols instituted in more geothermal drilling programs. I'd only want to see this, however, if results of this work are also immediately daylighted to anyone with an interest in the results.

PI Response:

Agreed

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Multifunctional Corrosion-resistant Foamed Cement Composites
Principal Investigator: Sugama, Toshi
Organization: BNL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 9.0

Comment: As the low-hanging fruit type fields in the geothermal business are rapidly being found and developed, exploration and development the world over has turned to drilling deeper into ever more corrosive, higher pressure regions. These efforts have made it very important to invent cements that can function in these environments so as to seal off lost-circulation zones, support casings without corroding them, prevent casing corrosion by naturally occurring H2S and CO2 derived acids, and at the same time withstand thermal shocks and cyclical stresses and strains on the casing. All of this must be achieved in a cement that costs less than $0.20/pound for the raw material, is in a form that is readily available, and can be easily emplaced in the field.

Creation of just such a cementitious product is being addressed in this project. If successful, it will surely address the GTO objectives of facilitating hydrothermal exploration and development while lowering costs and have an impact of the geothermal industry at a time when depth/temperature/corrosiveness-related challenges are increasing internationally.

To date the two BNL project proponents have made impressive progress towards achievement of the objectives. So far, they have formulated and tested numerous versions of relatively high cost cements. They have achieved all of the target parameters with regard to strength, corrosion resistance, adherence to carbon steel casings, and pumpability. They have tried numerous additives to accomplish this and have identified the best formulae to accomplish their goals. Along the way, they have employed state-of-the-art instruments and technology to measure and record their results. Overall, the project is approximately 75% finished and should be completed by the end of 2017 on schedule.

PI Response:

The project team thanks the reviwer for these positive comments.

Reviewer 23480

Score: 8.0

Comment: This project has demonstrated substantial progress through the formulation and testing of thermally stress resistant cements. The cements have been augmented with hardening retardants for easier placement. Carbon fiber additives provide strength enhancement. Good adherence between the cement and carbon steel casing was achieved. And corrosion inhibitors were identified. Class F fly ash reduces the cost without sacrificing important physical properties. The progress is exceptional for the short period of performance. CaP cement has comparable qualities by some measures but not all. Overall, TSRC appears to have superior qualities. The new cement has the potential to overcome some major issues with geothermal cements including breakdown due to severe thermal cycles and inconsistent bonding to the casing. The cost effectiveness of TSRC remains to be demonstrated.

PI Response:

We thank the reviewer for positively commenting on work. Some of the more cost-effective formulations with the calcium-aluminate cement replaced by OPC were presented (thermal shock tests). We continue our work with OPC-activated fly ash F blends.

Reviewer 25041

Score: 7.0

Comment: This is a very scientific project that aims to develop cost effective multifunctional corrosion resistant formed cement composites for carbon steel-based casings.
Clear justifications are provided and methods well described. This project is moving forward well with all milestones met.

The project focuses on small scale laboratory testing and short term effect of the proposed high performance cementing material.

The reviewer points out two issues:
1. Experimental results based on a small laboratory scale experiments may experience challenges when the cement is actually used at the field scale cementing purposes, and
2. Also, repeated thermal cycles are going to be more extended and much more severe than what the project indicates.

The reviewer could not identify if the project has actually give some thoughts on the issues above. It seems that there is a large knowledge gap between the laboratory scale performance and the field scale performance.

PI Response:

1. Yes, the project team seriously thought about moving to larger scale tests of the cement formulations developed within the project. We planned to follow American Petroleum Institute (API) standards and recommendations for testing well cements. The standard in service companies cementing products development procedures were followed along with the scientific methods of materials testing. Specifically, API standard procedure (10B) was followed for the cement mixing in the laboratory of the retarded cement slurry that was further tested according to the API procedures in thickening time tests for evaluation of the cement setting time. The next step in the project is technology transfer to a Schlumberger service company, which will be further evaluating it with the standard API tests and a pilot test if necessary. The company expressed interest in the technology and a CRADA between BNL and Schlumberger was prepared.

2. The bulk cement was tested in cycles between 600°C heating and 25°C water quenching. The bond strength was tested in in 350°C heating -25°C water quenching since the steel undergoes distortion under higher temperatures and changes in bonding strength of cement sheath would be difficult to interpret. In fact, these conditions are much more severe than those used by service companies for cement testing. However, if necessary, longer-term cycling could be envisioned during material testing by the service company.

Reviewer 23537

Score: 7.0

Comment: The project goal is to develop cost-effective, corrosion-resistant foamed cement for carbon steel casings to be used in high temperature environments. The team developed a cement that meets many of their initial criteria for high T cement including an ability to pump it and its apparent effectiveness with carbon steel. To meet their desired cost criteria, the cement mixture where RCAC would be replaced with OPC, has not been tested. It is unclear to this reviewer whether one should assume that the criteria will be met or not by this mixture; therefore, it may be premature to state that the new cement developed is cost-effective.

PI Response:

Some results of the tests with the OPC and FAF formulations were presented (thermal shock tests with 80/20 faly ash F/OPC blends). The further tests with the OPC replacing RCAC are on-going. Preliminary results suggest that in many cases OPC formulations could be sufficiently effective. However, it should be kept in mind that the cost-effectiveness of a cement includes not only the cost of raw materials but also the cost of the slurry that would include many additives to achieve desirable properties. In the case of the proposed cement formulations, these additives and their amounts may be limited. Specifically, the use of the fly ash allows mixing slurries at lower density without introducing antisettling agents, foaming agents (depending on the final density), it also makes slurries more fluid limiting amount of a dispersant that would be normally necessary for a regular class G cement formulation.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 9.0

Comment: BNL has been the site of geothermal cement research for several decades and many important contributions have been made to the field. The lab's work has required that they hire highly qualified staff and equip them with the newest and best instrumentation with which to measure the results of their experiments. This project is an excellent example of what can be accomplished when this type of research is conducted in the right environment like BNL.

The PIs have carefully identified and quantified all of the parameters needed by a new cement designed to address ever more aggressive geothermal reservoir conditions. They have started with a base formulation that meets the strength requirements and then they have methodically identified additives that help the cement meet the anti-corrosion, thermal stress resisting, and casing bonding requirements.

The next steps are to incorporate all of these capabilities in a cement based on ordinary Portland cement, a product that is low cost and readily available internationally. Additionally, tests must be made of the new product's ability to bond with rock types commonly hosting geothermal reservoirs. Lastly, the proponents need to finalize collaboration with Schlumberger (their industry partners) to agree on a formula that can be field friendly, low cost, and readily acceptable for field use.

All of these objectives are being pursued and they should be achieved by the end of 2017. This is a technically sound, well developed and implemented project that should have a very significant positive impact on the geothermal industry.

PI Response:

We strongly appreciate this encouraging feedback from the reviwer. Thank you, we are moving in the proposed directions.

Reviewer 23480

Score: 8.0

Comment: The PI is a recognized expert in well cement technology, and he used this expertise in considering the best candidate materials to satisfy the challenging, quantitative performance criteria of the project. The choice of a 600C thermal shock criterion is unclear since the largest thermal shock the cement is likely to undergo is ~300C. Acid resistance testing (Task 6) should be underway per the project schedule. No explanation is given for the delay. Cost assessments of the CFFA/RCAC formulation should be done before attempting to develop a less costly CFFA/OPC formulation.

PI Response:

We thank the reviewer for the suggestions. The 600°C limit was chosen based on communications with the Japanese geothermal industry. We also believed that 600°C accelerates the testing, and if the cement can withstand the extreme environments it will more likely to survive the lower temperature-stress for longer time. Although the acid exposure tests are completed, the results were not included in the presentation because no post-test analyses were made for interpreting the reasons why some cements had a good acid resistance, but the other did not at the time of the review meeting. Based on preliminary observations and sample analyses, the TSRC formulations survived 18 days of pH<1 at 90°C, unlike the class G-based formulations that were considerably damaged during the testing. The detailed report of the results will be submitted to DOE according to the schedule.

Reviewer 25041

Score: 8.0

Comment: Presented scientific and technical approach is well thought out and detail.
It may be challenging to meet all those material criteria listed in the project.

PI Response:

Thank you. Arguably, the geothermal wells are the most sever conditions that cement may ever encounter. However, we will do our best to create a resistant material meeting the criteria.

Reviewer 23537

Score: 8.0

Comment: The team undertook an ambitious program in order to meet their desired goals. They establish a set of cement attributes that would ideally meet their project goals although it was unclear how those attributes were developed (accepted industry standards for cements requiring these attributes or internally generated based on experience of investigators?).

The team identified and overcame three main challenges: "pumpability" of cement, cement-casing bond, and high-T corrosion inhibitors. These are significant challenges and therefore significant outcomes.

PI Response:

The criteria were based on both communications with geothermal industries and personal experience of PI and co-PI (from oil-field cementing industry).

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: The strengths of this project include the fact that it is being undertaken in a laboratory famed for its pioneering work in geothermal cement formulation over several decades and the excellence of the facilities, personnel, and the atmosphere of success that assure optimum working conditions and results. The proponents have access to extensive files documenting previous work and by culling the most appropriate information from work accomplished to date in the field, they are able to start at an advanced position and innovate from there.

Another strength of the project is the inclusion of a CRADA with Schlumberger, a leader in international geothermal casing installation, logging, and cementing. By cooperating with Schlumberger, field tests of the new cement can be greatly facilitated and also, the actual product might be further improved using input be experienced field workers.

Finally, the experience and talents of the proponent were very clear during the project presentation. This man knows his cement chemistry!!

PI Response:

Thank you very much for your strong support of the project.

Reviewer 23480

Score: Not scored

Comment: A record of accomplishment has been achieved. Several candidate cements, capable of withstanding thermal cycling and binding to both steel casing and rock surfaces were developed and laboratory tested. The work plan is complete and thorough and includes a CRADA with Schlumberger who could be expected to offer the final cement formulations in their product catalog.

PI Response:

Thank you for your comment.

Reviewer 25041

Score: Not scored

Comment: Well-designed laboratory scale experiments and the progress of the project meeting all milestones.

PI Response:

Thank you.

Reviewer 23537

Score: Not scored

Comment: Good slides in presentation.

PI Response:

Thank you.

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The only weakness that can be cited is the fact that to date, no testing has been undertaken on the OPC formulation. This will certainly lower the cost of the produce, but so far, it is not known whether there will be a reduction in the quality of the product.

All of the required testing of the OPC cement is planned for 2015 and 2016, so this weakness should be overcome by the end of the project in 2017. During the Review presentation, it was acknowledged that no studies of the cements resistance to very low pH acids as are common in high H2S environments. Also, to date there is no "feel" for the degradation of these new products with time.

PI Response:

We tested OPC formulations with 80/20 OPC/Fly Ash content in thermal shock tests (slide 6 of the presentation). Although the performance of this blend is not as good as that of the calcium aluminate cement-containing blends, introduction of activated fly ash F clearly improves OPC resistance to thermal shock. Blends with higher OPC content will be tested next year. As described above, the acid resistance tests are completed, however, the results were not analyzed by the time of the meeting. Nevertheless, TSRC withstood 18 days at 90°C and pH <1.

Reviewer 23480

Score: Not scored

Comment: A comprehensive, multiyear task schedule with target performance criteria would be helpful. The milestone schedule and task timelines given in the SOW, summary and presentation are incomplete or inconsistent. The rationale for the choice of material criteria is not given. The cement foaming agent is not identified. Cost considerations are not discussed, especially how TSRC compares against CaP cement.

PI Response:

Thank you for your suggestions. We will clarify both the schedule and the targets of the project. The name of the foaming agent provided by Halliburton is given in BNL reports and publications. As stated above, the criteria were chosen based on communications with the industrial sectors and personal experience. We will include the cost comparison for the TSRC and CaP cements, however, it should be kept in mind that the field applicable formula of CaP cement is a proprietary information of Halliburton and only basic formulations of the two cements can be compared.

<u>Reviewer 25041</u>

Score: Not scored

Comment: No description on how to connect what they may be finding at the laboratory scale experiments to the filed scale performance.
Quality control of the cement composites for field scale casing purpose may be a real challenge.

PI Response:

Thank you for your comment. This is a very valid concern. The laboratory tests performed at BNL are at the stage where the cement formulations should be taken and tested by the industrial sectors with the appropriate product development for the field applications. Such product development that would include API-defined rheological tests at mixing and after conditioning at temperature (plastic viscosity, yield stress), slurry stability, free water, thickening time, time to compressive strength development etc., compatibility with proprietary company additives (dispersants, anti-settling, foaming, anti-foaming if microspheres are used, fluid-loss control, gas-migration control, etc) will be conducted by participating the service company with the support of BNL.

<u>Reviewer 23537</u>

Score: Not scored

Comment: I could not understand the speaker very well. This is not a reflection on the science or the results but it is a factor that is hard to discount. I am unsure if this is a weakness of me (a reviewer who had difficulty understanding much of what was being said) or the speaker who does not articulate the English language well at all. As we are all convened at a common place (e.g., hotel in Westminster) to hear directly from the PIs, then I assume that DOE anticipates that these presentations have value. Therefore, the inability to clearly articulate is a very real weakness. And given that the speaker is mature, confident and has clearly spoken publicly before, he should be aware that his audience may struggle to understand him. Therefore he should never walk away from the microphone (as he frequently did) because then his poor presentation goes from being marginally audible to completely incomprehensible.

PI Response:

Thank you for your comment. We will try to improve the quality of the presentation.

IMPROVEMENTS

Reviewer 23478

Comment: None yet. I will wait until after the presentation in Westminster to suggest some ...... if any.

PI Response:

Yes, I received a very important suggestion regarding the current progress status of each material criterion from reviewer after presentation. Responding to this suggestion, in the future presentation, we will describe whether these criteria are already met or not; if not, the current status will be noted in each criterion.

Reviewer 23480

Comment: Exhaustive studies of carbonation (material criterion #8) should be conducted. The need for additional work depends on testing under the CRADA with Schlumberger. If Schlumberger adopts TSRC for its product catalog, further work under this project is unnecessary.

PI Response:

Thank you for your comment. For technology transfer to a company, initial BNL support to material testing and evaluating by private sectors will likely be necessary.

Reviewer 25041

Comment: Communicate with other researchers or drilling practitioners to understand issues that may come up in relation to bond durability at cement/rock/clay mineral interfaces.

Include a discussion on scale up in size and extended duration of thermal cycle.

PI Response:

Thank you for your suggestions. We plan to regularly communicate with Schlumberger service company within the CRADA.

Reviewer 23537

Comment: Presentation. How one presents results can sometimes be as important as the results themselves, especially if the objective of the presentation is to solicit additional funds or to pass some stage gate hurdle. I'd prefer someone else present the results; short of this, if the speaker were more self-aware of his communication shortcomings, perhaps he can work more diligently on speaking more clearly, speaking only into the microphone, and/or speaking more slowly. Please know, this is not a criticism of the science or the work of this team.

PI Response:

Thank you for your comment: We will work on improving the presentations.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002785
Project: Recovery Act: Development of an Improved Cement for Geothermal Wells
Principal Investigator: Trabits, George
Organization: Trabits Group, LLC
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 4.0

Comment: This project will have very modest impact on the geothermal industry and it does only a little to further the objectives of the GTO. Basically, its purpose was to create a relatively simple modification to currently used geothermal cements by using a zeolite-based formula to cement high temperature and high pressure wells. Because of the withdrawal of one of the proponents key partners, ThermaSource for undisclosed reasons and because the proponents were not able to access the high temperature well at Brawley, CA the work ended up cementing only six low temperature wells with a product that is minimally, or not superior to standard, currently used cements.

This project has been conducted by a family-owned business that is obviously not greatly involved in the geothermal industry. They have, wisely, included literature research and assessments of current cementing procedures/problems in their planning, but this confirms their minimal in-house familiarity with the topic. The speaker, Mr. Trabits, did however show considerable familiarity with the cement business (if not the geothermal cementing business).

Considering the loss of ThermaSource, delays in obtaining required testing machinery, and the unavailability of the Ormat Brawley well for testing, this small company made some progress and turned out a product that appears to be useable and easy to mix in remote areas. Nowhere in the project literature was the actual cost in dollars per pound mentioned.

In some situations, one can say that "simpler is better" and that this cement formulation is indeed simpler and easier to use than some of the BNL high temperature, high pressure cements. However, the cement formulated by these proponents does not address thermal shock resistance, corrosion resistance, or quantify bonding capacities as does BNL. It appears that this project has not resulted in the building of a better mousetrap.

PI Response:

We appreciate the comments. Unfortunately the limited time for presentation and the limit on the number of slides to be presented allowed only for an overview rather than a detailed review. The development of the interground zeolite technology provides an alternative to more expensive cements and as such could have a positive impact on geothermal development. The cost of the developed cement is not in dollars per pound but rather in cents per pound. The cost of the developed cement fob plant is $120 per ton which is only six cents per pound.

Reviewer 23480

Score: 3.0

Comment: Project did not achieve its primary objective: provide a high-T cement system for geothermal wells; cement formulation was not tested in a high-T well. Bench tests at 300C were apparently done but not included with the review materials. The new cement was used in 6 low-T wells, but results from those efforts (e.g., CBL) were not presented. Some tables of performance characteristics were included in results, but they need to be compared with baseline values for commercial Class G & H cements and CaP to gain insight on the level of improvement. Resistance of zeolite-based cements to carbonation looks promising, but testing should extend over longer periods. Increased setting volume of 15% with zeolite cement is notable. The project has very little to show after five years.

PI Response:

The final Scintific Report is comprised of 194 pages and provides detailed data. Multiple attempts were made at testing the developed cement in a high temperature well. The well at Brawley was never completed and was rescheduled several times during the Period of Performance. An alternate well at the Steamboat field was selected but from a Nevada regulatory constraint the operator had to go with a more conventional cementing approach. The Period of Performance was extended several times with the prospect that a well would become available but none did.

Reviewer 25041

Score: 7.0

Comment: This project develops a novel, zeolite-based light weight, high temperature, and high pressure geothermal cement.\

It is good to know that the PI consulted industry experts about their needs of casing cements, especially with Halliburton. Their vision is always focused on the production of economical high performing cement at industry scale. As such, they identified that micronizing is too expensive and moved to adapt intergrinding method.
They hope to produce large amounts of different grades of cement at Lehigh Southwest Tehachapi Plant.

The project approach is based on try-and-error and lacking scientific understanding in fine particle handing in comminution and mixing processes.

PI Response:

Extensive work was done on understanding fine particle size in not only handling and mixing but in the manufacture as well. The final Scientific Report provides this data.

Reviewer 23537

Score: 10.0

Comment: With the exception of down hole testing in a geothermal well, this project has addressed, met and completed all required steps despite the fact that their industry partner bailed out. It appears that the required criteria were met via this zeolite compound and that the Quality of this work and the Productivity standards were all met to a high degree.

PI Response:

Thank you for the positive comment.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 5.0

Comment: This project has been undertaken in a very elementary way. It resembles a project that might have been undertaken by a senior in college or by graduate students. Significant literature was done, then geothermal industry drilling and cementing experts were consulted, then four (of many possible) zeolites were chosen (there was no mention of how or why these four were picked) and then multiple trial and error-type experiments were run using multiple formulas in order to find a mixture that satisfied pre-determined physical parameters.

Though there were descriptions of the processes used to grind and size the zeolite powders as well as photographs of the facilities, there were no descriptions on the instrumentation and other equipment used in the project work and results were minimally quantified and presented in the documents. There was no mention of the experience or qualifications of any of the proponent family members who appear to comprise the bulk of the staff that worked on this exercise.

The end results of the cement formulation were tested only on low temperature wells and there were no details given regarding these experiences. It is therefore not known whether or not the project succeeded in creating superior, low cost, easily utilized, multi-purpose cement that is any better than the cements presently being used by the geothermal industry.

PI Response:

Most of the development work was completed by the Petroleum Development Lab at the University of Alaska Fairbanks. Perhaps the Reviewer missed this fact. Also Scientific Peer Review was conducted throughout the project by Dr. Karen Luke who is noted worldwide as a cement expert.

Reviewer 23480

Score: 2.0

Comment: While the project's approach is logical, the execution appears haphazard. Zeolites appear to be a vital component of the new cement formulation, but there does not appear to be any quality control on the purity of the zeolites used in mixing the cement. Zeolites collected from the natural environment would contain multiple impurities, including other zeolites that could affect cement performance. The materials provided for this review give no indication of the steps taken to control zeolite handling and analysis. The project suffers from the lack of an industry partner who would have the resources and incentive to maintain tight control over the variables governing cement performance. The performance criteria are mostly subjective and difficult to evaluate. For example, one criterion calls for "good bonding" to casing and formation. What constitutes "good"? How is "good bonding" evaluated and tested? Similar questions can be asked about the other criteria.

PI Response:

The zeolites selected were based on being consistent in deposit purity and commercially available. While there are many types of zeolite it would not be resonable to select a zeolite that was not available. The project did have two industry partners, Halliburton and Baker Hughes.

Reviewer 25041

Score: 6.0

Comment: In addition to industry experts in well cementing, they should have consulted experts in fine particle handling.

Comminution/Mixing/Segregation is a very active area of research in fine particle material and there are lots of useful information they can borrow to make their project more scientific.

PI Response:

Extensive work was done on fine particle size. The project did make use of CCE Powder Technology as the expert on fine particles.

Reviewer 23537

Score: 10.0

Comment: In hindsight, the approach designed to meet the initial project objectives were rigorous and appropriate.

PI Response:

Thank you for the comment.

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: The only strength that can be seen in this project is that "simpler may be better". The cements produced appear to be relatively easy to manufacture, they have far fewer additives or other chemicals, and are not complex. This probably means that they can be obtained easily for use in remote sites and that they can be emplaced without sophisticated equipment or procedures.

These attributes are important in situations where temperatures, pressures, corrosivity, NCG's, and associated aggressive conditions do not exist, but in deep, deviated, chemically aggressive situations, simplicity may not be result in the best cement over the long run.

PI Response:

We appreciate that the reviewer noted that the developed cement is easy to manufacture with far fewer additives which equates to lower cost.

Reviewer 23480

Score: Not scored

Comment: The PI showed determination to complete the project without an industrial partner and the resources that partner could provide. Despite this, the cost share requirement was exceeded. Production of 1000 ton of the cement formulation is notable, and the performance characteristics (e.g., compressive strength) are reasonable as reported. Use of clinker to modulate the zeolite grinding process in cement preparation is innovative.

PI Response:

We appreciate the positive comment.

Reviewer 25041

Score: Not scored

Comment: Good industry input.
Industrial scale production.

PI Response:

Thank you for the comment.

Reviewer 23537

Score: Not scored

Comment: Team, testing methods and results.

PI Response:

Thank you for the comment.

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The greatest weakness of this project is the failure to test the final products in high temperature, high pressure well(s) with corrosive fluids and high thermal shock tendencies. There was no mention at all of the possible suitability of the formulated cements for use in EGS wells.

Specifically, the proponents chose to test their cement in an un-named well at Chena Hot Springs, a conveniently located site, but one at which maximum thermal water temperatures are about 165F!! There was no description of this test during the Review presentation and neither were their descriptions of the claimed cement tests in six other low temperature wells. For that matter, neither "low" nor "high" temperatures were defined in the proposal documents.

Additionally, there were only brief explanations as to why four of many zeolites were chosen is a weakness. Finally, the apparent use of trial and error in identifying the best final cement product is not very scientific. There was no description of the final formulae or any comprehensive listing of all the qualities of the final products.

PI Response:

Unfortunately a high temperature well never became available. The final Scientific Report contains detailed information on the research approach and results. There was not the time to present a more detailed discussion at the Peer Review.

<u>Reviewer 23480</u>

Score: Not scored

Comment: Project has weaknesses that affect the credibility of the results. The experimental plan appears haphazard and not well-controlled. Cement performance criteria are largely qualitative, rather than quantitative. As presented, results are limited/incomplete. There is insufficient information on which the mixing, testing, and performance of the zeolite based cements can be replicated.

PI Response:

The final Scientific Report contains detailed information on the research approach and results. Unfortunately the limited time for presentation and the limit on the number of slides to be presented allowed only for an overview rather than a detailed review.

<u>Reviewer 25041</u>

Score: Not scored

Comment: Not enough science in understanding particle processing.

PI Response:

Extensive work was done on fine particle size. The project did make use of CCE Powder Technology as the expert on fine particles. The final Scientific Report provides this data.

<u>Reviewer 23537</u>

Score: Not scored

Comment: Presumably the anticipated industry partner may have expedited the timeline of this work.

PI Response:

ThermaSource would have been helpful but they withdrew causing not only delay but a loss of $270,000 in promised cost share and the loss of access to cement testing equipment which had to be purchased for use at the University of Alaska Fairbanks. The withdrawal of ThemaSource was a significant burden to the project and should be noted.

IMPROVEMENTS

Reviewer 23478

Comment: 1. Employ at least some geothermally experienced experts on the team to guide the project and provide input regarding the desired final product.

2. Explain why the four zeolites were chosen out of many possible candidates and what qualities made them stand out.

3. Present, in the documents, data regarding the trial and error results. If not for all the experiments, then for at least representative examples of some trials with differing formulae together with explanations as to why some were rejected and some approved.

4. Make sure that somehow, high temperature, high pressure tests are run in the field. This was an objective of the project and it was not attained. Without such tests, the impact on the geothermal industry and GTO goals cannot be assessed as anything but minimal.

PI Response:

1) The withdrawal of ThermaSouce did impact the project from both an expert standpoint but also a cost burden to the project that was overcome with unanticipated increased cost share required from Trabits Group.
2) Four zeolite were selected based on purity and commercial availability.
3) The final Scientific Report contains detail trial and error results.
4) Unfortunately a high temperature well did not become available during the project.

Reviewer 23480

Comment: An industrial partner who can carry the product to commercialization is essential. This could be an operator with available hot wells for testing, but a drilling service company would be preferred.

PI Response:

Very much agree with this comment, thank you.

Reviewer 25041

Comment: A combined input from the drilling industry and fine particle research experts will make this project more scientific and produce more universal data that can be used by other researchers and practitioners upon the completion of this project.

PI Response:

There is extensive data in the final Scientific Report which should be helpful to future researchers.

Reviewer 23537

Comment: NA.

Based on the data provided (to reviewers) and the presentation material, it is unclear what improvements should be expected.

PI Response:

The primary improvement is a low cost, wide application cement that should facilitate geothermal resource development.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: SURGE: Geothermal Drilling and Completions: Petroleum Practices Technology Transfer
Principal Investigator: Visser, Charlie
Organization: NREL
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 6.0

Comment: Anything that can speed up geothermal drilling will have a positive impact on the industry. Even though many of the drilling techniques employed by the geothermal explorers and developers have traditionally evolved from the petroleum industry (that's where most of the drillers and workers cut their teeth) the petroleum industry has great advantages of size, funding, locational opportunities, etc. and have therefore developed techniques that are superior to those still being used in the geothermal industry.

This project seeks to identify and quantify the drilling differences between the two industries and recommend ways in which the superior technology can be transferred to the weaker one. Obviously, geothermal drilling will always be done in geologic environments that are far more challenging than petroleum drilling. This alone slows geothermal drilling greatly. On the other hand, there are geothermal drilling management, data acquisition, and drill rig issues that can benefit from the petroleum industry and these aspects are the targets of this project.

To date, a total of 42 drill sites have been visited by Colorado School of Mines graduate students seeking to understand all procedures and processes on and off the rigs. They have compiles statistics that confirm that there geothermal wells tend to take 3-4 times longer to drill than do petroleum wells of similar depth and they have identified the drilling parameters that cause this situation.

Yet to be accomplished is determination of the best ways through which to transfer petroleum industry expertise to geothermalists and ways and site where this transfer can be accomplished. If successful, it is hoped that the drilling improvements that could accrue to the geothermal industry might decrease time and costs by up to a very significant 10%.

PI Response:

The FY14 work was to determine the focus of the issues of geothermal drilling operations that would have the largest and immediate impact. This required an in depth detailed study to figure out just where future efforts should be focused. This has been accomplished and the determination of the best ways to transfer technology and management processess are the subject of ongoing research efforts. Clearly, there are differences and similarities of petroleum and geothermal drilling operations. FInding the simularities and translating those differences are the ongoing research challenges.

Reviewer 23480

Score: 5.0

Comment: Project has been underway since FY14 without much to report on results/accomplishments after some seven months. The outcome of meetings with drilling experts is not covered in the documents provided. A good comparison of geothermal vs petroleum wells is given, but specific details of that comparison are not addressed. Which technologies perform best; which ones can be transferred successfully? These questions are not answered with examples. The comparison of 21 geothermal wells and 21 petroleum wells is striking. If the "petroleum" wells included oil wells, a fairer comparison would be with gas wells, which tend to have larger diameters and casing schedules that more closely resemble geothermal wells.

PI Response:

The project has identified many small process differences with the potential to collectively lower geothermal drilling costs, especially in nonproductive time. It is clear from the avialable data that large improvements in cost efficiency can be made. However, verifying the detailed benefits is more difficult due to the sparse and course data stream with geothermal wells. That lack of data specifivity and fineness was a major outcome and pointed out an intensed need for more fine and detailed data from geothermal rigs in order to wrought the types of significant drilling improvements the petroleum drilling sector has experienced.
The details of the interviews with goethermal and petroleum drilling experts is detailed in the project's FY14 final report. The project cannot share specific details of the wells used in the comparison due to to confidentiality requirements. However, the majority of the petroleum wells reveiwed were gas wells with well diameters and casing schedules similar to the geothermal wells.

Reviewer 25041

Score: 8.0

Comment: Similarities and differences between oil/gas and geothermal drilling have been identified and compared.

The project goal is to find way(s) to reduce geothermal drilling rig days by 10%. A good goal but how?

Selection criteria for drilling experts and kinds of drilling projects raised many questions by the reviewers and especially the consistency of analyzed data.

Some of the key non-productive time factors are identified but no detailed discussion was given to these factors at the time of presentation.

So far, the project is in the phase for data gathering and not enough time passed to analyze them yet.

Lack of drilling data; quality of data; consistency of data are some of the problem areas in this project.

PI Response:

The details of the drilling expert interviews are discussed in the FY14 report. The selection was based on a review of US based geothermal experts that were willing to discuss this. The lack of quality drilling data for geothermal operations is definitely an issue that the geothermal industry needs to improved.

Reviewer 23537

Score: 7.0

Comment: This project accurately points out that a current geothermal industry weakness is drilling costs. Data that might potentially come out of this work could dramatically improve drilling efficiencies (especially among the smaller "one project" companies that don't have the money, expertise or lessons learned of the Ormats of the world).

The project is based on at least one premise which is that O&G can inform the geothermal industry and provide "pathways" for technology transfer. The ultimate goal of this project is to provide ideas/protocols/concepts/tech transfer opportunities that will reduce drilling costs.

A geothermal and O&G industry survey was conducted and data were assessed.

Quality: Ok but not stellar. The project has made good progress so far in the 21 well data set that is has access to. A larger data set from a larger cross section of companies would be preferable.

Productivity: It was pointed out that geothermal drilling data are "scarce." Data exists but it is not readily available. It would be great if this project could leverage past DOE funds and remind recipients of these funds (e.g., Calpine, Mid-America, Terra-Gen and Ormat) that better access to their drilling records would ultimately provide value to the entire industry. A more robust industry benefits everyone. While O&G may lend some value to this undertaking, it can be argued that the larger companies still active in the industry have solutions to their unique drilling problems. The issue, unfortunately, is that they guard their successes and their failures. The productivity of this project would expand greatly if they could get access to drilling data sets from the major geothermal developers.

PI Response:

Larger data sets indeed would be preferable. Data from DOE sponsored wells were accessed; however, the records were marginally useful at best. This pointed out a great need for a more defined drilling data set procedures and analysis needs for any future DOE sponsored operations and is the subject of this year's work, One of the challenges, as noted, was that many operators consider this data propriatary and a competion advantage, making our access to that information impossible. This is yet another outcome that says, perhaps, a shared pool of drilling information could go a long ways towards improving drilling operations and could be something that the DOE could sponsor.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 6.0

Comment: The technical approach being used in the project seems appropriate. The idea of using a "Perfect Well" as a standard by which to compare drilling performance is never going to be met, but it should be possible by using this metric to quantify the deviation from "ideal". By using Colorado School of Mines (CSM) graduate students to do the drill site canvassing, there is the problem that these relatively young, inexperienced men and women are inexperienced in drilling techniques and that they therefor have to learn on-the-job. Accordingly, they are unlikely to get full cooperation from drillers who have jobs to do on the rigs. Drillers are notoriously uncommunicative with persons that they do not greatly respect, so students will have a hard time getting all the data that they would want.

It is not realistic to pay expensive, experienced geothermal drilling consultants to do the field work and it is certainly desirable to obtain field experience for the students, so the technical approach, though not ideal, will have to be adequate.

The graphs seen in the presentation in which the time in hours spent on non-productive operations in the geothermal industry versus those spent in the petroleum industry dramatically depict the differences between the two types of drilling. Not surprisingly, cementing, rate of penetration and directional drilling have emerged as the primary culprits responsible for slow geothermal drilling. This is not new news, but with this project, perhaps ways to mitigate these problems by adoption of petroleum industry techniques, can be accomplished.

PI Response:

The students did not actually have any contact with the field people. Instead, the records the field people create and supply were used, after the time the wells were drilled. The students reveiwed and catgorized the records into the various productive and non-productive times as recorded by the drilling records. When there was uncertainty by the students as to an operational issue, the PI, who has 37 years of experience in drilling operations as well as a doctorate in the subject was consulted to interpret the data.

Reviewer 23480

Score: 5.0

Comment: The approach, a comparison of geothermal and petroleum drilling experience, has merit. But the extent to which that approach has been exercised is not clear from the materials provided. How many geothermal experts were interviewed? The extent to which drilling experience was documented is not clear. Nor are assurances offered that the team has done its homework in studying previous work in this area. DOE sponsored several similar studies over the past 30+ years. Since the 1980s, geothermal wells were known to cost 2-3 times that of oil& gas wells. And the single major factor in the cost bump was lost circulation---which still seems to be the case. SNL should be consulted for additional information about geothermal drilling experience over the years. Perfect Well Analysis as an approach has merit. A challenge would be to define the perfect well environment for each well: Petroleum wells are usually drilled in mostly homogeneous, layered, soft rock. Such is not the case with geothermal which can occur in a wide variety of geologies and structures. These differences should be considered.

PI Response:

The project's FY14 year end report provided details on the geothermal and petroleum drilling experts interviewed and the criteria for selection. The interviewed experts typically had two to three decades of experience. The experts also had to be willing to share their knowledge, which wasn't always the case.
The project team has studied previous work in the field, as documented in project report.
The project is in close communication with Sandia National Laboratories. NREL, CSM and SNL are coordinating our respective drilling research efforts to build on past successes.
The project team recognizes the differences in the composition, fabric and structure of rocks between petroleum and geothermal, and recognizes that rock differences will always be a factor in geothermal drilling performance. A goal of the project is to better quantify how much of the performance difference is not due to lithology.

Reviewer 25041

Score: 8.0

Comment: The project approach is well described and fine.

PI Response:

Thank you.

Reviewer 23537

Score: 6.0

Comment: The data acquired thus far is small but appears to be solid. While O&G is orders of magnitude larger than geothermal, they don't routinely drill in hot, shallow fractured rock. I would like to see a greater focus on acquiring and assessing data from geothermal producers. The lessons learned from an assessment of drilling data from the big 3 or 4 producers, and/or others, would be huge. You could add to the mix, also, the data and lessons learned from historic HDR and more recent EGS efforts.

PI Response:

Acquiring and assessing geothermal data is the focus of FY15's efforts. The team has been given excellent drilling data from one geothermal operator that is far more detailed than any previous data accessed. The team is also developing a drilling sensor suite selection that the DOE should consider requiring for any future drilling sponsorship.

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: The strength of this project is that it addresses a situation that has long been recognized but never tackled. By funding the project and allowing it to focus on ways to identify the geothermal problems, compare them to those encountered in the petroleum industry, and solving communication barriers, progress may be made towards allowing the geothermal drillers to "catch up" to the petroleum drillers.

Another strength is that by identifying the drilling problems that slow the geothermal drilling, other research projects can be undertaken to find ways to solve the problems (in addition to adoption of petroleum techniques that may not always be the ideal solutions).

PI Response:

We agree.

Reviewer 23480

Score: Not scored

Comment: The study is incorporating a novel analytical technique from the petroleum industry. Establishing drilling data protocols will be a useful benefit for future work in this area. The comparison of geothermal drilling challenges versus those of petroleum drilling are particularly instructive and could be used as the foundation for the analysis.

PI Response:

We agree.

Reviewer 25041

Score: Not scored

Comment: A team of geologist and drilling experts working together for this project. This should give a balanced approach.

PI Response:

Indeed, there are synergies to be leveraged.

Reviewer 23537

Score: Not scored

Comment: This is absolutely the right type of project and worthy of DOE funding. Drilling efficiencies/drilling costs are among the biggest obstacles in the way of a more robust geothermal industry (along with permitting time, "competitive" leasing, low PPAs...). The team (NREL and CSM) has the capability to acquire and adequately assess these data.

PI Response:

We agree and are working hard to do this.

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The primary weakness of this project is the previously alluded to need to use young inexperienced CSM students to canvas drill sites and interview drillers. This work should ideally be done by geothermal consultants with long drilling experience who thoroughly understand procedures and why they are followed. Such persons would get much more cooperation from drillers who are typically not forthcoming with "newbies" as they regard students. Unfortunately, the use of experienced consultants might have increased project expenses well beyond the budget.

Another weakness is that one is comparing apples to oranges when one compares petroleum and geothermal drilling. The geologic environments are greatly different as are the exploration objectives. Accordingly, it should be expected that the geothermal drilling will be slower. I'm sure that there will be some petroleum industry practices and software that can and should be adopted to some degree by the geothermal drillers, but unfortunately, geothermal drilling in deep, hot, hard to altered rock under high pressure, will always be slower.

PI Response:

One of the reasons the project started with interviewing geothermal and petroleum experts, which was accomplished by the PI and co-PI, not the students, was to fine tune the areas the student team should be reviewing. It was clear from the interviews with these experts. where the team should look. Plus, these experts willingly gave us their time and insights. Using drilling records from wells already completed, the team then catagorized and recorded their observations. At no time was there any interaction with field people and the students. This process is tedious work and, frankly, well suited for an entry level data processor. But, by using petroleum engineering undergraduates with a passion for drilling gave them experience, insights and knowledge that cannot be gained in a classroom. The project team also allowed for the nucleus of a new generation of drilling engineers that have an appreciation, and perhaps the opportunity, for the challenges in geothermal drilling operations.
Geothermal drilling is understood to be different that petroleum drilling operations to some extant. It may always be slower than petroleum drilling due to rock differences. But, the project noted that the there are simularities in all drilling operations and opportunites to improve that are not related to lithology.

<u>Reviewer 23480</u>

Score: Not scored

Comment: Compelling data are shown comparing time vs depth performance of petroleum wells and geothermal wells. Rig time is a very important cost factor, but so are equipment and materials, especially for geothermal; these account for ~50% of costs. The analysis should examine cost (inflation-adjusted) as well as rig time to subsume all variables in well drilling. NPT is given for two sets of wells, but the root causes of the NPT are not listed or analyzed. Perfect well analysis was identified as a means of comparing real well drilling scenarios. But little explanation is provided for how the analysis is implemented in geothermal scenarios.

PI Response:

While economics drive decision making in any operation, operators consider that information propriatary and potentially an advantage over their competitors. They keep their costs "close to the vest". Since this data was not forth coming and since time-related operations are indeed major cost factors, the the team reviewed time issues as a proxy for costs. It is noted that equipment and materials are a factor; but, the team used what they could access for this analysis. Besides, these costs can vary significantly between wells and between operators making other non-drilling related inputs skew that information. Future work by the team will look into these factors.

<u>Reviewer 25041</u>

Score: Not scored

Comment: There is no clear vision on what will happen to their findings based on data they collected.

PI Response:

The findings have been published and submitted to the Geological Data Repository for public access. The findings have been and will be presented at various technical conferences and workshops. The findings are being used to focus future research efforts by this team, as well as other teams, to improve geothermal drilling operations.

Reviewer 23537

Score: Not scored

Comment: In the initial survey of O&G vs. the geothermal industry, it appears that geothermal drilling data may be biased by a lack of broader geothermal industry inputs. Along these same lines, the subsets like lost circulation and cement, for instance, may be biased by one geothermal company or one contractor (although we were told that this data set also includes wells from "some" DOE projects). While I'd rather have a lot of data from one company rather than no data. I'd much prefer larger data sets from more companies. Also, the premise that much can be gained from O&G drilling, especially from a limited (~21 wells) O&G data set, is not real clear from the written material and from the presentations.

PI Response:

While it is understood that more data is always more useful, the team determined that there was enough information available to start the process of understanding the similarities and differences between the two industries and to determine where synergies exist for transfer of knowledge, materials, and techniques in both directions.

IMPROVEMENTS

Reviewer 23478

Comment: 1. Use experienced consultants to discuss drilling with on-site personnel.

2. Find a way to "normalize" the two types of drilling so that the effects of their geologic environments and objectives are minimized in the quantification of drill speed differences.

3. More time should have been spent discussing at least the three most important unproductive time activities. They are controversial and deserve separate attention by the proponents.

PI Response:

Determining the impact of lithology on drilling operations is part of the ongoing research efforts. However, the team determined that some of the identified issues that impact geothermal drilling operations are not solely related to lithology. The unproductive time activities are discussed in detail in the FY14 report.

Reviewer 23480

Comment: Build on the work of others, notably SNL, who have addressed this problem in the past. Look at other factors besides rig time as a means of reducing costs. Seek the cooperation/input of the IADC in formulating protocols for data acquisition.

PI Response:

The project is in close communication with Sandia National Laboratories. NREL, CSM and SNL are coordinating our respective drilling research efforts to build on past successes. Drilling data aquistion protocols are the subject of this year's efforts.

Reviewer 25041

Comment: Once findings are understood, the PIs should provide technical solutions to make their goal of reducing the drilling rig days by 10%.

Provide steps to attain this goal.

PI Response:

By understanding when and where non-productive time affect drilling operations, the team can compare and contrast these areas with other drilling operations in other industries, identify solution and procedures, and developing processes to impletment those results. This is continuing with this year's project.

Reviewer 23537

Comment: The following is more a suggestion than an "improvement."

The initial premise of this work (which is beyond the purview of my role) is the pursuit of tech transfer opportunities in the O&G field to ultimately realize lower drilling costs in geothermal. There seems to be a DOE bias toward the O&G industry as the source of solutions for the geothermal industry because both (1) involve the extraction of fluids and both (2) apply geophysics, drilling, etc. to ultimately define and exploit the resource. I think there may be much better synergy between geothermal and mining. I would like to see this and any future such DOE funded analysis include mining. The reasoning is that mining is much more a kindred spirit to geothermal. Both industries are frequently trying to solve big technical problems with shoe-string budgets. O&G, by contrast, has orders of magnitude more money and bodies than geothermal ever will. Second, many mining operations (esp. epithermal gold systems) are currently working in very similar environments to geothermal so they too wrestle with drilling in hot, shallow environments. Finally, the project PIs include a CSM faculty. CSM has forgotten more about mining than all other National Lab university partners. They have a strong mining engineering department and a strong economic geology department. They also have a strong petroleum engineering department but the fact is, O&G has had many, many opportunities to support the geothermal industry in the past decade. They don't because they see no value in it. I'd like to see this project more rigorously pursue data from the major geothermal producers and also see if they can extract any data from the mining industry.

PI Response:

The PI's agree that mining is an attractive source of technology transfer to geothermal. Indeed, any subsurface resource development activity is a source of knowledge, technology, and procedure that all can learn from. That is beyond the project scope but a fruitful area for future research.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005502
Project: Advanced Percussive Drilling Technology for Geothermal Exploration and Development
Principal Investigator: Wolfer, Dale
Organization: Atlas Copco Secoroc LLC
Panel: High Temp Tools, Drilling Systems

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 7.0

Comment: Drilling cost reduction has long been a goal for the geothermal industry and for GTO. One of the keys to decreasing cost is diminution of rig time and this means increased Rate of Penetration (ROP). Percussion drilling with Down-the-hole-hammer (DTHH) drills has been used in the mining and petroleum industries for decades and has proven to be excellent under relatively low temperature and pressure conditions. DTHH has not worked as well in the high temperature, high hydrostatic pressure, and abrasive rock conditions being ever more encountered in modern geothermal exploration and development.

If this project is successful in developing a percussion drill that can penetrate to 3000 meters, endure temperatures of up to 300C, and triple the ROP from about 7 meters/hr. to about 21 meters/hr., drill rig time and costs will be reduced by 67%. This is not to say that the total cost of a well will be reduced that dramatically,
but there will be significant savings.

This project addresses well the GTO objective of cost reduction and while the project is only about 75% complete, the results of all early phase design, materials selection, test facility construction, and concept validation have been quite satisfactory. Low temperature (~135C) testing has been completed and high temperature testing (300C) is now under way with planned completion in 12/15. The only thing missing from this project is to try the new BHA in a real field experiment. A site like Coso, CA might be perfect.

PI Response:

Reviewer 23480

Score: 5.0

Comment: Project has been in place over 3 years. Results are not remarkable for the time involved. Percussive drilling has been a topic of research interest for many years. No strong indication why this research is unique relative to earlier work. Long list of accomplishments is provided, but not much in terms of actual hammer performance. Need to show how results represent significant improvement over conventional hammers and rotary systems. ROP results for prototype vs simulation show a reduction of 10-20%; this difference may be significant in achieving project goals. The project has the potential of making geothermal drilling much more cost effective--a potential game changer--if high ROPs and long bit-life can be achieved.

PI Response:

Reviewer 25041

Score: 7.0

Comment: This project proposes to develop an effective percussive hammer for height temperature geothermal.
The project clearly addresses challenges with polymer and elastomer components their percussive drilling equipments require. Difficult to withstand high temperature and corrosive environment.

Only data presented were based on simulation modeling.

The reviewer wished to see data on cuttings produced by their percussive hammer for different rock types. Size distribution on the cuttings may provide more direct insights in wear and coating design. How about the nature of cuttings of different rock type at different temperature? The reviewer has doubt that these data even exist.

PI Response:

Reviewer 23537

Score: 9.0

Comment: The purpose of this project is to develop a high T, downhole hammer technology for geothermal systems that is more effective (I.e., faster) than conventional geothermal drilling techniques and then test it. Specifically, this work proposed to develop, evaluate and model designs that would meet these objectives. Then they would build a prototype and establish laboratory procedures that would adequately test this at low and high Ts. Based on data presented, it appears that the all proposed steps were accomplished and targets, to date, were met,

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 8.0

Comment: In the geothermal drilling industry, there are no better participants than Atlas Copco and Sandia Laboratories. Atlas Copco has been making drill bits and assemblies for many decades and therefor have the staff and engineering expertise to conceptualize, design, and undertake this project; Sandia has long been involved in geothermal drilling research and also has the staff, equipment, and expertise to test this DTHH.

This project has been slowly and carefully executed so as to try and consider multiple solutions to the challenges of high temperature DTHH drilling. They have sought out new and innovative materials for seals, for lubricants, and for the drilling hardware (cutting assemblies and the drill bit body). They have tested and rejected numerous materials before settling on acceptable ones. In some cases, actual manufacturing procedures (such as hardening) have been re-specified so as to exclude processes that could actually weaken some materials.

The instrumentation and equipment used has not been described in detail, but suffice it to say that the safety of the staff and all personnel involved in this work has been paramount. Without the best instruments and lab techniques, this would not have been possible.

If anyone can design, test, and manufacture this new high temperature DTHH, it will be the proponents of this project.

PI Response:

Reviewer 23480

Score: 4.0

Comment: Approach seems somewhat distended and haphazard, judging from the presentation. All the pieces are there but not presented logically. The technical "targets" (performance criteria?) Are largely subjective, with use of qualifiers like "viable" and "reliably"; not obvious how to certify performance. For example, what are the parameters that demonstrate the hammer works "reliably"? Reliability can be defined in a variety of ways; there are no quantitative links to actual performance, such as hours of operation or drilled footage. No line drawing of the DTHH, its components, or the HT test facility are included with the presentation materials. There is no indication the design is innovative and/or leads to significantly improved performance.

PI Response:

Reviewer 25041

Score: 7.0

Comment: This project describes well the challenges associated with the sealing components and friction/wear testing. However, it is more important to address challenges when these drilling components interface against rock. No such attempt is made.

PI Response:

Reviewer 23537

Score: 9.0

Comment: The problems associated with effective, high T hammers appear to be well understood and were adequately addressed in the conceptualization and testing of this prototype.

PI Response:

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: The strength of this project lies in the level of detail that has gone into every step of the development of this high temperature DTHH. From the concept to the design, to the selection of materials, to the testing at low temperatures, to the testing at high temperatures, every aspect of every objective has been exhaustively studied and re-studied. There have been Go/NO Go decision points at each critical juncture and the DOE has already validated the adequacy of the Phase one, low temperature work.

The project is behind schedule, but the reason for this may be partly attributed to the diligence with which each project stage has been conducted.

Another strength lies in the long term experience of Atlas Copco and of Sandia. In geothermal exploration and development drilling. They have been involved in projects where time and money have been spent out of proportion to the results achieved and therefore they realize the importance of this project to the industry should it succeed.

PI Response:

Reviewer 23480

Score: Not scored

Comment: Hammers are known to have superior advantages in geothermal drilling including ROP and overall cost. The project correctly identifies the barriers/challenges to realizing those advantages. And progress on those has been made. After three years, project is in a position to test prototype performance in a HT test facility.

PI Response:

Reviewer 25041

Score: Not scored

Comment: Development of different types of drilling method with adequate understanding of challenges associated with polymer and elastomer components.

PI Response:

Reviewer 23537

Score: Not scored

Comment: The team, the approach, the equipment available and the work conducted to date are all strong.

PI Response:

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The only weakness that I can see in this project is the failure to include real-time, real field testing once the DTHH has been designed, built and lab tested. This would have been a logical end goal and should have been financially feasible (with DOE help). There are geothermal fields in the US, including the Geysers and Coso where hot, difficult drilling to depths of 3000 meters has been recorded and where costs have limited some exploration drilling consideration. If this DTHH could be used in one or both of these fields and possibly in one or more EGS project sites in or out of the US, the project could be truly completed and validated. To finish in the Lab testing stage, is to leave the project incomplete.

It was disappointing to learn that this DTHH will still be limited to dry, deep holes such as may be drilled for EGS projects. Hammer drills can be "watered out" and this is still true for this new version of the tool.

I really cannot cite any other weaknesses in the project. 500 words will be unattainable again!

PI Response:

Reviewer 23480

Score: Not scored

Comment: Success criteria remain ill-defined. HT test facility may not fully account for geothermal conditions, which can include highly corrosive fluids. Not obvious the team looked at previous work on percussion drilling and HT materials development sponsored by DOE. For example, BNL has developed several high-temperature elastomers, notably PPS, with 300C capability. The issue of cuttings removal is not addressed. This becomes important in deeper wells. While 3 km wells are increasingly common, deeper wells (up to 6km) are being considered for EGS applications. If conventional rotary drilling must be included to drill portions of wells, the economics of the percussive tool would have to be questioned.

PI Response:

Reviewer 25041

Score: Not scored

Comment: No data for the nature of cuttings that might be produced by the proposed percussive drilling are given.

PI Response:

Reviewer 23537

Score: Not scored

Comment: Unclear if all steps required to fully test this high T device will be accomplished by the stated project deadline, June, 2015. Assuming the HT testing is successful and a report fully documenting all facets of this project is adequate and submitted in a (relatively) timely manner, then the "weakness" of allowing this June 2015 deadline to slip a few months deserves no further attention.

PI Response:

IMPROVEMENTS

Reviewer 23478

Comment: I'm afraid that for this section I can only repeat the words that I have used under the "Weakness" section.

PI Response:

Reviewer 23480

Comment: Once the HT hammer has been tested at the high-temperature facility, the tool should be taken to the field for further testing under actual geothermal conditions. A willing geothermal operator should be recruited. Detailed economic studies should be performed to verify costs with actual experience.

PI Response:

Reviewer 25041

Comment: Need to discuss how to deal with the cuttings produced. Dust management maybe a significant risk for this project.

PI Response:

Reviewer 23537

Comment: Like many of the high T, high P drilling projects discussed at this year's Peer Review, I'd like to see the prototype hammer field tested and assessed in a high T, geothermal environment.

PI Response:

Innovative Stimulation Techniques Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Validation of EGS Feasibility and Explosive Fracturing Techniques
Principal Investigator: Carrigan, Charles
Organization: LLNL
Panel: Innovative Stimulation Techniques

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23454

Score: 9.0

Comment: This project comprises two separate but related activities. The major effort is related to optimization of EGS well placement and geometry, as they relate to productivity and longevity. This is clearly a crucial element of geothermal development, so successful results here would have a significant impact. The principal accomplishment of this element of the program is a thermo-hydro-mechanical code to be used in evaluation of this optimization scheme. Sample calculations using this code show that linking all three physical effects has a major impact on analytical results, but as far as this reviewer can tell from the background material, there is not yet any correlation with field data. This work seems very worthwhile and should be pursued as a valuable tool.

The second part of this project uses the code described above to support a Sandia project on propellant-generated fracturing technology. In a way, then, the value of this effort depends on the value of the project it supports, but given the assumption (covered more fully in the review of that project.) In brief, the Sandia gas-generator project is valuable, so the analytical support is also useful.

It appears that, for both parts of this project, both quality and productivity are very high, although an estimate of impact must wait until there is validation of results by actual deployment in development projects.

PI Response:

We substantially agree with the reviewer's assessment. GTO has benefitted significantly from LLNL's internal development of the GEOS code. With the code we are at the stage of understanding processes such as the negative feedback process resulting from thermo-mechanical coupling that leads to flow channeling. Some comparision with field results has been performed and general agreement has been found between observations of the decrease in pressure with loss of thermal output which is seen with the thermo-mechanical flow channeling phenomenon. Further comparision with data, to the extent the required data is available, is planned.

Reviewer 23527

Score: 6.0

Comment: The two thrust areas of this project are largely unrelated to each other: EGS validation and Sandia Borehole Gas Generator simulations. While simulation is undoubtedly necessary in the broader context and will ultimately be an important component in EGS development strategies, the goals associated with this project have little operational meaning (they represent the investigation of a basic scenario with unknown site specific relevance) and it is not clear how this project fits in with the other EGS or THM simulation efforts that have been performed over recent years on behalf of the program (e.g. ITASCA work, Golder and Associates work, Code Comparison Study, TOUGH code development, etc.). Does DOE have a strategy or road map for how simulation will be used to support EGS development? It is difficult to assess the technical knowledge gap and goal addressed by this project in light of the absence of guidance from the program in this area. There are many THM DFN capable codes available. Some have been used to explore arbitrary doublet configurations. What seems to be critical at this stage of simulation efforts is to define candidate EGS scenarios explicitly in order to investigate reservoir creation and production strategies. Does such a specification exist? If not, it can be argued that any EGS simulation effort does not address specific goals. This is not an indictment of the quality of work performed in the project. The simulation capability appears to represent critical physics (THM) with the ability to explore the influence of smaller scale (i.e. individual fractures) and composite (i.e. discrete fracture networks) features that are likely to have significant influences in engineered geothermal systems, and the PIs have shown some interesting system behavior. It is however difficult to evaluate the impact of these results in the absence of a higher level reservoir creation and production strategy.

The second thrust of the project, computational modeling of the Sandia explosive fracturing method, appears to address a more obvious gap. The reviewer is not an expert in this area, but assumes that there are not many such simulation capabilities generally available. The use of induced fracture simulation in explosive fracturing would seem to be extremely important for guiding the development of the technique. The simulation tool can be used to modify the design of the explosives and produced injection patterns to optimize the creation of a permeability field. It could also be used to explore multiple field implementation scenarios and develop a basis for comparing the explosive fracturing method to conventional hydraulic fracturing methods. The presented simulations of the HE front propagation indicate that good progress has been made in the development of this tool. With further development and validation, it has the potential to be a very useful design tool for screening explosives for use in fracturing applications as well as means of investigating field deployment scenarios.

If this explosive fracture propagation simulation capability is indeed unique, then it has value because it provides an important tool that can be used to further the development of explosive fracturing technology. The value of the EGS simulation capability in itself is not as obvious given that a variety of such tools are available and there is apparently further code development required for this package to introduce processes such as chemical reactivity and transport.

PI Response:

The reviewer's comments are particularly interesting considering the views of the other two reviewers, and we will address this somewhat different view. Regarding the EGS thermomechanical modeling work, most of the review presentation focused on work done in support of the 2014 GTO-sponsored EGS Validation panel having the mandate of evaluating the general feasibility of the EGS concept.That is to say, the models presented were never intended to consider only one specific EGS scenario. LLNL's objective was to isolate the most important parameters governing critical EGS characteristics such as the longevity of thermal output. Regarding the reviewer's questions about DoE's strategy, we believe that addressing basic questions of the feasibility of the EGS concept is a valid and required activity given the complexity of the EGS regime and the state of research in this area. Participants who provided simulations to the panel of EGS processes including thermomechanical coupling were only LLNL and ITASCA and we are unaware of the "many THM DFN capable codes" that the reviewer refers to. We also believe our simulations of EGS processes can contribute significantly to defining more specific models of EGS that the reviewer feels DoE needs to have. Regarding the statement that non-specific scenario models don't address specific goals seems to overlook the point that any model we evaluate does indeed represent a highly specific EGS scenario. It would be impossible to set up a simulation without completely defining the EGS model under consideration. That is, the EGS models we consider are highly specific. Again, LLNL's modeling objective in doing simulations for the panel was to perform a sensitivity study to determine what natural parameters, such as the fracture distribution, as well as what engineering parameters, such as well orientation, separation, pumping rates, etc., dominate in determing the long-term thermal output of an EGS system. Furthermore, we believe such sensitivity studies are highly significant from both an EGS design and operations perspective. The reviewer repeats the comment that a "variety of such tools is available" for doing EGS simulations. We would appreciate a more specific statement by the reviewer about what tools have the same multi-physics capability as GEOS. We agree that the two tasks (EGS Validation and Sandia Borehole Gas Generator) are somewhat different. The fruitful collaboration with Sandia was formed specifically at the request of GTO.

Reviewer 23567

Score: 8.0

Comment: This is the research project with the focus on development of numerical models related to stimulation of geothermal reservoirs and is in support of borehole gas generator simulation and development. The approach addresses several technical challenges and includes full thermo-hydro-mechanical coupling and discrete fracture network to improve fidelity of the EGS system simulation. Sandia gas generator project and field experiments will utilize data to validate experimental work in the field with models used as a diagnostic tool to improve fracking experiments. As some encouraging initial simulation results demonstrated capable to predict effect during energy release in the wellbore and propagation it into the fracture, there is the potential to incorporate realistic fracture network in the simulation model as well as extend simulations to evaluating effects of multiple well simulations for constructive/destructive interference effects. Timed detonation in multiple wells will be impractical to optimize in experimental way only and supporting modeling will play key role.

PI Response:

The reviewer makes a good point that timed detonation in multiple wells will be impractical to optimize experimentally and that modeling can help elucidate the effects of delays in multi-well detonations.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23454

Score: 10.0

Comment: Both components of the project have benefited from careful design and excellent execution. Because of length limitations on both written summaries and presentations, it is difficult to have a sense of how technical approaches were developed (i.e., what alternatives were considered) but it appears that considerable rigor was employed in the process. Objectives were clearly defined and the technical approach to them was well-focused. Progress appears to have been timely, with reasonable schedules having been met. There have not been any deviations from the original approach, which indicates that it was well planned.

Staffing, equipment, and computational resources appear to be more than adequate, in the sense that shortages in those areas have not limited or delayed the project. Special credit should be given to the excellent coordination and cooperation between the two National Laboratories involved.

PI Response:

Thanks for the kind comments.

Reviewer 23527

Score: 6.0

Comment: The technical approach is not clearly defined in the available documentation for the EGS simulation area. It is also not consistent between documentation sets. For example, the objectives for the EGS simulation effort are "to utilize the GEOS code capabilities to simulate fracture network enhancement through fracking processes as well as to simulate the long-term thermal output of enhanced systems for different injection-production geometries operating over a range of potential subsurface geothermal regimes" according to the statement of work. There is no discussion of fracture network enhancement in any of the provided documentation. The project objective according to the project summary is "to utilize the LLNL GEOS code capabilities, which include full thermomechanical coupling, to determine most important influences on long-term thermal output of enhanced systems for different injection-production geometries operating over a range of potential subsurface geothermal regimes." No fracture propagation modeling discussion is provided in any of the results discussion sections. In addition to this inconsistency, the technical approach is never really defined in terms that can be reasonably evaluated. The approach appears to be to utilize the code. No details are provided in regard to implementation other than a general statement that full THM coupling analysis will be performed for a pre-stressed thermal regime so it is difficult to evaluate this portion of the project.

The Sandia borehole gas generation system simulation technical approach is by comparison better defined. It endeavors to simulate explosion induced fracture propagation by combining shock and gas propagation evolution. It utilizes the CHEETAH thermochemical code to calculate state parameters of the gas products with hand-off of data to the GEODYN hydrodynamic code. The work elements are not described in detail but the general approach is sensible. It is noted that there is no validation component to this focus area. It would be worth linking the fracture characterization efforts associated with the Sandia field trials to validation of the developed code as an official task. This would provide greater confidence that the simulation tool is able generate results that reflect reality. It would also be useful to define at least a few specific deflagration scenarios to be simulated in order to assess prospective field implementations. This could include scenarios that involve pre-existing discrete fracture networks in order to assess the impact that such features might have on explosive fracturing.

PI Response:

The reviewer makes a valid point that the hydraulic fracturing part of the work is mentioned but not covered in the presentation. This was carried out before the work of the EGS Validation panel in 2014 but was not really covered in the presentation material. Please recognize that there was a lot to cover on two separate tasks in a 20 minute presentation and not every aspect of our work could be discussed or covered in the summary. This is a continuing project and the hydraulic fracturing work with associated compressive shadow zone was covered in the preceding GTO review. Extensive discussion of fracture propagation was presented at that time and there have been peer-reviewed papers and Stanford Geothermal Workshop contributions on the hydraulic fracking models. Regarding the Sandia work, we have just gotten to the point where we are doing models that include the physics relevant to the problem. Again, this work is leveraged on other projects. The types of validation the reviewer mentions are in the future and necessarily depend on the existence of adequate geologic descriptions of the borehole regime as well as information about operational parameters.

Reviewer 23567

Score: 8.0

Comment: The technical approach of the project includes novel full thermo-hydro-mechanical coupling simulation achieved by utilizing code developed at LLNL. A discrete fracture network coupled to porous flow is modeled and allows evaluation of stimulation by borehole detonation, which should serve well simulations supporting development of gas generators and related stimulation experiments. The evaluation of the chemistry and its impact has not been completed yet, but may play a role as fractured network could be affected by cracks sealing due to reactive nature of environments.

PI Response:

Indeed, chemistry may play an important role having a significant effect on the longevity of the geothermal system.

STRENGTHS

Reviewer 23454

Score: Not scored

Comment: The principal strength of the project is development of a code linking three physical elements of the subsurface geothermal environment. Designing an EGS project has many variables, the relative importance of which is not completely understood, so there are many possible uses for this code, including optimization of output from an array of geothermal injection and production wells, improved selection criteria for where to site those wells, and smaller scale analyses such as fracture propagation from various types of pressure loading. The latter application is just that used in the cooperative project with Sandia National Labs to assess fracturing with propellants.

It should be emphasized that the code has both an analytic and a predictive value -- It can not only provide guidelines for well design and geometry, but can help to interpret field data, when that becomes available. In the case of propellant fracturing, the code can show what pressure histories in the wellbore will produce optimum fracturing, but can predict fracture extent as the result.

The comprehensive nature of the code means that it will be applicable to a broad array of phenomena, all of which are important to successful development and extension of EGS.

PI Response:

Thanks

Reviewer 23527

Score: Not scored

Comment: The project leverages sophisticated simulation tools that have been developed in other efforts. The explosion simulation tools in particular have the benefit of extensive use in other applications and seem to be an excellent platform for developing a novel and beneficial simulation capability that supports technology development.

PI Response:

Thanks

Reviewer 23567

Score: Not scored

Comment: Full THM coupling has been achieved with efficient simulation code. Models are suitable for EGS stimulation evaluations when gas generators are used, which complements Sandia gas generator project.

PI Response:

Thanks

WEAKNESSES

Reviewer 23454

Score: Not scored

Comment: The principal weakness of the project is that, except for minimal coordination with the Sandia gas generator project, it has not been validated against actual physical data (or at least, that is what this reviewer gleans from the presentation.) All results presented to date appear to be reasonable from the standpoint of basic physics, but it will be extremely useful, in fact essential, to be able to compare calculations with field data so that the code can be "calibrated".

PI Response:

We have just reached the milestone of being able to do the physics necessary for the Sandia problem. Indeed, we need to validate against the Sandia results to the extent a suitable geologic description is available. We are starting to look more closely at matching field data for calibration given that we have achieved an good level of simulation capability.Thanks.

Reviewer 23527

Score: Not scored

Comment: The cases examined for the EGS simulation study are at best broadly defined. How such results will be used is not entirely clear at this stage. The sensitivity study that is to be performed may help clarify the question of relevance but the parameters to be evaluated are never defined in specific terms.

PI Response:

Thanks. We weren't able to go into great detail in either the presentation or summary concerning the sensitivity study. However, we have published papers and proceedings on this. We are now getting to the point of being able to meaningfully analyze data fron specific sites.

Reviewer 23567

Score: Not scored

Comment: Need a comparison and assessment of improvements over other codes and novelty generated with this project compare to other approaches and work already completed in the EGS systems modeling field.

PI Response:

The current code comparison effort that we are contributing to may address most of this concern. Good point. Thanks.

IMPROVEMENTS

Reviewer 23454

Comment: As noted in "weaknesses", the major improvement that could be made to this project is comparison of code calculations to actual data, even if only on laboratory scale.

PI Response:

This is a planned activity assuming that an adequate geologic/laboratory description of the field or lab host regime will be available at some point. Thanks.

Reviewer 23527

Comment: Provide more explicit goals for how the simulations will be used. Ensure that the selection of cases to be evaluated are relevant to the applications of interest. For the explosive fracturing simulations, establish validation tasks to calibrate model behavior against experimental and field data.

PI Response:

Thanks. Good point.

Reviewer 23567

Comment: Need to include chemistry effects to be accounted in the simulation models and code.

Integrate realistic fracture network into demonstrated 2D simulation code to extend model capability for evaluating stimulation efficiency during detonation and move on to multi-stage detonation scenarios where input parameters such as sizing of energetic materials as well as peak pressure and timing effects can be evaluated for creating far field fracturing.

PI Response:

Good comment. Thanks

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Reservoir Stimulation Optimization with Operational Monitoring for Creation of EGS
Principal Investigator: Fernandez, Carlos
Organization: PNNL
Panel: Innovative Stimulation Techniques

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23454

Score: 6.0

Comment: Evaluation of this project's impact is based on two factors: the effect on EGS development of a successful conclusion of this effort, and the likelihood of that successful conclusion.

Clearly, any EGS reservoir requires fracture creation, and a cheaper, more environmentally-friendly method of doing so would be valuable, but it is unclear how much this technology will improve those qualities (i.e., make them cheaper) over conventional methods, and how much that change will affect the pace of development. These answers will only come after scale-up to field-trial results, but even if these are impressive, there is often reluctance in the industry to use unfamiliar methods in major reservoir projects. It seems best to reserve judgement on impact until more data on performance and cost improvement become available.

As for the likelihood of success, several points seem to be unresolved at present. First, all the permeability experiments on core samples only opened a fracture across the wall of the core, a very short distance. Although the polymer fluid showed improved performance over conventional fluid, the crucial factor will be the capability to drive a fracture over long distances, and it's not possible to demonstrate this over the span of a core sample. Second, there has been no demonstration or discussion of a fluid-mechanical flow model that can be used to predict that fracture behavior. Finally, several points in the SOW are devoted to "showing an increase in viscosity" at high temperature and pressure, without an explanation of its importance. If the fluid expansion is localized, then higher viscosity will confine the fluid to produce higher pressures, but it also seems that increased viscosity would hinder the ability to drive a fracture over long distances.

Results to date have been promising, so it is reasonable to be optimistic, but much remains to be done before we can be confident in this project's impact.

PI Response:

We agree with the reviewer that the only way to truly evaluate the potential of PNNL stimuli-responsive fracturing fluids is by performing stimulations in an actual reservoir. We disagree though on the reluctance of industry to use unfamiliar methods for major reservoir projects. We have been contacted by AltaRock Inc, BP, Shell, Chevron and lately by Linde, requesting more information on the current technology as well as what additional studies/resources are needed to accelerate deployment of this technology in actual wellbores. This is a clear indication that novel fracturing fluids are needed to more efficiently and economically perform reservoir stimulation.

About the second part of the comment, we also agree that the lab-scale stimulation exps have consistently demonstrated a major increase in permeability enhancement as compared to conventional fluids and that these results are limited to short distances based on experimental design. This is a limitation that can only be overcome by performing foot (or meter)-scale fracturing stimulation experiments combined with coupled multiphase flow, geomechanics, and reactive transport modeling. This is something that we are proposing for FY16 and FY17. About the role of viscosity, we anticipate that an increase in viscosity will confine the fluid to produce higher pressures as well as to aid in reducing fluid leak off and facilitate the transport of proppants. The rheoreversible nature of the fluid will also enhance fracture propagation by introducing reversible volume expansion combined with low and high viscosity cycles where the polymer solution goes back and forth from a viscous fluid to a thin polymer solution by either modifying the CO2 pressure or by adding a mild acid.

Reviewer 23527

Score: 4.0

Comment: While the fluid that is the focus of this research is interesting, it is not clear why it is believed that this technology in particular will enhance permeability over conventional fluid driven fracture mechanisms. Hydraulic fracturing in general involves the initiation of a fracture utilizing fluid pressure, followed by expansion and advancement of the fracture by addition of fluid to maintain the pressure front at the crack tip. A slowly expanding fluid (i.e. if expansion occurs at subsonic velocities) will effectively create the same effect. Even if the total expanded volume contributed to fracture growth, the increase in fracture size would be small for the 1% by volume contribution provided by the expanding fluid. The basis for expecting permeability to increase should be justified.

The deployment scenario for this technology is also problematic. The fracture must essentially be created in order to deposit the special fracture fluid followed by activation when in place. Activation of the fluid prior to fracturing would fail to realize the benefits of the expansion. The ability to deliver CO2 towards the tip is therefore a challenge. The PI should explain how this would be achieved. Subsequent addition of fluid would be at the well bore entrance. How would this fluid contribute to further crack growth if it is not at the tip? Aside from the unclear basis for expected permeability increase, the lack of a deployment scheme, even conceptual, is a significant barrier to market adoption.

The work performed to date does not seem to address these issues and is not clearly presented. The pressure of the activated fluid prior to fracture is never stated. The permeability increase claim is also confusing. Any open fracture within low permeability rock will have orders of magnitude greater permeability compared to bulk permeability. This holds true for fractures created by water pressurization. Those fractures, if they are tensile, must subsequently be propped open or they will close upon the removal of fluid pressure. Presumably the same behavior will occur with this fracture fluid. This is also a critical issue that would not be addressed by merely extending a fracture.

PI Response:

The first paragraph of this comment seems to indicate that the CO2-triggered volume expansion process taking place in PNNL fracturing fluids was not clear to the reviewer. The volume expansion is not limited to a 1% by volume contribution. The volume increase can be as high as 2.5X the original TOTAL fluid volume when CO2 reacts with the polymer. We believe that this is the main reason why we are enhancing permeability by 5-6 orders of magnitude in highly impermeable ignesous rock at the lab-scale much more efficiently (i.e., pressures above the confining pressure required to create/propagate fractures in the core samples were up to an order of magnitude lower) than conventional fluids.

About the second and third part of the comments, we indeed mentioned during the presentation a few pathways to deploy this fluid in an actual geothermal wellbore. The first approach is to deliver the polymer solution and CO2 simultaneously. The reaction is driven by heat and the volume expansion together with an increase in viscosity is anticipated to occur in a time frame between 1 and 3 min depending on flow rates, temperature gradients, and CO2 and polymer concentrations.

These parameters can be, in principle, fine-tuned to warrant volume expansion in the deepest part of the wellbore. The second approach is to replace injection of CO2 with a bicarbonate solution delivered with the polymer. Bicarbonate is known to decompose with temperature to CO2, water, and carbonate salt. The rate of this process will mainly depend on temperature gradients, and concentration of bicarbonate. This approach then introduces an additional advantage, in terms of controlling the location at which volume expansion will occur, respect to injecting CO2. To further propagate fractures we plan to take advantage of the rheoreversible properties of these fluids. In other words, the ability to revert the volume expansion process multiple times and go from a viscous expanded fluid back to a polymer solution and back to an expanded viscous fluid. This can be done by simply deppressurizing the fluid or by introducing a mild acid and will aid to fracture growth provided proppants are in place to avoid closing back the initial fractures. We believe proppants are required to maintain permeability once the stimulation process is over independently of the fluid technology employed. This was also mentioned during the presentation (slide 14) and during the Q&A session. We also dedicated slides 12 through 15 to describe current work related to the above described processes as well as the technical challenges and path forward to address them. We regret our slides were unclear for this reviewer. For example, the overpressures generated during volume expansion were measured and the values obtained were significantly lower than the overpressures expected based on lab-scale stimulation experiments (slide 13). A plan was proposed to measure overpressures in-situ during FY16 (slide 13 and 14). Another task was proposed to measure CO2 diffusion in already reacted polymer solutions towards addressing questions on fracture propagation/growth (slides 14 and 15).

Reviewer 23567

Score: 9.0

Comment: This project is relevant to optimizing and improving fracking by reducing the number of stimulation stages and especially here to develop novel fracturing fluid which will provide additional mechanical stress. It should provide lower costs of stimulation phase when constructing EGS systems. Major project milestones including target fluid volume expansion and test at operating temperatures have been demonstrated on a small scale experimental setup. Overall project showed solid progress. Work is in progress to establish collaborators network and potentially commercialize technology through licensing.

PI Response:

Thanks

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23454

Score: 7.0

Comment: The design of the technical approach to this project is reasonable, having covered most of the criteria necessary to show feasibility, and the designed approach was executed closely. The work done to date is appropriate to the funding available.

It's difficult to evaluate the technical approach because it is, in a way, incomplete. A great deal of work is required to bring this technology to the point where it can actually support the GTO goals as described in the SOW, and the approach supplied with this presentation covers only a fraction of that work. All the activities described in the approach are essential, but it does not give a sense of how much remains to bring this project to fruition. Many crucial facets of the fracturing process are barely mentioned -- for example, successful creation of higher-volume fractures will make proppants even more important, but there is only one small mention of a "core/shell" proppant, with no explanation of what that means.

Certainly, a detailed approach to further work cannot be planned until preliminary results are known, but it would have been useful for the presentation to give some notion of what would be involved in bringing this concept to actual commercial deployment.

PI Response:

We agree with the reviewer that more work is required to bring this technology to the market. It is important also to remember that a technology usually takes more than three years to be commercialized. This project is in the third year and its evolution was described during the presentation as follows: Year 1, capability development and proof of concept demonstrating large and reversible volume expansion at geothermal P/T conditions and the potential of this volume expansion to more efficiently enhance permeability with respect to conventional fluids. Year 2, a number of lab-scale stimulation experiments were performed to demonstrate the flexibility of this technology to be applied over the entire range of EGS P/T conditions in the US reported by the GTO. During this year we also measured bulk overpressures generated by the fluid during expansion to understand/optimize permeability enhancement. Year 3 (current), demonstrated that this fluid undergoes volume expansion as well as an increase in its viscosity in a wide range of reservoir pHs (3.5-10 as reported by the GTO), we also performed volume expansion experiments triggered by a different source of CO2, water soluble sodium bicarbonate, as a way to simplify the delivery of this acid gas and make it more economical. We then reported the technical challenges and additional work required to facilitate transition of this technology to field deployment (slides 13-15). This include: 1) CO2 diffusion studies in already reacted polymer solutions to ensure reaction at the tip of the fractures and fracture propagation; 2) determine in situ fluid overpressures generated by the volume expansion in confined environments which will also provide information about the bulk modulus for the fluid; 3) perform lab-scale stimulation experiments with sodium bicarbonate as the source of CO2 and compare to the results of permeability enhancement when liquid CO2 is delivered; 4) scale-up stimulation experiments (foot-scale) combined with coupled multiphase flow, geomechanics, and reactive transport modeling to predict fluid performance at the field scale; 5) as a parallel concept we introduced a novel lightweight core/shell proppant. This new technology was briefly mentioned due to time constrains but has been submitted as a second project to the GTO. In summary, we have accomplished a great deal of work for the time and budget available and this technology has generated a lot of good press as well as already attracted a number of stakeholders. A list of tasks have also been identified and proposed to aid to transition of this fluid technology to field deployment.

Reviewer 23527

Score: 4.0

Comment: Some of the characterization tasks of this project have been appropriate and important, such as the rheology studies, but others, such as the volume expansion using sodium bicarbonate have limited value. Critical characterization tasks, such as evaluating the bulk modulus of the fluid were not undertaken. This should have been the first task performed since it quantitatively determines the potential benefit of this fluid. Knowledge of the bulk modulus is needed to calculate the expected pressure rise created by the expansion of the fluid when constrained. If the polymer is compressible, the pressure increase when expansion is impeded will be limited. This is especially important knowledge given that the polymer fraction in the fluid is only 1% by volume. A 2.5 time expansion of the polymer would therefore produce only a 2.5% expansion of the fluid volume if complete expansion occurs. It might be adequate to initiate fracture, but would produce little crack extension so would likely have little influence on enhancing the permeability field. A quick search of the web finds an ASTM standard (ASTM 6793) that describes procedures for measuring bulk modulus up to 200 degrees C. There are a number of companies that advertise bulk modulus measurement services as well.

The hydraulic fracture experiments that were performed appear to be reasonably well done. The middle core specimen on slide 8 is odd. The fracture is perpendicular to the cylindrical axis of the core. This would be expected if the minimum principal stress and maximum tensile stress are in the axial direction. For uniform confining pressure and internal pressurization of a hole within the sample the largest tensile stress should be a hoop stress at the inner wall of the sample. This is consistent with the fractures produced in the far left and far right images on the slide. The middle result is therefore unexpected unless the reviewer is misinterpreting the loading condition of the sample. Perhaps there was a small crack in the sample perpendicular to the core axis that changed the loading conditions.

Finally, there is a chicken and the egg dilemma of sorts associated with the use of this fluid that is not addressed by the technical approach. The fluid must be placed prior to activation which involves pumping, fracturing a crack extension (additional pumping). Thus conventional hydraulic fracturing must be undertaken prior to activation of the polymer. Activating the polymer once it has been placed involves transporting CO2 through the fluid in place to the crack tip. How can this be done? In order to further extend the crack the polymer must be deactivated (how will this be done?), which will produce contraction, followed by reactivation, which will most recent expanded state unless the crack is extended by further hydraulic fracturing. These issues are not addressed in the technical approach and would seem to be important.

PI Response:

In the first paragraph, the reviewer mentioned that other tasks such as the bulk modulus of the fluid should have been undertaken first to quantitatively determine the potential benefit of the fluid. Our approach, however, goes beyond this and consisted in performing lab-scale stimulation experiments in actual EGS rock cores to understand if the volume expansion of these fluids can be of potential benefit for reservoir stimulation processes. As stated before, we successfully demonstrated that PNNL's fluids consistently enhance permeability on highly impermeable igneous rock samples much more efficiently (overpressures measured were up to an order of magnitude lower) than conventional fluids on a wide range of P/T and pHs. We have then proposed a task to quantify these overpressures, which will provide the fluid bulk modulus and will help us optimize the stimulation process. The reviewer, however, mentioned this in the second paragraph but focused only on the result of one of the over 15 stimulation experiments instead of acknowledging the critical importance of the results reported by these lab-scale stimulation experiments.

We respectfully disagree with the reviewer in the last paragraph. We have proposed different approaches to deliver this fluid as described earlier. The first one, is to deliver the polymer solution and CO2 simultaneously. The reaction is driven by heat and the volume expansion together with an increase in viscosity anticipated to occur in a time frame between 1 and 3 min depending on flow rates, temperature gradients, CO2 and polymer concentrations. These parameters can be, in principle, fine-tuned to warrant volume expansion in the deepest part of the wellbore. The second approach is to replace the injection of CO2 with a bicarbonate solution delivered with the polymer. This was a very well received idea by not only the GTO but also by stakeholders including AltaRock and BP. Bicarbonate is known to decompose with temperature to CO2, water and carbonate salt. The rate of this process will mainly depend on temperature gradients, and concentration of bicarbonate. This approach then introduces an additional advantage, in terms of controlling the location at which volume expansion will occur, with respect to injecting CO2. To further propagate fractures we plan to take advantage of the rheoreversible properties of these fluids. In other words, the ability to revert the volume expansion process multiple times and go from a viscous expanded fluid back to a polymer solution and back to an expanded viscous fluid. This can be done by simply deppressurizing the fluid or by introducing a mild acid to aid fracture growth provided proppants are in place to avoid closing back the initial fractures. We believe proppants are required to maintain permeability once the stimulation process is complete independent of the fluid technology employed. Studies to learn about the diffusion of CO2 through an already activated polymer solution and further propagation of the fracture network were proposed for FY16 (slide 14: "Determine CO2 diffusion coefficients on viscous fluids and gels. Data will feed a computational model to estimate diffusion coefficients in large scale fractures"). In summary, although we have shown the significant potential of these novel stimuli-responsive fracturing fluids at the lab-scale, we have identified and proposed additional studies required to transition this technology to field deployment, as was presented at the project review.

Reviewer 23567

Score: 7.0

Comment: The idea of utilizing advanced volume expanding working fluid is very appealing as it allows for improved effectiveness of stimulation with the use of conventional stimulation techniques. Once the technique is proven to work it also can be used in adjacent industries involving borehole drilling and hydro-fracturing, which may include oil and gas. The approach of small scale experimental setup does not necessarily reflect all the mechanism which one could encounter in the field. Current approach for injecting CO2 in the well while pressurizing likely to encounter challenges as fractures will get blocked by polymer as it changes viscosity and may significantly limit fracture propagation. As PI indicated it may require development of sodium carbonite based alternative solution to overcome this obstacle. The current method relying on CO2 diffusion has not yet been proven and may fall short.

PI Response:

We agree with the reviewer and, as mentioned before, a research plan is in place to find the best approach for fluid injection and optimization of fracture creation/propagation.

STRENGTHS

Reviewer 23454

Score: Not scored

Comment: The principal strength of this project is that it has the potential to greatly improve the fracturing process, both lowering the cost and reducing environmental impact. The work done to date is of high quality, and appropriate to the funding available, so this gives confidence that the personnel, facilities, and equipment are adequate or better for the job.

Lab results are encouraging in that volume expansion has been confirmed and permeability enhancement has been shown, although in a rather crude way. Work done has been properly focused toward the ultimate goal of making this technology available in the field for EGS development.

PI Response:

Thanks

Reviewer 23527

Score: Not scored

Comment: The team has strong chemical expertise and chemical characterization capabilities.

PI Response:

Thanks

Reviewer 23567

Score: Not scored

Comment: Active polymer technology is very attractive for use in fracking and potentially very useful to the industry. The key advantages are low cost and potentially reversible volume changes coupled with minimum environmental effects.

PI Response:

Thanks

WEAKNESSES

Reviewer 23454

Score: Not scored

Comment: This project may be over-optimistic in assessing how much work remains before it is likely that an actual field trial or any commercialization takes place. Several major capabilities are not yet sorted out.

1. Diagnostics for assessing fracture formation are not ready. There is some capability of acoustic emission at lab-scale, but this method is not demonstrated at field-scale and alternative methods are not identified.

2. There is no mention of a hydro-mechanical computational model that can be used to analyze field/experimental data or to establish what wellbore conditions will be necessary to propagate fractures in a given reservoir. Modeling will be especially important because there is no empirical data on fracturing fluids with the properties envisioned here. In particular the viscosity change with temperature

3. If fracture apertures larger than conventional practice are created, then a method to preserve them is crucial; proppants for these large apertures are undefined.

PI Response:

We agree with the reviewer that there is still work to be done to transition this technology to the field. As stated before, we have identified a number of studies to assess each of the potential issues encountered during reservoir stimulation. For example, real-time acoustic monitoring is being performed during lab-scale stimulation experiments. In-situ quantification of overpressures generated during volume expansion combined with coupled multiphase flow, geomechanics, and reactive transport modeling was proposed. The goal of the later task is to identify the best approach for fluid deployment in order to maximize fracture propagation over large (hundreds of yards) distances. We completely agree that in order to maintain reservoir permeability for the entire lifetime of the reservoir, proppants are a must as stated by Prof. Moore (U. of Utah), during his talk at the GTO review. Prof. Moore has been working on sintered bauxite-based proppants for over a decade. We have proposed a project in collaboration with Prof. Moore and LBNL on a lightweight proppant technology that was very well received by the GTO.

Reviewer 23527

Score: Not scored

Comment: This project is missing critical geomechanical expertise and the primary tasks fail to characterize important properties of the polymer, such as bulk modulus, which must be used to assess its ability to augment pressurization through constrained expansion. Many of these characterizations could have been performed by other organizations that already have equipment in place that could be used or adapted to make the measurements. A reasonable concept for deployment of this technology has also not been proposed to date. It is therefore unclear how it can be used in practice to enhance permeability.

PI Response:

We disagree with this reviewer. We are working closely with geophysicists and experts in geomechanics and fluid transport including staff with expertise in computational fluid dynamics. As stated previously we have a clear plan to continue learning about these fluids properties and for addressing potential issues during deployment of this fluid technology in the field. This was described in detail during the presentation (slides 12, 13, 14 and 15) and during the Q&A session.

Reviewer 23567

Score: Not scored

Comment: The reduced viscosity of polymer when thermo-chemical reactions took place and volume expanded may be also blocking efficient fractures propagation. More studies are needed to understand how developed polymer technology will behave on a larger scale in EGS system during stimulation. The efficient polymer recovery after expansion needs to be demonstrated.

PI Response:

Agree and a plan is in place to answer these key questions. This also include the potential of this fluid for recycling (slide 14: "Recycling: Quantify polymer mass recovered after lab-scale stimulation by simple depressurization at different EGS P/T conditions")

IMPROVEMENTS

Reviewer 23454

Comment: In spite of the items previously identified as "weaknesses", no specific suggestions for improvements are given. All the work done and that proposed for ongoing effort, addresses the proper topics but is limited by the resources available. Whenever resources are limited, choices must be made and priorities established. It is difficult for a reviewer who is not intimately involved in the project to second-guess the PI on what those priorities should be, so this reviewer will not do that here.

PI Response:

As stated previously, a plan and required resources are in place. The team includes experts from materials and chemistry to geophysics, fluid transport and modeling. We are cautiously positive that we will able to answer some of the critical questions to move this technology forward.

Reviewer 23527

Comment: Address the characterization gaps mentioned in other sections. Develop a deployment concept for fluid activation.

PI Response:

Thanks, plan in place to do so.

Reviewer 23567

Comment: Confirm environmental concerns are low for developed polymer fluid.

Evaluate long term thermal stability of the polymer material at maximum operating temperatures and address degradation mechanisms as requirement for multiple stimulations may need extended working fluid lifetime.

Demonstrate efficient removal of fluid from fractures once expansion has happened.

PI Response:

Good suggestion, thanks. We have the capability to perform long-term chemical/thermal stability studies using HP/HT MAS NMR. About efficient removal of the fluid, we have proposed a task to demonstrate removal of the fluid and recovery of the polymer but it is limited to the lab-scale. However, it can aid to learn about the potential of this technology for reuse in multiple wellbores. Field tests though will be necessary to asses this property in full extent.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Gas Generator Development and Testing for Controlled Rapid Pressurization Using Liquid Propellants for EGS Well Stimulation
Principal Investigator: Grubelich, Mark
Organization: SNL
Panel: Innovative Stimulation Techniques

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23454

Score: 9.0

Comment: This technology has the potential for a major impact on EGS development. The ability to create fractures is clearly essential to EGS and an environmentally friendly way of doing so will become increasingly important. This work is not completely innovative, as similar methods were tried in the 1980s, but advances in modeling, instrumentation, and energetic materials have put this project far ahead of those efforts.

The project has identified barriers to successful development and has developed an approach to each of them. Time will tell whether these approaches are successful, but the way forward seems well organized. Several goals have been met, and are encouraging to further development, but much will depend on progress in the ability to tailor the energetic material burn rates. There is almost no information in the presentation describing how that is done, so it is difficult for the reviewer to assess this likelihood.

This project is greatly enhanced by its coupling to the modeling effort at Livermore, described in another presentation.

PI Response:

We look forward to working with Livermore to make this program successful. At present we are tailoring loading with non-ideal explosives.

Reviewer 23527

Score: 8.0

Comment: Explosives have been used to stimulate production in oil & gas applications for over 100 years, with limited success, and no clearly demonstrated advantages over conventional hydraulic fracture processes. The PI demonstrates a good understanding of this history and the limitations of prior efforts. This research provides a fresh approach to the use of explosives for fracturing with the potential to address many of the shortcomings typically associated with prior art such as excessive near well bore damage and limited range of propagation. While it still remains to be proven in application, the ability to develop multiple fracture propagation paths from the well bore would be a novel feature of this technique with the potential to produce a significantly larger permeability zone in the formation as compared to conventional hydraulic techniques where flow primarily follows the path of least resistance due to the more focused stress regime created by fluid pressurization. The decision to pursue an explosives formulation that produces a reaction type in between a deflagration and a detonation is well thought out from the physics perspective and there appears to have been considerable progress towards the development of the concept to date. A fuel and oxidizer injection and distribution system has been developed to facilitate demonstration of the technique and a limited field implementation has been completed. Characterization of the produced fractures has also been completed to assess the fracture damage zone. These are good results that have been achieved in a reasonable time period.

There has been no genuine effort to understand the economic aspects of the proposed fracturing method at this stage to the reviewer's knowledge, but the ability to perform fracturing without water is intriguing. The logistics of large hydraulic fracturing operations, particularly in shale gas and oil production, involve the transport of massive amounts of material, mixing equipment and pumping equipment with high associated costs. It would be interesting to investigate and compare the operational aspects of the proposed approach to current stimulation methods.

PI Response:

Thank you for the positive comments. At present we are focused on developing a technique/tool. As with everything the economics come from successful commercial deployment. We believe that this has merit in addition to hydraulic fracturing.

Reviewer 23567

Score: 9.0

Comment: Improved stimulation with the goal of creating fracture volume is of key importance for developing efficient EGS system. This project explores energetic materials of different phases to enable efficient fracture propagation by localizing the source of pressure putting it at depth in vicinity of volume being stimulated. Experimental test have been conducted up to date on small volumes of material and a relatively small scale providing basic feasibility insight and will require scale up and significant tests sophistication to achieve final goal of scaling up the approach to be useful for large scale EGS systems and especially effective for stimulating remote volumes for fractures at depth. Gas phase energetic materials seem to provide unique capabilities and large scale experiments needed to help validating pumping ability to overcome pressure drop in deeper wells.

PI Response:

We agree, as time and budget allow we look forward to moving this technology to a full scale field demonstration.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23454

Score: 9.0

Comment: This project has a sound technical approach. The crux of this technology is the ability to control pressure-rate loading on the wellbore wall, and this project's work elements are directed toward resolving that issue. It appears that a logical succession of experiments and analysis have led to progress on all the anticipated fronts.

PI Response:

Thank you for the positive comments.

Reviewer 23527

Score: 8.0

Comment: The work plan and technical approach appear to be sound. The project is based on the premise that high dp/dt rates can produce multiple fractures in comparison to the low dp/dt rates characteristic of hydraulic pressurization which tends to produce single or bi-wing fractures. It also defines what it considers to be an optimal burn rate that lies between a detonation and a deflagration such that the propagation length of the produced fractures are maximized while near well bore damage is reduced. These two guiding principles are a reasonable technical basis for the development of explosive fracturing methods and they represent an improved approach over prior art. The primary project tasks of fuel and oxidizer selection, test rig design and fabrication, explosive characterization, field trials and computational modeling represent systematic first steps to establishing proof-of-concept that explosive detonation can generate significant fracture zones.

The modeling and characterization tasks are particularly important because it must ultimately be established that this technique for creating fractures is an improvement upon conventional hydraulic fracturing methods. This will be difficult to establish from the proof-of-concept field trials because scale up of the technique to more realistic field situations may take some time, but characterization of the produced fractures should help validate and calibrate the computational model of the explosive fracturing process, and this tool can be used to provide an analysis based assessment of the potential fracture damage zone that might be achievable using this technique. The associated permeability field can then be compared to what is achievable using hydraulic fracturing methods. The reviewer recommends that this sort of comparison be used to determine whether or not the proposed method truly represents an improved stimulation approach. It is also noted that an audience member stated during the Q&A session that the production of tensile fractures without proppant injection is likely to result in low permeability of the fractures because they will close after pressure drops off. This is a valid concern, particularly at great depths where lithostatic stresses are high. The PI should address this concern.

PI Response:

Our future goal is to move to deeper and hotter test sites more representative of actual conditions. In this way we can assess the efficacy of this technique directly.

Reviewer 23567

Score: 8.0

Comment: Stimulation approach with utilization of energetic materials likely to involve multiple stages as PI bring it to the attention and at least two phases may be needed to first initiate fractures and then propagate them as far as possible. This seems to require tailoring peak pressures and energy releases using different strategies, which makes a lot of sense. There also seems to be a gain of understanding how energetic materials use should be tailored to maximize the effect of energy release and increasing far field fracturing. An interesting idea of utilizing constructive interference from stimulation involving multiple wells has been brought to the attention and in theory provides additional dimension for maximizing shear stresses which are preferred as most effective in EGS.

PI Response:

Thank you for the positive comments and recognition the potential importance of constructive & destructive interference in multiple simultaneous energetic events.

STRENGTHS

Reviewer 23454

Score: Not scored

Comment: The principal strength of this project is that successful development will make this technology very broadly applicable. "Successful" in this context means that at least the following goals will be accomplished.

1. Propellant will be shown usable at high pressure and temperature.
2. The Livermore model coupled to this project will be able to establish the necessary pressure-time profile for fracture creation at a given depth and in-situ stress.
3. Burn control of the propellant will produce the designed pressure pulse.

If these milestones are achieved, then it is certain that this technology will be widely used in EGS development, and both laboratory and field results to date have been encouraging.

This value of this project is greatly enhanced by the coupled Livermore model, assuming that it is shown to be valid.

PI Response:

We look forward to working with Livermore to insure success.

Reviewer 23527

Score: Not scored

Comment: The project proposes novel adaptations to the use of explosives for fracturing subsurface reservoirs and has the potential to address many of the shortcomings of prior explosive fracturing efforts. The PI has extensive expertise in the explosives domain and has assembled a team that is qualified to address the geotechnical aspects of the project. The technical approach has included limited field demonstrations relatively early in the project giving confidence that technique has at least notional feasibility at this stage. Such demonstrations can be crucial for giving preliminary indication that there is a path forward toward field implementation.

PI Response:

Thank you fo the positive comments and team recognition.

Reviewer 23567

Score: Not scored

Comment: Innovative approach with initial small scale experiments shows promising results. A large number of methods for improving and optimization of effectiveness of stimulation has been left in the project plan.

PI Response:

As we move forward we intend to re-engineer the materials and experiments as needed to focus on the most promising areas.

WEAKNESSES

Reviewer 23454

Score: Not scored

Comment: It is not clear that current seismic or borehole imaging techniques can show the pre- and post-test fracture pattern/density with as much detail as is desirable. Permeability or injection tests, particularly if using zonal isolation, can give an indication of these values, but a more direct image would be very useful.

There have been minor delays because of scheduling problems, but these have not hindered progress.

PI Response:

At present the imaging technique is the best one at hand and compares favorably to the video imaging. Suggestion for other techniques would be appreciated.

Reviewer 23527

Score: Not scored

Comment: The reviewer believes that this is a novel concept with potential to advance geothermal program goals, but the project currently lacks and objective basis for determining whether or not the proposed fracturing method will be an improvement over conventional hydraulic fracturing methods. A task that focuses on comparing the fracture field achievable using the explosive method to hydraulic methods should be added to the project. The concern that production of tensile fractures without proppant injection will result in closed fractures with low or no permeability should also be addressed.

PI Response:

We believe erosion from high velocity gas penetration and shear displacement will prevent closer fracture. Energetic should be considered for near field stimulation and re-stimulation while hydraulic fracturing is viable for far field stimulation.

Reviewer 23567

Score: Not scored

Comment: Large scale validation is very important to ensure successful technology demonstration and usefulness. Conducted small scale experiments do not provide sufficient aspect ratio to retire major risks for far field fracturing.

PI Response:

We are primarily looking at near field effects with this technology. Validation at smaller scales is used for economic reasons and to shake out each technique. We plan to proceed to large scale testing.

IMPROVEMENTS

Reviewer 23454

Comment: No changes in project direction are recommended, although priorities are not always clear. Some development tasks can proceed in parallel, but if a choice in resource allocation is required, then proving that the energetic materials can function at depth and temperature should be favored, because all else flows from that capability. Most important "improvement" is just to get on with the work.

PI Response:

We are presently expanding our scope to consider HNS and PYX with solid explosives. Gas phase mixtures have sufficiently ignition temperature for direct geothermal or oil and gas use.

Reviewer 23527

Comment: See weaknesses section.

PI Response:

Reviewer 23567

Comment: Explore synergy with conventional hydro fracking and explore potential of hybrid approaches to optimize performance of both in the scenario when applied simultaneously.

Evaluate gas and liquid phase gas generator approaches for delivering energetic materials at larger depths close to expected for normal EGS system to overcome future challenges for implementing high viscosity chemistries as may become unpractical.

PI Response:

A synergistic approach with simultaneous hydraulic fracturing may be the optimal approach of this technology. Pre-pressurizing and energetically initiating the fracture process may prove ideal. With the current scope and budget this would be difficult to incorporate at this time but is planned for the future.

Reservoir Fracture Characterization and Fluid Imaging Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Laboratory Evaluation of EGS Shear Stimulation
Principal Investigator: Bauer, Stephen
Organization: SNL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 8.0

Comment: The aim of this project is to produce laboratory-based experimental and numerical analysis results that will provide a physics based understanding of shear stimulation phenomena (hydroshearing) and its evolution during stimulation. Water will be flowed along fractures in hot and stressed fractured rock, to promote slip.

This and other similar laboratory studies will provide much needed data for validating/providing constrains on THMC models of fracture propagation. The design of the apparatus represents a significant accomplishment. The apparatus can vary and therefore control axial compressive (normal) strain, confining pressure, inlet and outlet injected fluid pressure and flow rate, and temperature, although all of these are within relatively narrow ranges.

Progress is good, with the method definitely in a productive phase. Overall, the project appears to be performing well, in that the project aims are solid and have the promise to contribute very valuable data for validating constraints in THMC modelling. The project appears to have established and tested the experimental apparatus, and results are being produced. However, Oklahoma University needs to perform analysis of the experimental results, and provide feedback to Bauer in order to establish further experimental parameters. This is essential, as there is a significant number of variables that can be controlled with the apparatus and testing protocols, a planned approach that seeks to address the conditions of greatest uncertainty will be much more effective than shotgun scatter or matrix approaches will be.

An expanded capability will only be achieved in the second stage of experimentation, when velocity measurements, AE transducers, elevated temperatures and pressures are introduced.

PI Response:

OU is in the process of more detailed/complete comparisons between experimental boundary condition and results and those obltained from numerical analyses. This work (hampered by mild delays due to summer time period and students experiencing internships) is now ongoing. The modeling will seek to assess/compare amounts of slip with experimental work and will also explore mechanisms to cause slip, for example thermal expansion of injected water, and thermal contraction of the rock surfaces--. The 1st locally decreases the normal stress and the 2nd decreases the real area of contact. Systematic studies are to be begun, now that the fairly complicated experimental system has successfully beed desgned, assembled, and demonstrated at elevated temperature, pore pressure, and temperature. Velocity measurements and AE are to be more fully integrated in the test system, once some electrical issues are fully sorted out.

The next stage of experiments will be driven by design prescribed by analyses.

<u>Reviewer 23434</u>

Score: 7.0

Comment: Understanding the impact of hydro-shearing on fractures in EGS fields is required for a true understanding of the sub-surface system. This work has the potential to improve understanding of fracture shear-permeability relationships.

PI Response:

We are continuing to evaluate experimental boudary conidions and compare them to numerical results with a view towards evalauting operative mechanisms and focusing on those that are relevant to field applications.

<u>Reviewer 24876</u>

Score: 6.0

Comment: EGS reservoirs are subjected to natural and induced stress fields and pore pressures that may result in shear displacements along pre-existing mechanical discontinuities such as fractures and faults. Shear displacements can lead to enhancements or decreases in permeability which strongly affect production in EGS. This project seeks to address the potential enhancement of permeability through shear displacements along fractures (“saw cuts”) on flow rates. It was hard to assess the quality of this project because the presentation was slow, confusing and graphs often had no units on the axes. While the equipment is quite impressive, it was not clear why certain test conditions were selected or what the preliminary results (initial testing) mean. In the comparison of the modeling to experiments, the axes for flow and displacement were swapped for the simulated and experimental data sets, and the modeling appears to only capture the gross behavior. Is that sufficient for EGS needs or is matching the details also important? Based on the time line, the personnel appear to have met the targeted dates.

PI Response:

The comment of axes swapping is quite valid and was the result of two groups plotting from the same spread sheet. We humbly apologize for this confusion.

The presenation was deliberately "slow" because a great deal of information was conveyed --and we wanted for the info to be understood. I

In reviewing the slides, one axis was unlabled--and I believe it was described in the presentation.

Matching gross behavior is a start, at this time, we hope to move forward from that point. A purpose of this work is to attempt to study similar physics between an EGS and a laboratory system. There may be connections and comparisons--we hope that the comparisons are valid.

Another purpose of this work is to utilize a numerical modeling approach which is also being used in an EGS application. Complete understanding EGS will never be achieved by a set of lab experiments--we only hope to gain insight into the field situation.

Test conditions: We recall test condition choice was communicated in the presentation. Generally, we wanted to create high temperature, confining pressure, differential stress, and pore pressure conditions upon a simulated fracture in a rock at EGS "relevant" conditions. We did some calculations to indicate that we needed a temperature difference of about 100C to cause slip. So we chose a test temperature of 175C (coupled with room temperature water flow) to achieve the 100C need. Basically we chose these conditions, and manipulated the effective stress and differential stress to be able to control slip. While this may be contrived, it represents thermal manipulation of the effective stress. And such a manipulation may be the cause for flow induced slip in an EGS.

Reviewer 23583

Score: 7.0

Comment: It makes sense that a clearer and more realistic, time-dependent, physics-based understanding of hydroshearing phenomena could lead to new and improved techniques to control, monitor, and optimize fracture creation and thus heat transfer in EGS systems—but not necessarily so. In many laboratory projects like this oversimplification driven by practical necessities leads to non-applicable results and conclusions. That being said, coupling laboratory results with numerical modeling is a key feature of this project and critical in discovering insights into fundamental parameters in hydroshearing. A better understanding of these phenomena might impact our ability to perform, in-field controlled methods to create sustaining EGS reservoirs and close an important existing knowledge gap.

Further, greater insight into hydroshearing fundamentals should reduce costs by modifying existing or creating new, less costly techniques. Performance could be improved if insights allow for greater fracture volume and density per stimulation. Thus, key applications and new markets could be stimulated for reservoir creation, a critical cornerstone in EGS successful implementation, if insights gleaned from this research would generate new field approaches.

Progress is good and results promising: experimental apparatus has been constructed, initial experiments run, and results obtained. If realized, stated objectives to provide insight into the role of fracture slip on hydroshear and toward the relationship between pore pressure and thermal stress and fracture shear deformation, fluid flow and AE, would be very significant to key, critical goals of EGS; create and operate economical, subsurface, heat transfer reservoirs.

PI Response:

We are actively moving towards achieving these goals through analysis/experiment comparisons.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 7.0

Comment: Progress in the second stage will earn a higher score, as a greater range of properties (i.e. flow rate, AE, temperature, pressure) will be tested.

The approach is definitely novel. It recognizes that the dominant fracture mechanism is shear rather than tensile opening. The design of the apparatus allows many of the variables thought to impact EGS reservoir development to be tested; the protocols employed in the first stage of this project appear to be aimed at testing the performance of the equipment as well as providing basic (fundamental) data. The second stage of testing will expand the testing protocol. It doesn't take much imagination to envisage a long term experimental program utilizing several sets of experimental equipment. Hopefully this project will demonstrate the usefulness of the experimental protocol so that further rounds of experimentation continue, and that the results are usefully incorporated in modelling software and thermodynamic data bases.

Overall, I am impressed by the approach developed to enable lab-scale testing of the key parameters of EGS systems. Previously, lessons were learnt empirically in uncontrolled and hideously expensive field 'experiments'.

PI Response:

We are respectfully moving towards achieving these goals through analysis/experiment comparisons whille understanding the limits of laboratory work..

Reviewer 23434

Score: 6.0

Comment: Combining experimental and numerical examinations should improve understanding, but there is a lot going on in this project,

PI Response:

The experiments are in fact quite complicated to set up and conduct. The numerical modeling helps greatly in trying to understand the operative mechanisms. We will continue on this path.

Reviewer 24876

Score: 6.0

Comment: The experimental equipment enables monitoring of displacements, fluid pressures, and flow through a sample with a mechanical discontinuity undergoing shear and in the future will also contain acoustic emission sensors to detect potential “seismic” slip events. The protocol or potential experimental conditions (e.g. injection pressure duration, stresses, amount of displacement allowed) and reasons for the length of the experiments (duration) are not clear. What parameter or duration indicates that an experiment is “complete”? If the experiments are so difficult and time consuming, what are the selection criteria for determining which experiments to run achieve some understanding of shear-enhanced permeability?

PI Response:

Excellent comment. Thus far we have ended tests solely based on observations during the test, for example slip for an extended amount of time, no slip, flow, no flow, end of travel on one of the pumps, etc. In the future, we will let analyses guide the set up of tests and how test sre run.

Reviewer 23583

Score: 6.0

Comment: Overall quality of the technical approach is adequate to perform the work proposed. On the plus side, laboratory experimental apparatus is well-constructed, able to make required measurements and the sensors reliable. Scientific rigor is adequate and work elements, procedures and methods are appropriate in order to achieve project objectives. However, in projects like this details are important. Instrumentation and equipment are deemed adequate for the purpose. Research team is strong and has necessary facilities, expertise and experience. Work elements are general and not specific enough to evaluate proposed experimental methodology.

PI Response:

Another excellent comment. The write up and presentation was somewhat constrained. More detail and rigor will be provided in ongoing drafts of publications of the work.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: The apparatus can control most aspects of a natural EGS system, including composition (brine and rock), temperature (of rock and fluid), strain versus temperature, fluid pressure, making it possible to isolate the relative importance of each parameter to the onset of slip. Further, the apparatus is instrumented to detect these parameters, and additionally chemical and mineralogical components and changes, and the texture and mineralogy of the fracture surface can also be examined directly (i.e. optically and physically, not only by Xray, neutrons or other similar method).

Of the various lab-scale experimental apparatus considered within this stream, this appears to be the most flexible. It has scope to incorporate periodic pressure oscillation, it could be used to fracture foliated samples (i.e. cause opening of fractures rather than cutting the sample - see Improvements), it is linked to chemical kinetic experiments, it operates in shear mode fracturing. The pressure of fluid injection may be limited - it could be interesting to see a scaled-up version with wells constructed to allow higher-pressure injection.

PI Response:

The test system is somewhat flexible in experimental parameters, within apparatus limits. If numerical modeling suggest we need to modify the setup and or test conduct,--we will strive to do so.

Reviewer 23434

Score: Not scored

Comment: Beautiful experimental system, nice core size and reasonable flow/temperature/pressure conditions.

PI Response:

We will continue to attempt to improve the test system (as needed) to achieve stated goals--and only in concert with analysis driven experiments.

Reviewer 24876

Score: Not scored

Comment: The potential strength of this project is the fantastic experimental equipment that is available to study shearing along a saw-cut with and without pore pressure at elevated temperatures and pressures.

PI Response:

We believe the test can succesfully be deployed to study the above stated phenomena.

Reviewer 23583

Score: Not scored

Comment: If project objectives can be met, i.e., a better understanding of hydroshearing physics, then, EGS program goals to characterize, create and operate EGS reservoirs will be advanced significantly because hydroshearing is the process whereby EGS reservoirs are made. This project tackles a critical and significant process in creating fractured reservoirs, namely, hydroshearing. A better understanding of these phenomena would undoubtedly impact our ability to perform, in-field, controlled hydroshearing and close an important EGS knowledge gap.

Hydroshearing fundamental insights have the potential to reduce costs by enabling modifying existing or creating new, less costly techniques. Performance could be improved if insights allow for greater fracture volume and density per stimulation. Thus, key applications and new markets could be stimulated for reservoir creation, a critical cornerstone in EGS successful implementation, if insights gleaned from this research would generate new field approaches. project objectives can be met, i.e., a better understanding of hydroshearing physics, then, EGS program goals to characterize, create and operate EGS reservoirs will be advanced significantly because hydroshearing is the process whereby EGS reservoirs are made. This project tackles a critical and significant process in creating fractured reservoirs, namely, hydroshearing. A better understanding of these phenomena would undoubtedly impact our ability to perform, in-field, controlled hydroshearing and close an important EGS knowledge gap.

PI Response:

We will continue this study, employing a combination of analysis and experimental methods to achieve the goals as stated above.

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: The experiments being run to date have approximated a fracture surface by roughening the cut face. This exposes fresh minerals as the fracture surface, which is probably not natural. It has been recognized for a long time that hydroshearing re-opens existing fractures, rather than initiating new ones. Natural fractures or foliations are generally lined with fracture-filling minerals such as quartz, calcite, chlorite, epidote or clays. See suggested Improvements.

The preparation of the sample is obviously time-consuming and probably relatively expensive. I can see no way around this – the method does appear to allow a lot of use of each sample, and they can probably be re-made and re-used.

Difficulty has been experienced in detecting acoustic emissions. Either/or a quieter environment is needed, or the transducers need work (upgrading, tuning, more, repositioning).

PI Response:

We are working towards solving this set of problems related to the AE system. We feel this is achievable.

Reviewer 23434

Score: Not scored

Comment: Poor characterization of rock fractures prior to experiments.

Numerical modeling does not seem to have the same level of sophistication (yet) that the experiment has, though I understand that is more development work in progress.

Lots of different phenomena are going on at the same time and pulling out what the relevant processes are is difficult with the current methods.

PI Response:

The numerical analyses are ongoing, and quite sophisticated. A great deal of time and energy goes into developing a three dimensional mesh/model which can handle heat transfer, fluid flow, and mechanical response (with a slip condition interface)--none of this is trivial. This is the first comment about the analyses in this comment set. The analyses--are an integral part of this study--perhaps the focus of the presenation was on the experimental work. This is my error. We are actively working on the analyses and using them now to guide experiments.

Reviewer 24876

Score: Not scored

Comment: Sandblasted surfaces are not the same as fractures with asperities. The presenter stated that he didn't think shear displacement would occur if rough surfaces were used. This does not make sense as other groups have used mated-surfaces and achieved displacements. The results from experiments performed on sand-blasted saw-cuts will never capture the range of potential behavior observed for rough mated or partially-mated surfaces, especially if shear-enhanced permeability is the goal. The amount of opening or closing during the shearing process is intimately linked to the roughness of the surface. Often, sand-blasting only produces pits in a surface and is not likely to result in any significant amount of shear contact between what few asperities may exist.

PI Response:

We agree that sand blasted surfaces are not the same as a fractured surface, and that there will be differences between sawcut behavior and fractured rock behavior. We are exploring using rougher surfaces, and better charaterizing surfaces. Shear enhanced permeability is part of the goal; another goal is to use cool water flow while increasing the far field normal stress (by decreasing far field pore pressure) to induce slip.

Reviewer 23583

Score: Not scored

Comment: This is a laboratory-driven inverse problem and data collected will be simulated if the correct phenomena is being measured and modeled. In detail, it is not clear how this will be accomplished when there is a difference. What about chemical effects? Will the impact of ignoring them be wise?

Project stated, "The work will provide valuable input data for stimulation models, thus helping design effective EGS." When the results don't match the simulation how will the research team proceed? This issue is very important because it is at the core of the concept of obtaining insight. Maybe the physics is wrong maybe the apparatus is measuring the wrong parameters or doing the wrong experiment; this issue needs to be addressed. Another important question that needs addressing is, "What is the specific problem we are trying to solve?" The materials presented do not adequately address this question. A "better understanding of hydroshear phenomena" is a very general goal and one possible alternative approach is to answer the question, "What do we not know about hydroshearing that this project will make clearer?"

Specific costs and performance savings are not accessible to quantitative calculations at this time due to the state of understanding of hydroshearing phenomena. Comparing simulation results with experimental results alone does not necessarily produce insight. From the material presented not clear how project will proceed. Work elements are general and not specific enough to evaluate proposed experimental methodology. What are specific hypotheses that are being tested regarding the hydroshearing process? What do we specifically need to know that these experiments/modeling can illuminate and how can you advance our understanding on hydroshearing phenomena?

It is not clear what the specific hypotheses that are being tested are regarding which unknown aspects of the hydroshearing process? What do we specifically need to know that these experiments/modeling can illuminate and how can one advance our understanding on hydroshearing phenomena? These questions need to be addressed.

PI Response:

Our test system is a bit complex in terms of plumbing, jacketing, etc; to have made the test system sufficiently "clean" to be able to handle chemical effects would have made this experimental program cost prohibitive. One cannot do every thing in a labe test--We concede that we are only trying to evaluate thermal-hydrologic-mechanical effects on this test system response. If chemical effects are dominant we are perhaps missing that.

We have sampled pore water with each refill of our fluid flow pumps--we have measured the presence of silica. We have observed some deposition at the flow inlet sites on the rock surfaces.

We think we have stated our goals are to evalaute thermal-hydrologic-mechanical response.

IMPROVEMENTS

Reviewer 23418

Comment: As a way to more closely approximate natural fracture systems, the experimentalists could try using a suite of foliated samples, cut so that the foliation is oriented at the same 30 degree angle as the ‘isotropic’ samples are cut. The sample should not be cut along the foliation, rather the experiment should be run to see if fluid injection under strained conditions causes fracturing of the rock. If this is achieved, it is likely that this will be along a mineral-lined fracture. This should be characterized mineralogically, texturally and chemically at the completion of the experimental runs. It would be interesting to vary the relative angle of the foliation, to see how far off alignment it might be possible to still achieve fracturing.

This experimental apparatus could be used for similar chemical dissolution/precipitation experiments as done by Kneafsey/LBNL.

A wide range of rock types should be evaluated, varying composition, mineralogy, grain size, grain size distribution (e.g. equigranular versus porphyritic), fabric anisotropy.

Include oscillatory/dynamic stressing protocols of Marone/Elsworth (GTP150036).

Include protocols to replicate effect of turning flow on and off – cooling of bores, precipitation due to kinetics.

PI Response:

The comment to use a foliated rock sample is a great positive suggestion. We feel it difficult to use the current test system to do rigorous chemically controlled/monitored work--and we are doing some (for example water chemistry from pore pressure pumps). We are not budgeted (should end there) to evaluate many rock types, while that was an initial desire. we will pursue additional stressing prootcols as directed by analyses.

Reviewer 23434

Comment: Spend a little more time getting an accurate base condition of the fracture prior to the experiment.

PI Response:

Agree, and we plan to do this.

Reviewer 24876

Comment: Potential Improvements: use rough fracture surfaces (mated / nonmated), induce a fracture which is another method for obtaining rough surfaces, at the end of an experiment use a dye to trace the flow paths along or across the saw-cut, include the concept of a system returning to equilibrium after a pressure step (relaxation times, etc.).

PI Response:

We will attempt to use rougher fractures--we are unsure if we can introduce dyes at these conditions.

Reviewer 23583

Comment: Project would benefit if a methodology were developed and communicated on how the model and/or experiments will be modified when results do not match. Initial SOW says, "No risk" and Summary says there are complications, please explain. What about chemical effects? You stated, "The work will provide valuable input data for stimulation models, thus helping design effective EGS." The project would benefit if an example of such input data and why the simulation would benefit. The project would benefit from a more formally stated methodology between laboratory and simulation in order to attain the insight sought. When the results don't match the simulation how to proceed needs to be stated. Project would benefit from a focus on specific phenomena and designing experiments to prove or refute hypotheses regarding these phenomena. Comparing simulation results with experimental results alone does not necessarily produce insight. Not clear how they will proceed. Scientific rigor could benefit from greater concentration on hypothesis testing with regard to furthering our current knowledge of hydroshearing.

PI Response:

We believe we have developed an experimental system in which we can prescribe the confining pressure, temperature, differential stress, pore pressure, and flow rate through a simulated fracture in rock. We have deveolped fairly sophisticated 3-D numerical models which attempt to model, in a fully coupled manner the experiments. Based on the parameters we are studying, we feel that thermal, hydrologic, and mechanical conditions are key drivers in hydroshearing. Based on the above comments, the system has its share of shortcomings. We are not evaluating rock or fluid chemistry in a detailed manner. That does not mean it is deemed unimportant.

Comparison of simulation results with experimental results does not necessarily produce insight. We feel we are collecting a pretty well constrained thermal/mechanical/hydrologic data set response--this data set should be a good test bed for a physics based fully coupled model. Models of this type are used for EGS simulations. Similarly, the physics based fully coupled model can be used to design experiments, and predict responses.

It is a valid comment to request a formally stated methodology between laboratory and simulation. Thus far we have really gotten to a situation where we feel we have a sound experimental system, and a robust simulation method.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006763
Project: Phase I Project: Fiber Optic Distributed Temperature Sensing for Periodic Hydraulic Tests
Principal Investigator: Becker, Dr. Matthew
Organization: California State University Long Beach
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 8.0

Comment: This project has significant potential but is in early stages, hence a score of 8.

The project has made good progress by demonstrating an ability to use a Distributed Acoustic Senor (DAS) for the purpose of measuring hydraulic pulsing.

This appears to be a very useful complement to fluid tracers, but with the additional possibility of detecting connected fracture zones from the outside of well casing, identifying zones suitable for perforation.

The use of packers to isolate zones of a well for hydraulic stimulation has been problematic in open hole sections. The application of a Distributed Acoustic Sensor on the outside of well casing (presumably can't be cemented) for periodic hydraulic testing to identify hydraulically-connected zones between wells may help to solve the issue of poor zonal isolation. Packers work well with casing: the testing protocol being investigated by this project will mean that the reservoir section of a well can be cased, and perforated only where good hydraulic connection is measured.

PI Response:

It may be possible to measure pressure in a cemented well if the cement is deformable. We will perform simulations to test this in Phase 2.

Reviewer 23434

Score: 7.0

Comment: It's fairly early in this project, so there is little that has been accomplished to date, but the impact could be large later in the development of this technique.

PI Response:

None

Reviewer 24876

Score: 7.0

Comment: Geothermal reservoir efficiency requires connectivity between wells. The goal of this project is to provide an additional tool for determining the hydraulic connectivity between wells with a down hole fiber-optic pressure sensor for less cost than traditional tracer techniques. This project is in the early phases of demonstrating the robustness of DPS (distributed pressure sensors) for determining changes linked to well-to-well connectivity. So far, laboratory and computer simulations have been performed to test different components of the DPS approach. The laboratory component would benefit from additional experiments (see weaknesses) while the computational component has provided important insight into data analysis and interpretation (e.g. sensitivity of phases, frequency tuning, etc.).

PI Response:

None

Reviewer 23583

Score: 5.0

Comment: Providing greater spatial information of connectivity between wells would lead to more precise fracture monitoring and creation. Initial positive laboratory technology performance results are promising and very simple, numerical modeling is demonstrating potential insights barriers of the true potential of the technique. If project objectives can be met, EGS program goals to characterize, create and operate EGS reservoirs would be advanced. In addition, project addresses our lack of understanding of created fracture network size, volume and location, a significant EGS knowledge gap. Knowing where the created fracture system is located would certainly reduce costs, improve performance and stimulate key markets for reservoir monitoring, a critical conversation in successful EGS creation and monitoring. Laboratory work is ahead of schedule, an appropriate simulator, COMSOL, has been selected, and initial simulations have been run with promising results. If project reaches stated objective of developing and testing DAS-based periodic hydraulic tests conducted during EGS extraction operations to provide greater spatial information than constant rate or pulse injection tests, then key, critical goals of EGS; to and operate economical, subsurface, heat transfer reservoirs, will be advanced.

PI Response:

None

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: Translates deformation/strain at all points along a fiber optic cable, detected by laser, to pressure. Proposes that periodic pulsing induced by pumping may be used to detect fluid communication between wells. This will provide some, but not all, of the same information as fluid tracers, but may be installed permanently and does not require a suspension of operation, and therefore may provide a more practical method of reservoir monitoring.

One application is to help solve the issue of poor zonal isolation in open hole sections. Those sections can now be cased, without the loss of the ability to determine zones of good hydraulic connection between wells. The casing can be perforated, with packers used to isolate the rest of the well while hydraulic stimulation is conducted in the desired interval.

Hydraulic pulsing can be tuned, for example phase is more sensitive to heterogeneity than is amplitude, and frequency can be tuned to local reservoirs.

PI Response:

None

Reviewer 23434

Score: 7.0

Comment: The confirmation of the equipment in the lab space is logical. The next step of bringing this equipment to a well characterized fractured field and testing it these makes sense as well.

PI Response:

None

Reviewer 24876

Score: 8.0

Comment: A nice feature of using DPS for measuring well-to-well connectivity is that EGS production is not significantly affected by running a test. The methodology will use pressure pulses in the injection well and DPS in the production well during operations. For perforated wells, the DPS will sense pressure change along the entire length of the well to monitor changes in connectivity. Until field testing is performed, it is not possible to assess the success of the method.

PI Response:

None

Reviewer 23583

Score: 5.0

Comment: Overall quality of the technical approach is acceptable. The scientific rigor is adequate and work elements, procedures and methods are appropriate in order to achieve project objectives. Instrumentation and equipment are deemed adequate for the purpose. Research team is adequate and has rudimentary facilities, some expertise and understanding of the technology.

PI Response:

None

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Appears to have passed first stage-gate criteria – demonstrating the ability to translate acoustic signal to pressure using a light interference in a fiber optic cable. This allows a distributed acoustic sensor to become a distributed pressure sensor.

DAS relatively cheap to install as part of well completion.

Permanent installation – provided it is not damaged by any subsequent well perforation.

Offers benefits of using a cased well section, which facilitates zonal isolation using packers for hydraulic stimulation of specific intervals which can be measured by the DAS and periodic hydraulic testing to show good hydraulic connection between wells.

PI Response:

None

Reviewer 23434

Score: Not scored

Comment: The ability to better understand fracture flow conditions from distributed wellbore measurements is needed in EGS. If this can be proven to be functional the benefits should be large.

PI Response:

None

Reviewer 24876

Score: Not scored

Comment: The use of the flexible liner is a nice work-around to the potential problem with open hole wells where the pressure is nearly uniform throughout the well. An important component of this project is the field test to be performed at Mirror Lake Fractured Hydrology Site in New Hampshire. This is a highly studied fractured site. The proposed field experiments coupled with the collaborative work with colleagues from Cornell will enable a data set to fully evaluate DPS for assessing well-to-well connectivity (i.e. assess the resolution of the device as well as the data analysis/interpretation approaches).

PI Response:

None

Reviewer 23583

Score: Not scored

Comment: Greater spatial information regarding connectivity between wells would lead to better monitor and fracture creation because we never have a clear subsurface view of where the created fractures have gone. Certainly, EGS program goals to characterize create and operate EGS reservoirs would be advanced if this project was to reach its goals. Overall, the EGS reservoir would benefit with a higher fracture density and a larger surface area heat exchanger. Sustaining the reservoir would also be easier and less costly. Experiments have been successfully performed ahead of schedule and an appropriate simulator, COMSOL, has been selected. Initial simulations have been run and results are promising. Developing and testing DAS-based periodic hydraulic tests conducted during EGS extraction operations to provide greater spatial information than constant rate or pulse injection tests, would be a benefit to EGS implementation.

PI Response:

None

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: My understanding is that a separate fiber optic cable is needed to be used for temperature (DST), and temperature is backed out for the calculation of strain (and therefore pressure) on the DAS. Can both be done on the one cable?

I assume the cable needs to be in hydraulic connection with the reservoir. A distributed temperature sensor will still work once it is grouted in the annulus between casing and rock. However, the distributed pressure sensor presumably won’t work if it is grouted against the well casing, rather than the rock wall. This may present difficulties in placing the cable – it will probably need to be held against the rock wall using an expandable flexible liner, while the casing is inserted and grouted into place. This is an additional expense, but if it results in a well that can effectively be perforated at several levels to allow multiple connection points to the reservoir, then it is a significant advance.

PI Response:

The reviewer is mistaken, a separate fiber optic cable is not necessary only a second fiber within the cable. Most FO cables have multiple fibers installed anyway. Also, we do not propose a flexible liner for application in geothermal systems, only in our field test. We believe that pressure can be sensed through well cement/grout if it is plastic. Most cements are plastic (e.g. bentonite/cement mixtures) to prevent gaps between casing and the borehole wall. We will examine this pressure transfer using COMSOL simulations in Phase 2.

Reviewer 23434

Score: Not scored

Comment: It's early in the project, so difficult to analyze fully the scope of the work.

PI Response:

None

Reviewer 24876

Score: Not scored

Comment: Additional laboratory experiments should have been (or should be) performed that subjected different parts of the fiber cable to different pressures and temperatures. Such experiments could be used to calibrate the sensitivity and ability of the fiber sensor to delineate differential pressures along a borehole. While the cyclic loading of the entire fiber enabled calibration of strain to pressure, it is not clear how or if this relationship is affected by differential pressure (or the spacing between pressure changes along the fiber) as well as the effect of elevated temperatures such as those found in deep EGS boreholes. What is the minimum required separation between fractures or pressure differences in order to locate the change? Can you differentiate temperature-induced strain from pressure-induced strain?

PI Response:

Firstly, we can account for temperature because we measure temperature along the cable using DTS. Secondly, the ablility to distinguish pressure responses at different locations along the cable is a function of the sampling resolution (0.25 m in the iDAS) and the signal to noise. Because we will test the ability of the instrument to detect pressure changes at a point in our field experiments (using the flexible liner equipped boreholes) we did not see the need to develop laboratory tests for the same response.

Reviewer 23583

Score: Not scored

Comment: How the technique will actually characterize hydraulic conductivity between wells is not clear to this reviewer. How detecting a varying signal generated downhole, in another well, will map out hydraulic pathways as presented in the viewgraph cross-sections, needs to be explained further. Blotto-line, how hydraulic path information can be generated from this technique is not obvious. A critical question to be addressed: How will this technique better inform fracture pathway locations? Clearly, cross-borehole pressure variations can be detected but pathways could be very circuitous. The design of the laboratory experiment with the coiling of the cable enhanced the signal every time the cable wound around, whereas, in the field the detection will have to be made over a very small single cable section pressed up against the borehole. The laboratory experiment needs to be re-run. This reviewer is concerned about signal to noise S/N ratios. S/N issues are critical to extracting a signal in the field, how will they be reduced? What are the specific simulations and techniques to be applied to reduce noise? Maybe another Go/No-go milestone is needed if S/N cannot be enhanced. In proof-of-concept field projects like this, experimental design is critical to a positive result. Significant planning and careful design are needed. Concerned about the field experiment and what exactly will be tested. If the subsurface is unknown then the results will be ambiguous. What are the specific hypotheses that are being tested regarding the ability of this technique to "inform perforation"? Are the specific hypotheses that are being tested in the field regarding the ability of this technique to "inform perforation"?

PI Response:

The reviewer has a great number of concerns, most of which we felt we addressed in the presentation. Firstly, we did not claim we could infer complete pathways from one well to the next, only hydraulic connections at discrete depths. Well completions can be adapted based on reponses, even if the entire pathway is not known. The reveiwer does raise a key point, which is signal to noise. The purpose of the field tests is to determine if pressure can be measured at descrete depths. We hope that the S/N will be suffient to make pressure measurements from cable strain information. The laboratory tests suggest that it will for head oscillations of 5 cm or more. This is the first time pressure has been measured using DAS. We do not test hypotheses about application in the field, we only hypothesize that hydraulic responses can be measured by DAS in a fractured rock system. We believe this would be a highly significant advancement and, if successful, can be followed by later projects at a geothermal field site.

IMPROVEMENTS

Reviewer 23418

Comment: The system needs to be demonstrated, and deployment methods worked out.

PI Response:

None

Reviewer 23434

Comment: Reviewer did not provide comments for this criterion.

PI Response:

None

Reviewer 24876

Comment: Use the fiber as an acoustic wave or pressure wave sensor to obtain additional information about the subsurface.

PI Response:

None

Reviewer 23583

Comment: The project would benefit from a re-run of the laboratory experiment with the proper length of cable not a coiled cable. A more detailed list of simulations to be performed, leading from simple models to more complex, realistic models with the final simulation mimicking the field test are needed. Project would benefit from a strong focus on reducing signal-to-noise ratio. Field experiment should be careful though-out to guarantee a non-ambiguous result. Work elements and milestones would benefit from more specificity, especially for the field experiment.

PI Response:

None

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Viability of Sustainable, Self-Propping Shear Zones in EGS: Measurement of Reaction Rates at Elevated Temperatures
Principal Investigator: Carroll, Susan
Organization: LLNL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 8.0

Comment: Precipitation or dissolution of minerals in EGS fractures will undoubtedly occur; the question is at what rate and whether it can be controlled by chemical (or other) treatment. Reliable data on reaction rates for the range of fracture-filling minerals at geothermal conditions is necessary to improve THMC models being used to make predictions about fracture behavior in EGS systems. The data being generated by this work fills an important data gap, and will greatly help to answer questions about how long fractures will stay open – especially in combination with the collaborative work by Kneafsey (LBNL).

The project has really only just started. A great many more mineral species and compositions need to be tested against a range of fluid compositions and temperatures.

I have given a score of 8 because of the impact that the work will have, even though the project is in its early days.

PI Response:

Reviewer 23434

Score: 8.0

Comment: Understanding the reaction kinetics of relevant minerals under geothermal conditions (which is not available in the current literature) is critical for improving models and a general understanding of subsurface evolution. This project is accomplishing this for illite and chlorite.

Publishing the reaction rates (and updating them as the description improves) on the geothermal data repository is a great way of getting this data out to the people who need it.

Collaboration with LBNL is good. The results from this project should feed into future models by LBNL. To date it doesn't seem like there was a lot of direct collaboration because this project is focused on fundamentals of individual mineral reaction rates and the LBNL project is looking at more complex fractures in natural rocks, BUT the building of this collaboration is an accomplishment that should improve future efforts at both labs. '

Biotite experiments seem like it may or may not work. The effort to test this logical as the project winds down, but it may not actually yield meaningful results yet because of experimental difficulties.

PI Response:

Reviewer 24876

Score: 10.0

Comment: Accurate predictions of EGS reservoir permeability require knowledge of mineral reaction rates under elevated temperatures. Mineral responses to chemical reactions can lead to enhanced flow from dissolution of fracture-filling material or sealing from precipitation in fracture voids or mobilization of particles. The results from this research project provide fundamental insight and quantitative information on chemical reactions rates of fracture-filling minerals at temperatures comparable to those found in EGS systems. The project has made significant progress and produced high quality results for chlorite and illite for temperature ranges from 100o to 275o and for a range of pH (3 – 10). The quality of the data arises from the number of experiments that were performed at each conditions (the relatively small error bars) and the good physical understanding of the results. The work on illite was particularly fascinating as deviations from the low temperature reaction rate arose because of unexpected precipitation of secondary minerals at elevated temperatures. The project is nearing completion and appears to be on target for determining reaction rates for biotite, refining the illite dissolution rate equation and submitting the results to the Geothermal Data Repository.

PI Response:

Reviewer 23583

Score: 8.0

Comment: Expanding the geochemical kinetic database for shear zone fracture minerals to 300°C will improve EGS models and further our understanding of fracture pathway performance, ultimately, positively impact reservoir creation, monitoring and operations performance models. Surely, rock/fluid chemical interactions are essential to EGS reservoir creation and longevity. If project objectives are met, EGS program goals to more realistically model the creation and operation EGS reservoirs will be advanced. This is a good project and this work needs to be done and extended to other key minerals.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 9.0

Comment: The approach is straightforward, which means it is robust. The apparatus and testing protocol varies pH, temperature, surface area and solution chemistry to derive a reaction rate. 'Pure' (meaning only one composition) mineral separates are used which eliminates mineral chemistry as a variable within a single experiment (i.e. it is controlled). Solids are characterized before and after runs, using TEM/SEM/XRD/BET.

I have scored 9 because the experiment controls most of the variables relevant to mineral solution/dissolution to replicate a natural EGS system. The only variable not being examined is strain.

PI Response:

Reviewer 23434

Score: 9.0

Comment: By using a proven technique, as shown by previous publications on the researchers, this has filled gaps in the literature required for accurate geothermal field modeling. As such, the approach is good. The need to have this data is there in the modeling realm, and this is an excellent example of the fundamental relationships being determined experimentally.

PI Response:

Reviewer 24876

Score: 10.0

Comment: The mixed flow reactors and particle characterization techniques (TEM/SEM/XRD/BET) appear to be appropriate based on comparison to other data available in the literature at lower temperatures.

PI Response:

Reviewer 23583

Score: 8.0

Comment: Overall quality of the technical approach is superior because methods and procedures are simple, clear and rigorous. Scientific process is followed throughout and is exceptional. Obviously, work elements, procedures and methods are appropriate in order to achieve project objectives. The scientific design is simple, elegant yet very effective. Research team is strong and has necessary facilities, expertise and experience. Research team has years of experience in application of these laboratory techniques to geothermal-relevant materials. Results demonstrate the superior quality of the technical approach. If project objectives can be met, EGS program goals to characterize, create and operate EGS reservoirs will be advanced significantly.

PI Response:

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: This approach is able to provide well-constrained reaction rates, which will help to reduced uncertainty in THMC models. Key parameters (brine composition, mineral species, and temperature) will be able to be varied so that individual EGS projects can have their mineral reaction rates characterized.

PI Response:

Reviewer 23434

Score: Not scored

Comment: Equipment to run the tests, knowledge of what the gaps in the field are and personnel available to run the tests are all strengths of this project.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The strengths of the project include (1) a good experimental approach, (2) significant progress on measuring reaction rate for common fracture-filling material at EGS temperatures (3) a good data set that is being made available to the community through the Geothermal Data Repository and (4) the development of rate equations that can be used in existing reactive flow codes.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Improving EGS numerical models' ability to more realistically simulate rock/water reactions will further our understanding of fracture kinetics and eventually fracture pathway performance. Specifically, adding geochemical, laboratory-derived, reaction rates for key shear zone fracture minerals to 300°C and deriving equations useful to modelers will improve EGS models and further our understanding of fracture pathway performance. At this stage, laboratory results are promising and insights into rock/water interactions are becoming clear. If project objectives are met, EGS program goals to more realistically model the creation and operation EGS reservoirs will be advanced.

This project directly addresses our lack of understanding of EGS-relevant rock/water interactions; a significant EGS knowledge gap. Knowledge gained in this project directly influence reactive models used to create and operate EGS reservoirs. Including the experimentally-determined chemical effects of water/rock integrations for models that attempt to simulate EGS fracture systems creation and operations would certainly reduce costs, improve performance and stimulate key markets.

Experiments have been successfully performed on schedule and appropriate dissolution rate equations have been derived for chlorite and illite for a broad range of temperature and pH. Reaching stated project objectives of measuring and deriving dissolution equations to be used in models then will positively impact key, critical goals of EGS; create and operate economical, subsurface, heat transfer reservoirs.

PI Response:

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: A wider range of minerals (both species and compositions) and fluids (brines) needs to be run. The use of catalogue standards may be convenient, but is not specific enough to the geothermal reservoirs for which the data is being generated for. The project may need to do its own mineral separation from relevant EGS reservoir rocks.

Consideration should be given to incorporating strain into the experimental apparatus.

PI Response:

Reviewer 23434

Score: Not scored

Comment: Inability to run complex minerals through the system could be a weakness of this project. But since the project goals are to understand fundamentals so they can be applied to more complex situations, I think this is a minor weakness at best.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The reaction rate equation does not appear to capture the observed experimental behavior. While the presentation showed different theoretical expressions for rates, it was not clear how to select the appropriate one. More work is needed in this area.

PI Response:

Reviewer 23583

Score: Not scored

Comment: The project has few weaknesses, however, some issues come to mind that might strengthen the project further: sample preparation realism, secondary precipitation problems and solutions, sensitivity to fluid composition, and to grain size.

PI Response:

IMPROVEMENTS

Reviewer 23418

Comment: Incorporate strain – create a flow reactor through two pressure plates to simulate grain size comminution during fracture movement.

Only a limited range of mineral species will be available as separates from the Clay Mineral Society (or wherever they have been sourced to date) – consider making your own collection for separation.

A wider range of fluid compositions needs to be tested – especially of brines.

Ngothai et al. (2011) summarizes experiments on fluid-rock interaction for EGS (Ngothai et al., 2011, a review of current experiment fluid-rock interaction in EGS reservoirs, New Zealand Geothermal Workshop Proceedings 2011, 21-23 November, Auckland, New Zealand). This may be of interest, and differs from the current work in that determining reaction rates was not the purpose. However, the experimental process of the University of Adelaide workers described in that paper is similar. The paper also points out that the Energy & Geoscience Institute utilizes flow reactors for the purpose of rock chemistry characterization prior to reactive tracer studies.

PI Response:

Reviewer 23434

Comment: Publication outside of the geothermal data repository would enable a broader set of researchers to access this data.

PI Response:

Reviewer 24876

Comment: It would be interesting to examine the effect of grain size and fines on the measured reaction rates.

PI Response:

Reviewer 23583

Comment: Laboratory projects like this, experimental design is critical to a positive result. Significant planning and careful design are needed. The project would benefit from explanation of experimental controls and scientific rigor involved in making the measurements to strengthen the understanding and appreciation for the results for non-specialists.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006761
Project: Surface and Subsurface Geodesy Combined with Active Borehole Experimentation for the Advanced Characterization of EGS Reservoirs
Principal Investigator: Elsworth, Dr. Derek
Organization: The Pennsylvania State University
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 8.0

Comment: The project makes the point that EGS reservoirs are stress-sensitive, and all THMC properties influence a reservoir via effective stress. Effective stress influences permeability, reactive surface area and induced seismicity. Measuring movement within a well, or deformation at surface in real time, will give information about changing strain, and therefore about changing conditions within the reservoir.

Work to date has concentrated on surface geodesy, and separately identifying how the HPP tool needs to be upgraded to be able to operate at higher pressure and temperature. The surface deformation resolution available from tilt meters is impressive, as demonstrated by other researchers' previous studies at several (shallow) geothermal fields.

I have scored the project at 8 because of the potential impact of the work, and not higher because the project is in early stages and has not yet demonstrated the combination of multi-modal surface geodesy with parameters recovered from the HPP tool to image flow structure in an EGS reservoir.

PI Response:

Reviewer 23434

Score: 8.0

Comment: The development of the HPP for use in geothermal fields should result in a very useful measurement of subsurface fracture properties.

The models and description of idealized subsurface activity to measurable surface deformations appears to provide meaningful results to compare field measurements to, which should result in improved understanding of EGS field management techniques.

The large number of publications already prepared from this work highlights the progress and the desires of the researchers to get this information out and used.

PI Response:

Reviewer 24876

Score: 8.0

Comment: Identifying and characterizing potential EGS subsurface reservoirs as well as long-term monitoring of productive reservoirs requires robust and hopefully somewhat inexpensive geophysical techniques. This project presented two approaches for characterization of reservoirs: (1) a surface geodetic method that responds to subsurface strains and (2) a borehole technique (hydraulic pulse protocol – HPP) for probing properties of mechanical discontinuities such as fractures, in-situ. For the surface geodetic method, preliminary modeling has been performed to determine if the strains/displacements/tilts would be large enough to measure for a given set of assumptions (i.e. an idealized EGS subsurface reservoir). The approach is based on existing ("off the shelf") analytical and numerical approaches for deformations caused by temperature changes and fluid pressures. The results to date demonstrate that sufficient displacements and tilts should occur as a reservoir is altered by production.

The HPP is currently in the design/assessment phase: what capabilities are needed for given temperature and pressure ranges. The proposed approach is interesting as it enables perturbation of a fracture under reservoir conditions in the subsurface. It is too early to judge the quality of this approach.

PI Response:

Reviewer 23583

Score: 6.0

Comment: Proving the feasibility of measuring reservoir characteristics, insitu, such as, permeability and stress, using a modified, downhole HPP tool coupled with surface tilt data could lead to better informed fracture creation, monitoring and operations. If project objectives can be met, EGS program goals to characterize, create and operate EGS reservoirs would be advanced. Project has just started, initiated in 2105. Initial research demonstrates the potential usefulness of geodetic signals to infer reservoir evolution and development of methods to link observed seismicity to permeability evolution have been initiated. If project reaches stated objectives: 1) establishing if geodetic signals are available at sufficient magnitude for current instrumentation, 2) determining advantage of downhole measurements, 3) developing methods to combine these data into information on the reservoir evolution, and 4) defining the feasibility of a tool surviving EGS environments, then key goals of EGS; to create and operate economically, subsurface, heat transfer reservoirs will be advanced.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: The project identifies that EGS reservoirs are stress-sensitive, and seeks to use information about deformation, fluid injection and recovery rates to infer and/or image flow structure in EGS reservoirs in real time.

In order to utilize strain information, it must be measured. The researchers are investigating improvements to a borehole tool to enable measurement of key reservoir characteristics related to fluid transmission, heat transfer and the propensity for induced seismicity at temperatures ~300 °C and pressure ~100 MPa. Also, measurement of surface deformation by elevation and tilt sensors is being investigated.

The researchers present the mathematics behind the models that predict inflation/deflation at surface resulting from deformation with a deep geothermal reservoir. This work predicts that surface elevation changes fall beneath the sensitivity of instrumentation, while tilt and strains are generally detectable with tilt meters.

Measured deformations are larger than the source volumes reasonably expected from volumetric sources alone.
I have scored 8 because the approach is novel, recognizing the fundamental nature of an EGS reservoir as being strained. A higher score may eventuate depending on the outcome of the work.

PI Response:

Reviewer 23434

Score: 8.0

Comment: This project felt like two separate projects, both of which are good, but joined together in an ad hoc manner.

The development of the HPP tools for direct measurement of subsurface fracture properties seems like a meaningful tool development that will be useful in direct field measurement of fracture properties of encountered natural fractures and/or generated fractures.

The linkage of the surface properties to understanding reservoir evolution is important to understanding the longevity of EGS fields is also useful.

But the linkage of these two things in one project is a bit confusing. Both seem logical, both seem to be developing meaningful results (i.e. a useful subsurface tool and meaningful parameters to compare surface measurements to), and both appear to be well managed and well thought out.

PI Response:

Agreed that it really is two separate projects. Joining them together yields some economy of scale but makes it busy for a single gradaute student who will be stretched by its scope.

Reviewer 24876

Score: 8.0

Comment: The scientific approach for the surface geodesy approach has been well thought out, conceptualized and analyzed rigorously with existing analytical and numerical solutions.

PI Response:

Reviewer 23583

Score: 5.0

Comment: Overall quality of the technical approach is acceptable. The scientific rigor is adequate and work elements, procedures and methods are appropriate in achieving project objectives. Research team is adequate and has rudimentary, basic facilities, some expertise and adequate experience.

PI Response:

Ouch!

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Detection of subsurface deformation due to contraction by cooling may be more representative of fluid pathways than mapping by acoustic emissions. Acoustic emissions can occur without any fluid movement along the fracture, and so are not necessarily representative of created reservoir volume. The volume of cooled rock may be backed out from the amount of surface tilt observed. However, this does not provide an estimate of the whole volume of the geothermal reservoir, rather the volume of the cooled part of the reservoir.

PI Response:

Acoustic and geodetic techniques are largely complementary - geodesy will pick up aseismic deformations and changes in permeability related to these. Acoustic techniques will detect permeability changes beyond the cooling front. Together, they provide more information than separately.

Reviewer 23434

Score: Not scored

Comment: Combination of the testing development of the HPP to measure in-situ fracture permeability and the ground measurements enables two different, yet important aspects of EGS systems to be examined.

PI Response:

Reviewer 24876

Score: Not scored

Comment: If this technique works, the surface geodesy will provide a method for monitoring subsurface geothermal systems without having to drill.
The development and deployment of the HPP will lead to important brand new datasets and insights into fracture behavior at elevated pressure and temperatures in-situ. The strong analytical background of the PI on coupled processes improves the potential for success of the project.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Project explores the feasibility of applying an HPP tool combined with surface tilt to address our lack of knowledge of created fracture network characteristics and processes; a significant EGS knowledge gap. Further the project seeks to explore the usefulness of combining these data with surface tilt data to further constrain fracture conditions. Being able to directly measure subsurface reservoir stress and strain would be useful in designing and operating EGS systems and would most likely reduce costs, improve performance and stimulate key markets for reservoir creation, a critical cornerstone in successful EGS implementation and monitoring. Insitu stress and strain measurements would be useful in designing and operating EGS systems and would most likely reduce costs, improve performance and stimulate key markets for reservoir creation, a critical cornerstone in successful EGS implementation and monitoring.

PI Response:

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: The project is not sufficiently advanced to see results of the application of the HPP tool for the purpose envisaged by the project proponents.

The HPP tool will sit within a well through which water is injected for reservoir stimulation. The tool should be effective at measuring strain during early reservoir growth, but may be less effective as the reservoir grows and deformation occurs further away from the tool.

It is not clear from the presentation and other documentation that this work will be applied at a developing geothermal field, or how it may be otherwise validated.

PI Response:

The expectation is to attach a subsequent phase of this work into FORGE.

Reviewer 23434

Score: Not scored

Comment: Could be two different projects and could possibly be fragmented work because of competing interests between the two different types of studies that are being done here. Does not appear to be the case, but a potential concern.

PI Response:

The team has the breadth to be sufficiently strong in both domains.

Reviewer 24876

Score: Not scored

Comment: Surface geodesy responds to the entire rock volume and all of the natural and anthropogenic processes that occur within or that affect this volume. What if pre-existing cracks/fractures external to this volume take-up the strains caused by contraction or expansion of the thermally altered rock and results in no measurable changes at the surface? It would seem that this is reservoir dependent (rock type, structural features, local tectonics, temperature gradients, etc.). The simple parallel fracture model, the spherical cow (reservoir) and isotropy, result in a highly idealized system, unlike nature. Geodetic techniques are and have been used in the oil and gas community, yet it is not the premiere technique and interpretation is often complicated.

PI Response:

Agreed. These points are valid - geodesy is not THE Rosetta Stone in deconvolving the system - but is an important and useful data set and source of information to add to existing techniques. We presented data that defines some conditions where useful information may not be available due either to resolution limits or due to the physical limits of the systme (the soft reservoir and low modulus in extension). Defining these limits is important in being able to decide when useful information can be recovered, and when it cannot.

Reviewer 23583

Score: Not scored

Comment: Not sure the measurements will be useful to practical monitoring and operations tasks at the typical depths of EGS reservoirs. Signal might be too small. Also, a separate monitoring borehole is needed, which dramatically increases the cost of using this technique. There is significant risk this might not work. Is there going to be a formal joint inversion of tilt and insitu stress strain measurements? If tool cannot survive EGS subsurface environments then will all the previous work be for naught? Shouldn't the detention of the tool to HTHP be tested first? In proof-of-concept projects like this significant planning and careful design are needed in order for a clear, unambiguous result. With this in mind, this reviewer is concerned about the field experimental design strategy.

PI Response:

Tilt and strain signals do not seem too small. Signal to noise ratios are typically enhanced by installing sensors in shallow boreholes (CALIPSO project in Montserrat at 200m depth). All the geodesy will work independent of the HPHT HPP - so little risk there.

Whether the tool can survive is an open question - still to be addressed. Likely a very radical change in design will be needed but the desireability of such measurements seems true.

IMPROVEMENTS

Reviewer 23418

Comment: None to suggest at this stage - it will be very interesting to see the application of this work to a live EGS stimulation.

PI Response:

Reviewer 23434

Comment: An EGS site where the HPP tool will be tested and the insar measurements will be performed would be a good addition to show the usefulness of this project.

PI Response:

Agreed. But beyond the scope of this 1-yr project, that this reviewer noted was 2 ad-hoc projects together.

Reviewer 24876

Comment: Model more complex systems.

PI Response:

Understanding the controlling variables in a straightforward manner is the best way to understand the potential and limitations of the proposed techniques and the utility of the tool. We certainly have complex coupled THMC tools that could easily be applied to this - but distilling the essential first-order elements of behavior of these processes is likely more informative - to us and to others.

Reviewer 23583

Comment: The project would benefit from a 'back-of-the-envelope' calculation on the economics of the technique to demonstrate the possibility of receiving a measurable signal in the field at EGS depths and potential cost savings over current geophysical techniques. Project would benefit from modifying schedule to perform the HTHP work first in order to stave off unnecessary future costs if the tool cannot handle the EGS environments. Project needs to answer this question directly, how does the technique reduce fracture network creation costs? From the materials presented the answer to this question is not clear to this reviewer. Project would benefit from expanded work elements with more specificity, especially for the inverse technique to be employed and the data analyses.

PI Response:

As noted before - the success of geodetic imaging does not rely on the success of the HPHT HPP. They are two separate projects in this regard.
The technique can reduce the prospects of thermal short circuiting over operation by imaging the form of depletion in the reservoir - catching this early can avoid the loss of the reservoir - epecially in the case where we move towards "engineering" the reservoir through things like cased holes or horizontal boreholes.

Understanding material properties such as permeability, friction, RSF has the potential to inform the stimulation effort - defining zones for stimulation and how to prescribe the stimulation schedule.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006765
Project: Laboratory-Scale Characterization of EGS Reservoirs
Principal Investigator: Ghassemi, Dr. Ahmad
Organization: The Board of Regents of the University of Oklahoma
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 8.0

Comment: The project seeks to scale EGS reservoir conditions to the laboratory, enabling controlled experimentation without the huge cost and uncertainty of drilling. It addresses many of the significant uncertainties in EGS reservoir creation, and will undoubtedly contribute to a better understanding of how to create and manipulate EGS reservoirs. Therefore, the project is well-aligned with the R&D needs to enable EGS development.

The project is at only an early stage. It appears that the experimental equipment is ready for deployment.

Other laboratory-scale EGS experiments start with fractured samples – this experiment seeks to fracture the sample as part of the experiment. However, it does this in normal rather than shear strain, whereas field experiments have determined that fractures in EGS reservoirs occur as shear fractures. There may be ways to establish shear strain (see comments in other review sections). The experimental apparatus allows measurement of most key parameters, such as temperature, pressure, recording and location of acoustic emissions, fluid composition, mapping of developed fractures via Xray, and characterization of the fracture surface after the experiment.

A score of 8 is given because of the contribution that I am confident this research will make to addressing knowledge gaps in EGS development, although the method has not been fully developed and implemented yet.

PI Response:

Reviewer 23434

Score: 6.0

Comment: This project will evaluate the fracturing potential of a well within a large-lab-scale block of material under elevated pressures and temperatures. I think this is interesting as a 'next generation sandbox' type of model, similar to flow of DNAPL in the vadose zone that have been accomplished before, but I'm not convinced the results will be directly meaningful to the geothermal community.

All of this review is a bit premature since the project has not had a lot of time to mature yet.

But, the matter of scale concerns me. The scale of the structure of the rock material (sierra white granite) is fixed, the scale of the 'reservoir' to be looked at is limited to (18") ^3, but the wellbore size is variable. Putting a 5-spot reservoir into an 18"x18"x18" block of rock should require that very small well bores are used, but the PI is planning on 2 cm diameter well bores. If there is any way to reduce that dimension while still getting the instrumentation in and the ability of the wells to hold the pressure required to fracture the rock, I think that would be an improvement.

Also, how this scales up to 'real field' conditions isn't really clear. More of a connection between this lab scale and full scale would make for a better project impact.

All that being said, I think it's an interesting project and it may yield useful insights into fracture generation dynamics. It feels more like a project that is well suited for the enhanced oil/gas recovery as opposed to geothermal EGS stimulation though.

PI Response:

We are closely examing the scale issue to optimize the wellbore size.

Analysis of the experiemental results will characterize surface area of created fractures and so the work is strongly related and useful to EGS.

Reviewer 24876

Score: 8.0

Comment: Stimulation and maintenance of productivity in geothermal reservoirs requires a firm understanding of how to stimulate the rock, the permeability structure (before and after stimulation) and the area/volume stimulated. This project seeks to quantify these parameters for elevated temperature and pressures often found in geothermal reservoirs but under the controlled environment of the laboratory. The work to date has focused on the experimental set-up and characterization of one rock type. The refurbishing of equipment, design and initial testing of experimental components (heaters, flat jacks, AE layout) and some experimental protocols have been completed. This is a complicated but important experimental system for determining the effect of reservoir conditions on inducing fractures and the resultant effect on permeability. This project is in the early phases but the PI has made significant progress on the experimental set-up and the characterization of at least one rock type (work associated with Task 1), and appears to be on track for Task 2.

PI Response:

Reviewer 23583

Score: 9.0

Comment: This project seeks to improve our state-of-the-art knowledge in EGS reservoir creation, monitoring and operations by building and testing laboratory-scale, cubic reservoirs of appropriate rock type, under EGS temperature and pressure conditions, and apply a range of current EGS techniques to this more accessible volume, albeit at a smaller scale, and make measurements and observations. In addition, this particular configuration would allow new ideas to be tried that would be prohibited ably expensive in the real subsurface. In fact, project proposes to have miniature wells drilled to induce fracturing and initiate fluid and heat transfer and a host of other EGS technologies/concepts/ideas will be implemented and tested. These tests will include tracer, SP, and AE technologies. Finally, high-resolution X-ray techniques will map fractures within the cubic rock volume both before and after the stimulation. This will potentially enable estimation of stimulated volume, permeability structure, surface area, sweep efficiency, heat recovery, and finally, improve use of injection induced seismicity in reservoir characterization and will lead to new and improved techniques to control, monitor, and optimize fracture creation and thus heat transfer in EGS systems. A great idea and a superior project.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: The experimental apparatus utilizes 13” cube rock blocks, significantly larger than other laboratory fracture experiments in EGS. Hopefully this extra volume will mean that the results are more faithful to full-scale rock stimulation behavior. The larger sample size allows ‘wells’ to be ‘constructed’, which hopefully will allow significant fluid pressure to be applied. A single injector well will be constructed, centered in the block, and surrounded by four ‘producer’ wells. Five detection methods will be employed: fluid temperature for temperature break-through; fluid tracer; acoustic emission; electrical self-potential; and X-ray imaging. Results will be integrated to better describe and assess reservoir stimulation and production.

PI Response:

Reviewer 23434

Score: 6.0

Comment: The large-lab-scale of these tests are unique and could yield interesting insights. The lack of any discussion about scaling factors and how the results obtained from these experiments will be made to be relevant for processes at the larger scale though troubled me a bit. While these drilling of a five spot formation into a relatively large block of rock to create fractures will look a bit like a small scale EGS reservoir, I'm not convinced that the phenomena observed in the lab will correlate in a meaningful way to fracture formation in an actual field.

Scanning these small fractures networks with 18" of rock using CT scanning seems like it will be difficult, if not impossible as well. But as I stated previously, this project is in the very early days of starting and this problem may be overcome.

PI Response:

Yes, upscaling is always an issue in subsurface science and engineering. We hope to be able to contribute to solving its challenges through this project.

Reviewer 24876

Score: 9.0

Comment: The experimental design is well thought out and contingencies have been planned where needed. The use of flat jacks in the system will allow true-triaxial conditions, while the heater design will enable the implementation of isothermal and non-isothermal conditions. Both of these components are necessary to achieve the goal of stimulating rock under reservoir conditions.

PI Response:

Reviewer 23583

Score: 8.0

Comment: Overall quality of the technical approach is superior. The facilities are excellent and resident staff experience in performing these kinds of experiments has matured over many decades of pertinent O&G experience. The scientific rigor is exceptional and work elements, procedures and methods are appropriate in order to achieve project objectives. However, projects like this are defeated in the details and those details have not been presented, but hopefully, all technical challenges can be surmounted. Instrumentation and equipment are deemed adequate for the purpose. Research team is strong and has necessary facilities, expertise and experience.

PI Response:

Yes, we agree that details provide many unforeseen challenges. We are dealing with practical issues as we go on and hope to present results and more details in the near future.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: The large sample size is strength of this project. It is almost an order of magnitude larger in scale than the other laboratory EGS experiments presented in the Peer Review, and is therefore scaled down less than the others. One thing that this allows is the creation of ‘proper’ wells, with high-pressure injection, along with the use of more than two wells.

The apparatus allows many types of measurement to be made during and after the experimental runs.

PI Response:

Reviewer 23434

Score: Not scored

Comment: Nice large rocks to work with. Unique experimental setup and experience with AE measurements.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The well thought out and detailed understanding of the experimental equipment and the experimental protocols.

PI Response:

Reviewer 23583

Score: Not scored

Comment: This project will construct and test laboratory-scale, cubic cut rock under EGS temperature and pressure conditions and uses this laboratory EGS field equivalent to test EGS technologies for fracture creation and reservoir monitoring. If project objectives can be met, EGS program goals to characterize create and operate EGS reservoirs will be advanced significantly. Project has the potential to address all critical and significant processes in creating, monitoring, and operating EGS reservoirs by building a physical model of the EGS subsurface environment in the laboratory. This miniature EGS model along with scaled-down wells, monitoring instrumentation will surely impact our ability to "close" many important knowledge gaps. Greater insight into EGS subsurface fracture processes, technology effectiveness and a whole slew of other EGS-related phenomena will undoubtedly, reduce costs, improve performance and stimulate key markets for reservoir creation, a critical cornerstone in EGS successful implementation. Experimental apparatus has been designed and initial rock samples acquired. Progress is good. Research team has the necessary expertise, experience and skills to make this project a success.

PI Response:

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: Shear stress cannot be imposed. This means that in the case where wells are drilled to equal depth, any failure will be open mode failure, which is not how field EGS developments occur. Perhaps this can be manipulated by drilling the wells to a depth that results in an oblique plane of hydraulic stress, which would result in shear stress (see experiment of Bauer et al.). Alternatively, anisotropic (e.g. foliated) samples could be used, with careful positioning of the wells to match up with the foliations.

PI Response:

We are considering these possibilities. Initially, however, we want to avoid complications.

Reviewer 23434

Score: Not scored

Comment: Lack of a way to upscale the results to a meaningful field scale (or at least a lack of discussion of ideas on how to) is a bit troubling. Student labor force being able to work intermittently on the project may end up being a problem as well, though time will tell. It seems like there are a number of hurdles that still need to be overcome, but there is time.

PI Response:

Please see previous comments on upscaling.

Reviewer 24876

Score: Not scored

Comment: How do you get “high-resolution” X-ray CT images on a 0.3 x 0.3 x 0.3 m block of rock? What is meant by “high-resolution”? The layout of the AE sensors was not discussed. Is there an optimal design for the proposed 12 AE sensors in order to achieve maximum potential coverage? Is this something you can model before building them into the system?

PI Response:

We have approached a commercial entity to do this work and are currently negotiating the details and possibikity of implementation.

Reviewer 23583

Score: Not scored

Comment: The overall question to be answered by this project is: Can EGS simulation be scaled-down and still provide realistic and significant results?

Also, can wells and other current EGS techniques be implemented in the cube under pressure?

It is not clear to this reviewer what specific problems the project is trying to solve?

Specific costs and performance savings are not accessible to quantitative calculations at this time due to the state of scaling-down knowledge.

Testing hypotheses is an effective method to guide experimentation/simulation experiments.

PI Response:

IMPROVEMENTS

Reviewer 23418

Comment: Shearing rather than opening is the dominant fracture mechanism identified in EGS developments to date. It is unclear how the experimental apparatus will be used to simulate shearing.

PI Response:

That is true in some cases. But in many situations mode 1 fractures, or a combination of the two , prevails. In fact we hope to be able to design experiments to test different hypotheses.

Reviewer 23434

Comment: More consideration on how to scale up these tests early on (i.e. now) in the planning process may result in more meaningful results from this project.

PI Response:

Reviewer 24876

Comment: Use your AE sensors to send/receive a signal every so often to characterize changes in the rock properties during testing in addition to using them to “listen” for acoustic emissions. Quantification of the changes in compressional and shear wave velocity (attenuation) of the "intact" rock with temperature and pressure is required to accurately locate AE events.

PI Response:

Thank you for the useful suggestion.

Reviewer 23583

Comment: The project would benefit from making a list of specific problems and associated experiments to further illuminate the value and logic of this particular approach. Another idea to think about to improve the project is hypotheses testing. This could help focus the experiments to look at and illuminate certain EGS-based questions and/or known problems.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006766
Project: Seismic Analysis of Spatio-Temporal Fracture Generation During EGS Resource Development
Principal Investigator: Gritto, Dr. Roland
Organization: Array Information Technology
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 7.0

Comment: This project seeks to provide more reliable and accurate estimates for source type, slip and fracture area of induced seismic movements during EGS hydraulic stimulation. Further, it seeks to estimate spatio-temporal variations of fluid saturation in the subsurface, from microseismic monitoring data. If the project can demonstrate the mapping of fluid movement, this will be a significant advance for EGS developments.

The project has demonstrated the feasibility of determining joint waveform first-motion source solutions and finite-source slip models. Source rupture models vs magnitude for five events were found to be consistent with extrapolation of a published area vs magnitude relationship.

This project is in early days, with little to report in the way of results other than progress in compiling earthquake catalogues in the Prati 32 development area of The Geysers. This area was chosen because of high quality geophone and broadband seismometer networks in an area of high seismic activity.

The project is rated at 7 because of the promise that the approach holds to map the movement of fluid during hydraulic stimulation, and is not rated higher because the research is in early days and has not reached a significant results stage. If shown to be successful, the project will undoubtedly shape the way that EGS developments are instrumented for seismic monitoring, as well as how hydraulic stimulation is conducted and how the field is developed subsequently (e.g. targeting of production bores).

PI Response:

Reviewer 23434

Score: 7.0

Comment: Early days, difficult to fully analyze the entire project at this point, but seems like it's on a good path.

PI Response:

We agree that it is early, however the initial results do appear promising.

Reviewer 24876

Score: 9.0

Comment: Monitoring EGS reservoirs during production is complicated by the range of processes occurring in the subsurface both induced and natural. This project seeks to use induced seismicity to monitor spatial and temporal changes in fluid saturation as well as use source mechanism to determine fracture/rupture volumes. The beauty of this project is the amount of data available, data from sensors that record different frequency ranges and data from an ongoing production site with a long history. The PI has made significant progress on the cataloging of events, testing of depth location methods and identifying the need to relocate events using a 3D inversion technique with the double-difference location method. One of the strengths of this project is using the frequency content to develop scaling relationships. Frequency content is linked to the magnitude of the event and in turn the area of rupture. This approach uses full wave-form information which is most ideal for developing better methods for interpreting "fracture" size. They appear to have made significant progress on the first Tasks of the project. The results of this project will improve EGS site monitoring using induced seismicity.

PI Response:

Thank you for the assessment. We think the moment tensor results thus far are very promising, and we have gathered enough information to begin developing a more automated approach to analyze more events.

Reviewer 23583

Score: 9.0

Comment: Project proposes application of state-of-the-art seismic techniques from NNSA-funded R&D, such as, Moment Tensor (MT) analyses and double-difference Wadati (DDW), to the Prati 32 Geysers EGS demonstration project, multiple data sets, to estimate spatio-temporal variations of fluid saturation in subsurface and characterize subsurface fractures, stress state, and location of inject ate. This project is cortical to understanding, controlling, monitoring, and optimizing fracture creation and thus heat transfer in EGS systems. These proposed techniques, MT and DDW, are standard earthquake analysis techniques but are advanced to the geothermal industry for various reasons and specifically have not been applied to EGS MEQs let alone an EGS stimulation data set. Another positive note is that the three data sets include BB and high frequency geophones. This is a great idea and a superior project.

PI Response:

Reviewer 29854

Score: 8.0

Comment: The project aims at improved monitoring of evolution of fluid flow during EGS development. This addresses a gap in the geophysical characterization of flow pathways, a critical parameter of EGS.
This project is in its initial phases and current progress is reasonable.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: Any new method for interpretation of seismic data for monitoring of hydraulic fracturing is of interest. This method will attempt to identify fluid movement during injection stimulation, and assess uncertainty in micro-earthquake locations.

The Prati 32 well stimulation at The Geysers was chosen because of the extensive high-frequency geophone and broadband networks.

The project has two components: subsurface fluid imaging, and subsurface fracture and stress characterization.

For subsurface fluid imaging, a double-difference Wadati (DDW) will be used to estimate spatio-temporal variations of fluid saturation in subsurface and assess applicability during EGS development.

For subsurface fracture and stress characterization, the first-motion mechanisms will be compiled to determine source solutions for events spanning the volume of the stimulation experiment. Solutions for possible non-double-couple, volumetric source components will be examined. An empirical rupture area – magnitude – corner frequency relationship to enable mapping of seismic fracture density model will be developed for the Prati area. Source parameters will be determined and used to investigate the evolution of in-situ stress during the stimulation experiment.

Previous study of the earthquake catalogue at The Geysers suggests that Vp/Vs can reveal fluid saturation, with injected waste water seen to re-saturated part of the reservoir.

PI Response:

Reviewer 23434

Score: 7.0

Comment: PI seems knowledgeable of the hurdles that remain and has what appear to be logical approaches to accomplishing this work.

PI Response:

Reviewer 24876

Score: 8.0

Comment: The project uses a sound technical approach for interpreting seismic data that uses information from the full waveform to obtain spectral content, first motion and amplitude attenuation. The spectral content and amplitude are directly related to the event but also to other scatterers (fluid saturations, fracture clouds, etc.) in the subsurface that interact with the waves. Their analysis approach should help identify the phases that are sensitive to fluid saturations and delineate “fracture” parameters.

PI Response:

Reviewer 23583

Score: 9.0

Comment: Overall quality of the technical approach is superior because the methods and procedures are simple, clear and rigorous. The scientific process is followed throughout and is exceptional. Obviously, work elements, procedures and methods are appropriate in order to achieve project objectives. The scientific design is simple, elegant yet very effective. Research team is strong and has necessary facilities, expertise and experience. Research team has years of application of these techniques to EQ research and it is exciting to think of the possibilities. Results demonstrate the superior quality of the technical approach. If project objectives can be met, EGS program goals to characterize create and operate EGS reservoirs will be advanced significantly.

PI Response:

Reviewer 29854

Score: 8.0

Comment: The project focuses on developing seismological methods to constrain the evolution of fluid pathways. In particular, tools are developed or implemented for the characterization of micro-earthquake source parameters that may relate to the geometry of fracture networks (fracture orientation, size, and aperture). Methods are also applied to image Vp/Vs ratios, possibly related to fluid saturation, with a technique focused on scales within MEQ clusters. Other factors affecting Vp/Vs, besides fluid saturation, may need to be considered. The plan includes uncertainty quantification and elements of experimental design. Model-dependent trade-offs among source parameters in conventional source estimation approaches (e.g. stress drop vs rupture speed) are mitigated by finite source imaging techniques. These robust source parameters will be the basis for scaling laws that will link moment to fracture density and stress. The effect of 3D velocity model uncertainties on MT inversion may be important to consider. The methods are developed and tested in a well-chosen dataset from The Geysers (Prati 32).

PI Response:

We agree that Vp/Vs is effected by parameters other than fluid saturation. In previous studies Gritto et al. (2004a, 2004b) investigated the effects of fracturing on Vp, Vs and Vp/Vs. In general, an increase in fracturing, which is associated with the generation of EGS, will lead to a small decrease in Vp and a larger decrease in Vs, resulting in an increase in Vp/Vs. Increasing the fluid saturation in the subsurface will also result in an increase in Vp/Vs and typically constitutes a more pronounced change. In our previous study, we found that fracture induced velocity changes do not represent a first-order effect at The Geysers (Gritto, 2014). Nevertheless, we will investigate whether the observed changes may be attributed to the generation of fractures in the subsurface.

We agree that 3D effects could be important in both waveform and amplitude based source inversions. Our initial work is based on the assumption of 1D models. However, we will derive more representative models from 3D velocity models obtained through body wave tomography, which we developed during our previous project at The Geysers. In our study we will address uncertainty in the results due to the application of different velocity models. However, future work should address in more detail 3D wave propagation and the effect on recovery of source parameters. We are presently developing that capability in other studies of nuclear monitoring and mining induced seismicity, and that capability will be available for studies at the Geysers in the future.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Selected a demonstration area with high-quality data. Has produced a compilation of high-quality seismic data for further study. Has developed a joint waveform – first motion – amplitude source-type moment tensor inversion method.

The Vp/Vs relationship has previously identified changes in fluid saturation at The Geysers. New work will provide additional information from the seismic data, with improved automation.

PI Response:

Reviewer 23434

Score: Not scored

Comment: Obtained data and demonstrated feasibility of the methodology of this technique within the first months of the project shows that the researchers are well suited to accomplish the goals of the project.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The broadband data set which will enable creative new ways for interpreting variable magnitude seismic events for relevant reservoir parameters.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Clearly, this project focuses and advances critical and significant EGS monitoring knowledge gaps that will also benefit EGS reservoir creation and operation using induced and natural seismic events. This project will surely impact our ability to "close" many important EGS knowledge gaps. Greater transparency and understanding of EGS subsurface stimulation processes enabled by this project will undoubtedly, reduce costs, improve performance and stimulate key markets for reservoir creation, a critical cornerstone in EGS' successful implementation.

Considerable progress has been made considering the fact that research team did not start until 2015. For example, complied four high-frequency data catalogs, developed a joint-waveform, first motion, amplitude, source-type MT tensor inversion methods for these low amplitude events. Progress is excellent.

If stated objectives, to provide an opportunity to observe using AEs the entire EGS process from initial reservoir stimulation to final thermal depletion on short time scales, are realized new and innovative applications will emerge and these technique will be applied at all EGS sites. These techniques could have potentially far-reaching impacts on key, critical goals of EGS; create and operate economical, subsurface, heat transfer reservoirs.

PI Response:

Reviewer 29854

Score: Not scored

Comment: The project aims at improved monitoring of evolution of fluid flow during EGS development. This addresses a gap in the geophysical characterization of flow pathways, a critical parameter of EGS.
This project is in its initial phases and current progress is reasonable.
The project focuses on developing seismological methods to constrain the evolution of fluid pathways. In particular, tools are developed or implemented for the characterization of micro-earthquake source parameters that may relate to the geometry of fracture networks (fracture orientation, size, and aperture). Methods are also applied to image Vp/Vs ratios, possibly related to fluid saturation, with a technique focused on scales within MEQ clusters.
The plan includes uncertainty quantification and elements of experimental design. Model-dependent trade-offs among source parameters in conventional source estimation approaches (e.g. stress drop vs rupture speed) are mitigated by finite source imaging techniques. These robust source parameters will be the basis for scaling laws that will link moment to fracture density and stress.
The methods are developed and tested in a well-chosen dataset from The Geysers (Prati 32).

PI Response:

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: None identified so far

PI Response:

Reviewer 23434

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The project should provide a comparison of other analysis techniques on the same data set and the effect on interpretation. A little of this was given in the presentation.

PI Response:

Other techniques applicable to imaging Vp/Vs based on the same data include seismic tomography. We will compare our results to the findings of a parallel DOE study conducted by Lawrence Berkeley National Laboratory (Rutqvist, PI) on the northwest Geysers EGS demonstration project. As part of this study, seismic tomography was conducted to assess subsurface changes during the water injection phase.

Reviewer 23583

Score: Not scored

Comment: The only weakness discovered by this reviewer, though it not really a project weakness but more like an intrinsic, fundamental problem that could derail this team's best efforts, is that majority of MEQs are of such low magnitude that first arrivals are weak and difficult to detect and determine first motions. And, the bulk of the events are way below 2.5 Mo. It will be a challenge for the research team to develop new methods to access the large number of events below 2.5 Mo.

PI Response:

It is true that as we analyze smaller events the work will get more difficult and fewer events will have the complete analysis. However, we have already investigated events to catalog magnitude of 2.0. All of these events have good signal-to-noise ratios indicating that we can go to lower catalog magnitudes. For a number of these catalog M2 events the Mw is in fact lower than 2.0. The idea of developing the scaling relationship is that if it can be shown to be effective over a relatively wide range then it will provide extrapolation power to lower magnitudes for fracture area. Relative moments can be obtained from spectral ratios when events are too small for effective moment tensor inversion. We feel that the initial results are very promising, however only time will tell as we are able to analyze more events and push to lower magnitudes.

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

IMPROVEMENTS

Reviewer 23418

Comment: No suggestions

PI Response:

Reviewer 23434

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 24876

Comment: Can you get any data from a high-frequency (1 kHz) downhole array? Is one available?

PI Response:

While such data would indeed be valuable for our project, such an array does not exist at The Geysers. The geophone network operated by LBNL includes a few borehole stations, each equipped with a single-level 3-component 4.5 Hz geophone, typically deployed at a depth of ~50 m below surface.

Reviewer 23583

Comment: None can be found that would benefit this project.

PI Response:

Reviewer 29854

Comment: Other factors affecting Vp/Vs, besides fluid saturation, may need to be considered.

The effect of 3D velocity model uncertainties on MT inversion may be important to consider.

PI Response:

Please refer to our reply to reviewer 29854 in the section "SCIETIFIC/TECHNICAL APPROACH".

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Sustainability of Shear-Induced Permeability for EGS Reservoirs
Principal Investigator: Kneafsey, Tim
Organization: LBNL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 8.0

Comment: The sustainability of EGS fractures – how long they will stay open – is a key question in EGS development, one that has perhaps not received enough attention, and one that field experiments have not been able to quantify. This lab-scale experimental system addresses the key areas of mineral dissolution and precipitation, and deformation, to inform the selection of reservoir rock type for optimization of EGS development.

Although this project has not yet delivered much in the way of results of analytical runs, I have given it a relatively high score because of the relevance of the approach to key knowledge gaps about EGS. Quantifying mineral solution and precipitation within stimulated fractures, at reservoir conditions, is of high priority.

PI Response:

Thank you.

Reviewer 23434

Score: 8.0

Comment: The use of a novel lab scale fracture flow measurement device with improved measurement of deformation is a notable achievement. I don't think there are many results yet that show how this will be able to be scaled up to relevant field scales, but the building of the equipment and spreading knowledge about how this could be used to evaluate fracture evolution are critical steps towards accomplishing just that. I feel that the research is going in the right direction, just needs a bit longer to bear fruit that is directly meaningful to the geothermal community.

To date the coupling of numerical and experimental work is a bit lacking, but that seems to be on the edge of happening and should be an important contribution.

The publication to date is good, with a full peer-reviewed journal article coming (also good).

The collaboration with LLNL does not appear to be strong in terms of moving the science forward, BUT is a perfect example of building bridges between labs that I feel has a strong potential to improve the overall programs in both lab beyond this project alone which is commendable.

PI Response:

Thank you.

Reviewer 24876

Score: 9.0

Comment: Sustainable production from geothermal reservoirs requires a firm understanding of the evolution of the flow paths through the rock of a given type. This project is examining the effect of elevated temperatures and pressure on fracture evolution caused by mineral dissolution and precipitation. The results of this research will impact site selection for EGS and operation procedure to reduce the need for refracturing during the lifetime of the site. The project has made significant progress on the experimental design, fabrication and initial testing. Several challenges were encountered (e.g. generation of HF from elastomers, sealing of the borehole, analysis of aperture etc.) and overcome by the personnel by re-designing of components of the equipment and development of analysis algorithms. The personnel also developed a new clever technique for inducing tensile fractures across a core and have performed a number of tests on such fractured core. The project has also made progress on characterizing mineralogy before and after experimentation in collaboration with colleagues at LLNL.

PI Response:

Thank you.

Reviewer 23583

Score: 7.0

Comment: Furthering our understanding of how different EGS-relevant rock types, fluid compositions, and fracture surface textures determine longevity of fracture apertures to reduce future refracturing will clearly and positively impact EGS reservoir creation, monitoring and operations. A custom experimental apparatus was designed, built and tested, relevant EGS site samples obtained, and sustainability tests are underway. Some results are presented and data looks promising. Analyses and insights into sustainability of fractures are yet to come. If project objectives are met, EGS program goals to more realistically understand and model fractures will inform reservoir rock selection and/or reservoir fluids to avoid unsustainable environments and operation of EGS reservoirs will be advanced. Coordination with the LLNL mineral kinetics project is a real plus. This is a reasonable project and this work will have considerable impact if successful.

PI Response:

Thank you. We agree, and particularly would like to comment about the positives accompanying coordinatino with the LLNL team.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: The project has built a new experimental apparatus. It creates a fracture in a rock disc, rotates the discs before re-assembly in the apparatus, so that asperities are created and mechanically ground as normal pressure is applied. Fluid is introduced through a hole drilled through the center of the top disc, and this flows outwards through the fracture between the discs. The apparatus controls temperature, pressure on the disc stack, and fluid pressure. The chemistry of the fluid can be measured to show dissolution or precipitation. The surface of the fracture is scanned before and after the experimental runs, allowing measurement of dissolution and precipitation volume.

The rock faces will be created by initiating a new fracture within each machined rock sample, meaning that fresh rock will be tested. This does not reflect geological reality, where it is only existing fractures that can be stimulated, and these will be lined with secondary minerals. The PI discussed a sample run that resulted in mineral deposition in the fracture – such samples should be re-used in the experiments.

A score of 8 has been given on the basis that the experimental apparatus and protocol will provide basic data that will greatly improve THMC models.

PI Response:

Thank you. We appreciate your comment, and are thinking about reusing samples.

Reviewer 23434

Score: 8.0

Comment: The unique experimental setup with radial fractures, high pressure/temperature capabilities, and the ability to measure deformation with a high level of accuracy is a useful tool development.

Evaluating tensile fractures as opposed to shear fractures (as is stated in the project title and in more common in an EGS field) may yield different results than what is specifically obtained from this project due to the different fracture characteristics. But I think that is overall a fairly minor point; having a tool that can look at fractures in this fashion is useful.

Advancing the numerical model to time periods longer than can be studied in the lab will extend the relevancy of this work and potentially provide a logical way of upscaling. It is smart for the research to be going in this direction.

PI Response:

Thank you.

Reviewer 24876

Score: 10.0

Comment: The methods and designs of the equipment and experimental protocol are of high quality and sound design. The experimental set-up accounts for high-temperature effects on seals, geochemical interaction with components other than the rock, and accurate measurement of deformation and flow under elevated PT conditions. The project personnel have a firm understanding of the effects of deformation, reactive flow and temperature on fracture aperture evolution. It was not clear which numerical approach would be used to model which aspects of fracture evolution.

PI Response:

Thank you. Our approach using TOUGHREACT/ROCKMECH will perhaps give us some perspective on this.

Reviewer 23583

Score: 7.0

Comment: Overall quality of the technical approach is solid. Scientific rigor is good and work elements, procedures and methods are based upon accepted practices and will provide realistic and workable results. Instrumentation and equipment are deemed more than adequate for the purpose. Research team is strong and has necessary facilities, expertise and experience. In particular, LBNL's labs are first-rate and equipment is state-of-the-art but best of all the research team and the greater LBNL community have decades of applicable experience.

PI Response:

Thank you.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Combines many key parameters of EGS fractures into one experiment: temperature, hydraulic pressure, strain, minerals and fluid chemistry. This could be very effective experimental apparatus for the evaluation of individual geothermal developments, as well as for contributing knowledge to the development of EGS exploration models (e.g. are there favorable rock types for the prevention of scaling and strength of crystal bridges for holding asperities open?).

There is a considerable matrix of possible experimental runs with this apparatus – I hope that the experimenters are able to work on this long term, and develop new collaborations to distribute the workload.

PI Response:

Thank you. The matrix is huge. Hopefully we can shed light on making it smaller.

Reviewer 23434

Score: Not scored

Comment: Collaboration with LLNL.
Unique, high precision equipment that is capable of studying fracture flow at relevant conditions. Experience in doing lab experiments has enabled the researchers to develop a very unique system.

PI Response:

Thank you.

Reviewer 24876

Score: Not scored

Comment: Strong experimental design and appropriate equipment.
Knowledgeable personnel

PI Response:

Thank you.

Reviewer 23583

Score: Not scored

Comment: Project clearly addresses our lack of understanding of EGS fracture longevity as a function of insitu rock/water interactions; a significant EGS knowledge gap. Knowledge gained in this project should significantly contribute to our understanding of fracture dynamics and may impact current reactive models used to simulate continued operation of EGS reservoirs. Understanding experimentally-determined rock/fluid combinations that are detrimental to EGS reservoir longevity is an important consideration to be taken into account of when future sites are selected. Specifically, the particular unique combination of temperature, stress, mineralogy, chemistry, grain size and surface topology that adversely reduces fracture propagation and thus heat transfer would most likely reduce costs, improve performance and stimulate key markets in the long run. A custom experimental apparatus was designed, built and tested, relevant EGS site samples obtained, and sustainability tests are underway. Some results are presented and data looks promising. If project objectives are met and technical targets reached positive impact on key, critical EGS program goals is assured, namely sustainable operation of an economical, subsurface, heat transfer reservoir.

PI Response:

Thank you.

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: The researchers will characterize the mineralogy of the fracture surfaces before and after the experimental runs. I suggest that the faces be characterized chemically (e.g. via SEM (although coating could be problematic), hyperspectral), as this will provide additional information about mineral reaction rates (see collaborative project of Carroll et al.).

PI Response:

Thank you. We agree as well. This is one of our design trade-offs.

Reviewer 23434

Score: Not scored

Comment: Numerical modeling appears to be in very early stages. More parallel progress of experimental and numerical work could have been useful to both ventures.

Fracture size and structure is limited in the new system, which will make examining some conditions difficult.

PI Response:

Thank you. We agree. Getting the experiments and modeling in parallel aids both efforts.

Reviewer 24876

Score: Not scored

Comment: Quantifying fracture aperture from profilometry data is always a challenge. My only comment is how do you know that your apertures are really that small? I will say that having the titanium alignment pegs probably greatly reduces your errors in alignment.

PI Response:

Our initial thoughts were that this would be a no-brainer. We should have realized that the mere presence of a literature on the subject states otherwise. We would like to implement multiple pins, but it increases setup difficulties.

Reviewer 23583

Score: Not scored

Comment: Even though this work is an important component of the entire EGS effort, the overall contribution is less critical compared to other components because sustainability is secondary to actually creating, monitoring and controlling the fractures to produce a sufficiently dense volume for heat transfer. Now, if fluid/rock interactions react to produce a precipitate, reducing permeability over short timeframes like months or years, then we have a problem that is much more important. But first we need to figure out how to fracture rock in a way to maximize fracture density in a controllable, accessible volume.

Underlying simplifications, e.g., using deionized water as the testing fluid, may reduce the significance of the results. More realistic fluids need to be used that better reflect the rock samples and sites.

How many rock type/fluid chemistries can be tested with this budget?

This reviewer has seen over the years several experiments of this nature and wonders about the uniqueness of this work in light of previous work or if this has not been done before, how is this project unique or how does it add a technical or scientific advancement?

Is the project on schedule or not? Milestones are few and do not capture the project's progress or lack thereof.

Laboratory projects like this, experimental design is critical to a positive result. Significant planning and careful design are needed. Some explanation of experimental controls and scientific rigor would strengthen the acceptance of results.

PI Response:

Thank you for the comment. We agree that implementing EGS will be complicated, and feel that in addition to reservoir formation, fracture and reservoir sustainability will be critical to the effort. One of our goals directly impacts reservoir formation - where to put the reservoir in light of sustainability. We feel that it is important to consider this.

IMPROVEMENTS

Reviewer 23418

Comment: The asperities created during hydraulic fracturing are not likely to be faceted by ‘new’ mineral faces, but rather by fracture-filling minerals. To date in all geothermal EGS developments, hydraulic injection has taken place below the least principal stress, meaning that hydroshearing rather than tensile opening is the fracture mechanism. Fracturing takes place along pre-existing weaknesses, which are most often lined by fracture-filling minerals. Therefore, the sample selection matrix should incorporate foliated and fractured samples, with attempts made to break the sample along existing fractures.

The matrix of sample lithologies should include igneous rocks, metasedimentary rocks, limestone, and sandstone. The method can provide useful information on chemical and mineralogical evolution of strained ‘hot sedimentary aquifer’ systems, not just EGS.

PI Response:

Thank you for this comment.

Reviewer 23434

Comment: Strengthen LLNL collaboration by using geochemical relationships determined at LLNL in this project's modeling efforts.

PI Response:

We have begun to work together and would like to strenghten the collaboration. We think that the SubTER framework will also encourage this.

Reviewer 24876

Comment: None at this time.

PI Response:

-

Reviewer 23583

Comment: The project would benefit from using as realistic components and processes as are possible to better gain an impact on the EGS program.

How many rock type/fluid chemistry combinations can be tested with this budget? Is there a way to determine the most likely EGS rock/fluid combinations?

The project would benefit from: 1) a brief statement to better gage and understand the significance of this work in comparison to other work of this nature, 2) adding more milestones to capture the project's progress more precisely, and finally, 3) a brief explanation of the experimental controls and scientific methods used.

PI Response:

Thank you. I feel that much of what is requested is contianed in the presentation, the summary sheet, and the conference papers. I would be happy to discuss this further with the reviewer at a time of mutual convenience if desired.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006762
Project: Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production
Principal Investigator: Marone, Dr. Chris
Organization: The Pennsylvania State University
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 7.0

Comment: This project recognizes that natural fractures heal with time, and this process is often cyclic. This is well-recognized in the formation of mineral ore deposits. It is an outstanding un-answered question in EGS: once fractures are created, how long will they stay open for, will hydraulic stimulation need to be periodically repeated? This project focusses on seismic perturbations or cyclicity, as a mechanism for fracture creation or fracture permeability maintenance, including the phenomenon of fines migration and pore throat blockage.

Results of the project to date show that fluid flow rate dictates permeability enhancement during fluid pressure oscillations. The continuation of this work will help to dictate pumping schedules for EGS projects. Further the recognition of remobilization of clogging particulates in very important, see additional comments in Improvements section.

The project has shown that elastic wave speed and amplitude vary systematically during the cycle of stick and slip, which is an analog for the earthquake cycle, and that P- and S-wave speeds decrease during fault slip and recover with log time during interseismic restrengthening.

The project is working to use data on dynamic earthquake triggering to infer the critical stress state in Earth's crust. Investigating the role of fluid injection and associated changes in stress state and fault zone frictional strength are key to understanding EGS systems, as these are stress-sensitive reservoirs.

PI Response:

These are good points. We agree with the comments about important directions. We're still in the early stages, but full speed ahead!

Reviewer 23434

Score: 8.0

Comment: The impact of shearing on rough fracture mechanical and hydraulic apertures is critical in EGS fields, as well as many other subsurface environments.

PI Response:

Reviewer 24876

Score: 10.0

Comment: EGS subsurface reservoirs are subjected to changes in stress from production and operational processes. This project looks at the very important aspect of EGS reservoir alteration, namely, shear-induced enhanced (or shear degradation of) permeability of fractures/faults. The project uses a well-designed experimental set-up and protocol to quantify the effects of cyclic fluid pressure (dynamic loading/unloading) on permeability. In addition, the incorporation of nonlinear elastic wave monitoring into the experiments is a novel and exciting development. A key concept in fracture characterization is perturbations or stress trajectories. Perturbations enable delineation of a fracture and characterization of fracture properties. Working with Paul Johnson on this component of the project will ensure success on Task 2. Overall, this is very high quality project.

PI Response:

Thank you for these comments.

Reviewer 23583

Score: 7.0

Comment: Project aims to develop methods to understand and manage permeability enhancement and shear failure by dynamic stressing using carefully designed laboratory experiments focused on natural feedbacks between fluid flow and fracture permeability. The ultimate goal is an improved understanding of fluid flow and fluid-rock interaction, specifically focused on the impact of stress-enhanced dissolution and precipitation. In addition, the project aims to develop acoustic techniques to visualize fracture geometry and fluid flow pathways evolution during deformation. Hopefully, successful project completion will lead to new and improved techniques to control and thus optimize fracture creation and thus heat transfer in EGS systems. Coupling laboratory results with numerical modeling is key to discovering insights into critical parameters in reservoir stimulation. If project objectives are met, EGS program goals to characterize, create and sustainably operate EGS reservoirs will be significantly and favorably impacted.

PI Response:

Thank you for these comments.

Reviewer 29854

Score: 7.0

Comment: The project aims at developing a mechanical understanding of the link between induced seismicity and permeability evolution, in particular the role of dynamic stresses generated by induced earthquakes on the enhancement of permeability. Laboratory experiments revealed systematic permeability changes induced by dynamic loads and a conceptual model (clogging/unclogging) was proposed. Some interesting ideas are discussed, such as velocity changes in fault zones and dynamic triggering as a stress probe, but not developed yet into potentially feasible tools applicable to geothermal environments.

PI Response:

Thank you for these comments. Yes, we're still in the early stages.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: The project seeks to address four broad areas:
1. Fracture formation and the relationship between fluid flow and shear failure;
2. Assessment of fracture geometry and fluid permeability using novel acoustic measurements;
3. An improved understanding of how drilling, injection and geothermal production influence local seismicity; and
4. Development of process based models for using induced seismicity to assess the critical stress-state in Earth’s crust.

Small blocks of granite and sandstone will be used as analogs to typical EGS reservoir rocks. Fractures will be produced in situ using a novel true triaxial deformation machine. The cracking process will be monitored using detectors that measure microseismicity as Acoustic Emissions (AE), temperature, stress, and deformation-induced strains. These observations will allow discrimination between focal mechanisms, seismic stress drop, and characteristics of permeability evolution resulting from early-time fluid pressurization relative to later-time thermal effects. The resulting fracture networks will be analyzed quantitatively in terms of their extent, fracture length, crack density, and degree of connectivity. These results will inform an upscaling effort to connect laboratory-based understanding to field-scale geothermal systems.

Three mechanisms for permeability evolution in EGS will be examined: 1) dislodging of fine particles by oscillatory fluid flow followed by the progressive re-clogging of pore throats, 2) shear induced fracture asperity damage triggered by fluid injection under undrained loading, and 3) fracture dissolution sourced from the fracture faces or bridging asperities, with associated enhancement or degradation of permeability.

The experimental apparatus and protocol vary loading conditions, fluid draining states, and fluid injection rates (including oscillatory flow).

This experimental protocol is unique in the application of controlled hydraulic pulsing to simulate and examine the role of dynamic stressing on permeability.

PI Response:

Thank you for these comments.

Reviewer 23434

Score: 7.0

Comment: Overall good. I question the use of sandstone in the presented work since that does not seem to be representative of the typical rocks that would be found in an EGS reservoir, but the overall plan, experiments and methods seem valid.

PI Response:

We'll start with sandstone but we plan to use granite and other rock types.

Reviewer 24876

Score: 10.0

Comment: The experimental approach is excellent because the shearing rate can be controlled, the dynamic loading through pore pressure can be tuned in frequency and magnitude, and the acoustic sensors enable geophysical monitoring as well as dynamic perturbations. This approach enables interrogation of fractures under several different loading and pore pressure conditions which are highly relevant to the goals of EGS. The personnel are highly qualified and collaborate well. This project will produce interesting results and fundamental understanding of shear-enhancement (or shear-degradation) of permeability.

PI Response:

Thank you for these comments.

Reviewer 23583

Score: 7.0

Comment: Overall quality of the technical approach is good because the experimental set-up is well thought-out and constructed. The scientific rigor is superior and work elements, procedures and methods are appropriate in order to achieve project objectives. However, in projects like this details are important and were not presented to this reviewer. Instrumentation and equipment are deemed more than adequate for the purpose. Research team is strong and has necessary facilities, expertise and significant experience.

PI Response:

Thank you for these comments. We intend to provide additional detail in our published papers and we will include this in future project reports as well.

Reviewer 29854

Score: 7.0

Comment: The approach is mainly based on laboratory experiments of fluid flow through fracture, and the system response to oscillatory loads. The project nicely leverages quite unique experimental capabilities and expertise. Systematic perturbations of permeability by dynamic stresses are quantified, as a function of frequency and amplitude of the stimulus. The permeability changes by a factor of about 2 at 1 Hz and seems to increase with frequency. If would be interesting to examine if the permeability changes keep increasing at higher frequencies than currently tested, or if there is a limit. The clogging/unclogging concept is appealing and developing a quantitative model (even a toy model) for validation versus experimental data could be a priority. Dynamic triggering is rare and fault zone velocity changes are spatially localized, making their practical utility uncertain in geothermal exploration/production environments. Developing a conceptual field procedure based on these phenomena could help convey better their potential outcome for EGS.

PI Response:

Thank you for these comments.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Apparatus can apply a shear load, and allow fluid flow across fracture face. Results are consistent with natural earthquake cycle.

PI Response:

Reviewer 23434

Score: Not scored

Comment: Top notch experimental equipment and a good understanding of the fundamentals that control fluid flow/mechanical properties in rough walled fractures.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The technical approach and knowledgeable project team.
Experimental equipment and approach.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Project focuses on a significant process in creating fractured reservoirs, namely, fracture formation and the relationship between fluid flow and shear failure and the assessment of fracture geometry and fluid permeability using novel acoustic measurements. A better understanding of these phenomena would surely impact our ability to perform controlled reservoir creation and close an important EGS knowledge gap. The development of methods to understand and manage permeability enhancement and shear failure by dynamic stressing while improving our understanding of stressed-enhanced fluid flow and fluid-rock interaction, specifically, stress-enhanced dissolution and precipitation as well as developing acoustic techniques to visualize fracture geometry and the evolution of fluid flow pathways during deformation would, most likely, reduce costs, improve performance and stimulate key markets. Laboratory data is being collected and analyzed, laboratory techniques and capabilities, have been developed and project personnel are being trained. Analyses of results have already discovered important insights. Progress is good and results promising. If realized, stated objectives to provide insight into the fundamental role of fracture permeability, fluid flow and shear failure in geothermal energy production would be very significant in achieving the key, critical goal of EGS; to create and operate economically, subsurface, heat transfer reservoirs.

PI Response:

Thank you for these comments.

Reviewer 29854

Score: Not scored

Comment: The project aims at developing a mechanical understanding of the link between induced seismicity and permeability evolution, in particular the role of dynamic stresses generated by induced earthquakes on the enhancement of permeability. Laboratory experiments revealed systematic permeability changes induced by dynamic loads and a conceptual model (clogging/unclogging) was proposed.
The approach is mainly based on laboratory experiments of fluid flow through fracture, and the system response to oscillatory loads. The project nicely leverages quite unique experimental capabilities and expertise. Systematic perturbations of permeability by dynamic stresses are quantified, as a function of frequency and amplitude of the stimulus.

PI Response:

Thank you for these comments.

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: Parts of tasks 1.1 and 1.2 address issues of scaling of fractures, and the overall chemistry of a geothermal system, but this important aspect was not otherwise mentioned in the presentation, including no mention of how it forms part of the experimental apparatus.

Acoustic emissions appear not to have been part of the project to date. Project objectives discuss developing acoustic techniques to visualize fracture geometry, but this was not mentioned during the presentation. It is stated that a post-doc has recently joined and is focused on the use of acoustic measurement, so presumably this will improve.

PI Response:

Thank you for these comments.   The project is still in the early stages. Future work will address these issues

Reviewer 23434

Score: Not scored

Comment: By using sandstone I think the experiments are losing grains of sand, which then are likely to flow down the fracture and clog narrow aperture locations. I don't think this same behavior would be expected in a typical EGS metamorphic rock.

PI Response:

Thank you for these comments.   The project is still in the early stages. Future work will address these issues

Reviewer 24876

Score: Not scored

Comment: None at this time.

PI Response:

Reviewer 23583

Score: Not scored

Comment: The methodology used to attain insight between comparing laboratory and simulation results needs to be better thought out because the insights will come from such disparities. One possibility is to employ hypotheses testing as an effective method to guide experimentation/simulation tests, highlight progress and shows the advancement of scientific ideas. A list of experiments that will be performed and results anticipated given our current understanding would allow for informed future experiments. This is critical to the discovery of future meaningful insights.

PI Response:

Thank you for these comments.   The project is still in the early stages. Future work will address these issues

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

IMPROVEMENTS

Reviewer 23418

Comment: Apply hydraulic pulsing to other apparatus with different geometry.

Work by the South Australian Centre for Geothermal Energy Research (SACGER) at the University of Adelaide investigated the occurrence of fines migration which adversely affected permeability in the Salamander-1 geothermal well (Hand et al., 2015, Case study: Reservoir quality in sedimentary geothermal settings in Australia, Proceedings, Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, January 26-28 2015). Would oscillatory injection help to remove the fines particles from the near-well bore?

What's the relationship between fluid oscillation and step-rate injection of EGS experiments? Are there existing datasets that would be relevant?

PI Response:

Thank you for these comments. These are good points. We'll follow up on them as the project progresses

Reviewer 23434

Comment: Using more representative rocks would make a lot of sense.

PI Response:

Reviewer 24876

Comment: No suggestions at this time.

PI Response:

Reviewer 23583

Comment: It is assumed that laboratory results will inform numerical simulations and conversely numerical simulation results will inform what experiments are needed. Surely, an experimental plan has been developed but was not presented. It would benefit the project to share the highlights of their plan. Of special interest is how particular hypotheses will be tested and modified if the experimental results are not matched.

PI Response:

Thank you for these comments. The project is still in the early stages. Future work will address these issues

Reviewer 29854

Comment: Some interesting ideas are discussed, such as velocity changes in fault zones and dynamic triggering as a stress probe, but not developed yet into potentially feasible tools applicable to geothermal environments.

The permeability changes by a factor of about 2 at 1 Hz and seems to increase with frequency. If would be interesting to examine if the permeability changes keep increasing at higher frequencies than currently tested, or if there is a limit. The clogging/unclogging concept is appealing and developing a quantitative model (even a toy model) for validation versus experimental data could be a priority. Dynamic triggering is rare and fault zone velocity changes are spatially localized, making their practical utility uncertain in geothermal exploration/production environments. Developing a conceptual field procedure based on these phenomena could help convey better their potential outcome for EGS.

PI Response:

Thank you for these comments. The project is still in the early stages. Future work will address these issues

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005128
Project: Novel Geothermal Development of Deep Sedimentary systems in the US
Principal Investigator: Moore, Joe
Organization: University of Utah
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 9.0

Comment: This project addresses the prospectivity of a potentially huge geothermal resource, and has implications for many other parts of the world as it deals with large areas of moderate (conductive) heat flow not focused on small areas of active magmatism having high heat flow.

Deep Sedimentary Systems (also known as Hot Sedimentary Aquifers in other parts of the world) occur at shallower levels than deep EGS, and therefore may have lower drilling costs, but perhaps more importantly, should have higher permeability. They will have lower temperature than EGS resources, but the combination of cheap drilling, and high flow rates at moderate temperatures, may mean that these are cheaper reservoirs to develop per MWh generated than EGS reservoirs. They should be less technically challenging also, and this is very significant in lowering overall project risks which is a significant barrier to investment.

This project appears to have made good progress, having identified four 'best' sites for further on- and in-ground work. Economic modelling has been completed, as have heat-sweep simulations.

PI Response:

We thank the reviewer for these positive comments. We would add that this project has utilized techniques that would be appropriate in the analysis of the play fairway projects. Not only does this project predate the play fairway projects by several years, it has identified significant new prospects without the collection of new data. We believe it would be appropriate for the PI's to expand this project through the play fairway program. We urge DOE to consider this possibility.

Reviewer 23434

Score: 9.0

Comment: Overall I am very impressed by this project. The project scope and presentation appear to have shown an understanding of how EGS could be broadened to include opportunities that are currently (for the most part) overlooked. This work does appear to already have direct impacts in how EGS is described. Using data that was 'resurrected' from a garage for meaningful analysis, targeting zones that appear to have a reasonable LCOE, and directly identifying best prospects for future/detailed examination are all commendable accomplishments. Combined I hope that this projects impact will be seen for years in how sedimentary EGS systems are thought out. And the wide range of publications (40!?) from this project make it quite likely that the impact will be felt for years.

PI Response:

We thank the reviewer for his complimentary remarks.

Reviewer 23583

Score: 10.0

Comment: This project offers a fresh and exciting way to expand the EGS resource into new and promising arenas, i.e., deep stratigraphic reservoirs in the Western U.S. In addition, this project points the way to an easier transition from traditional O&G E&P to geothermal EGS, such that they might be interested in getting involved, a real plus. This is a great project and has already had tremendous success, e.g., several new very promising prospects have been discovered. As stated, this idea is a fruitful transition technology effort, to move from more traditional O&G exploration and drilling to technology applications in these deep stratigraphic permeable reservoirs that require little enhancement to similar ones that require some permeability enhancements. A great idea and a superior project. This has the potential to smoothly transition current EGS strategies as well as expand geothermal energy in general on the grid. This is a very exciting project that goes way beyond EGS program goals to characterize, create and operate EGS reservoirs yet will significantly impact geothermal energy and EGS.

PI Response:

We thank Reviewer 23583 for his compliments and comments regarding the significance of this project.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 9.0

Comment: This project has compiled relevant data in order to complete an area-selection process for Deep Sedimentary Systems/ ‘Hot Sedimentary Aquifer’ plays in the Great Basin area. I don't know if this project has developed a 'play-fairway' approach, or some form of systemized exploration approach as that level of detail was not presented. In general terms the project has evaluated temperature profiles, and permeability from wells. Where available, seismic data has been used. Water chemistry from stratigraphic reservoirs in hydrothermal systems has been assessed for thermodynamic equilibria - an important step for assessing potential for adverse water-rock reactions.

Compiling permeability data from all available drilling is a useful and important step, however caution needs to be used with this data. In sandstone reservoirs in particular, if the drilling data is from offset wells which targeted petroleum, these wells may not be an accurate indicator for permeability if a proposed geothermal well targets an area of higher temperature. See Weaknesses section for more discussion.
The project has applied GETEM for economic modelling. This is important as economics plays an important role in selecting amongst competing potential reservoirs for development. Lowering economic risk is an important part of lowering overall risk.

I am a little skeptical of simulating injection-production until 'real' reservoir data is available from drilling and testing.

PI Response:

We thank Reviewer 23118 for his constructive comments. This project has not attempted to provide a "statistical" evaluation of the proposed targets using approaches being applied by play fairway projects. This was never part of the SOPO but certainly could be incorporated into our work. We understand the reviewer's comments regarding permeability data and its limitations. Unfortunately, as noted by the reviewer, we must use the data that are available. It is our hope that "real" reservoir data will ultimately become available. As this data is not available, modeling is the only approach we can take.

Reviewer 23434

Score: 9.0

Comment: Again, as far as I can tell, an overarching approach of evaluating reservoirs using fairly traditional techniques to find overlooked regions of interest with specific criteria appears to have been very successful. All presented aspects of this work appear to have been well coordinated, with perhaps the only exception being the simulations, which seemed a little out of place and disjointed from the rest of the project. But overall, I think the 'proof is in the pudding' and this project was well run with a logical approach that resulted in meaningful results.

PI Response:

We appreciate these comments.

Reviewer 23583

Score: 10.0

Comment: Overall quality of the technical approach is superior because the methods and procedures are clear and rigorous. The scientific process is followed throughout and is exceptional. Obviously, work elements, procedures and methods are appropriate in order to achieve project objectives. The scientific design is simple, elegant yet very effective. Research team is extremely strong and has necessary facilities, expertise and experience. Results demonstrate the superior quality of the technical approach.

PI Response:

We appreciate the reviewer's compliment and comments.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: This project assess (or proposes) a geothermal reservoir play type which may be of lower risk than EGS projects. The main reservoir rock type is likely to be limestone, which often has excellent permeabilities preserved/available at depths of up to 3 km. Sedimentary reservoirs often have drilling and seismic data available from petroleum exploration activities, which helps to narrow down the search area and identify the most prospective areas for more detailed exploration. Four high priority areas have been identified to date.

If one of these projects can eventually attract an investor, and ultimately successfully come into production, it will help geothermal energy move away from only high heat flow areas. There 'should' be lower risk around reservoir permeability in these systems compared to deep EGS systems (given current knowledge about EGS reservoir stimulation and performance), meaning that this is a very important area of geothermal RD&D.

PI Response:

We appreciate the compliment and agree that the work we are doing should be expanded because of its significance to the overall geothermal program.

Reviewer 23434

Score: Not scored

Comment: See above. Well managed, well thought out problem, staffing to accomplish was adequate to accomplish.

PI Response:

We appreciate the compliment.

Reviewer 23583

Score: Not scored

Comment: Project address all critical and significant processes in creating, monitoring, and operating EGS reservoirs by expanding our ideas about what EGS reservoirs are: from technically difficult hot-dry-rock regions to more easily, economically accessible regions, which will, in turn, expand interest in marginally accessible regions. Rather than jumping from today's mix of operating fields and one 'green fields' EGS (Newberry Crater), to pure EGS production scenarios, this project will accelerate our ability to "close" many important EGS knowledge gaps by easing into EGS as a promising technological approach.

Because this idea is a great transition technology effort that moves from more traditional, less expensive O&G exploration and drilling to technology, undoubtedly, costs are reduced, performance improved and key markets will be stimulated a perfect stepping stone to successful EGS implementation. ? In addition, specific costs and performance savings were calculated and show several locations with ~10c/kWh costs; very good for geothermal. Excellent project.

Considerable progress has been made and the project is wrapping up. For example, all the research work has been done and results presented with over 40 papers, presentations, and posters at national industry and scientific conferences, Many presentation awards were garnered and, in general, accomplishments vastly exceed original expectations.

Results are very promising and many basins in the northern Great Basin having both the recommended thermal criteria (150 - 200 °C at 3 - 4 km depth) and stratigraphic units with potentially good permeability within this depth range. Progress is excellent.

PI Response:

We appreciate the positive comments of this reviewer.

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: Two wells in Australia - Salamander-1 and Celcius-1 both targeted hot spots in basins 'known' from offset (1 - 10s kms) petroleum drilling to have high permeabilities. When these sandstone reservoirs were drilled however, the high temperature hot spots were found to have caused diagenesis and/or gave rise to fines migration which adversely impacted permeability. The same diagenesis will not occur in limestone reservoirs, and the two Australian basins (Cooper and Otway) undoubtedly have very different geodynamic histories to the Great Basin. However, attention does need to be paid to the possibility of adverse effect on permeability having occurred during the basins history.

PI Response:

We agree with the reviewer's observation that diagensis can have a detrimental role on reservoir permeability. For this reason, we have targeted limestones, where diagenesis is not anticipated to be a problem and may in fact, increase permeability through mineral dissolution and formation of dolomite. Clean sandstones (quartz-rich sandstone with little clay or feldspar) may be suitable hosts for the same reason.

Reviewer 23434

Score: Not scored

Comment: Perhaps the modeling aspect was a bit over simplified to provide meaningful results to this project.

PI Response:

Sufficient time was not available to discuss the modeling in detail. Additional information can be found in: Deo, M., Roehner, R., Allis, R, and Moore, J., 2014, Modeling geothermal energy production from stratigraphic reservoirs in the Great Basin: Geothermics, v. 51, p. 38-55.

Reviewer 23583

Score: Not scored

Comment: None to be found. This is a perfect example of what GTO should fund.

PI Response:

Thank you.

IMPROVEMENTS

Reviewer 23418

Comment: The geodynamic history of the Great Basin should be evaluated for the potential to cause adverse effects on permeability of the likely target lithologies. This should not be a difficult task – identify the important lithologies prospective as geothermal reservoirs (i.e. sandstones, limestones), identify the key parameters in the history of the prospective geothermal areas (e.g. burial depth, shortening, peak temperature, retrograde paths if present) and then identify the likely mineral reactions that would have occurred to the primary lithologies.

For information, the South Australia Centre for Geothermal Energy Research (SACGER) at the University of Adelaide recently completed a study on the genesis of permeability at the Salamander-1 and Celsius-1 well reservoirs. Some of this work can be seen at https://www.adelaide.edu.au/geothermal/, and the most up-to-date publications can be gained from the researchers contactable via the SACGER website. A useful overview paper is (Hand et al., 2015, Case study: Reservoir quality in sedimentary geothermal settings in Australia, Proceedings, Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, January 26-28 2015).

PI Response:

We thank the reviewer for providing this reference.

Reviewer 23434

Comment: Reviewer did not provide comments for this criterion.

PI Response:

None.

Reviewer 23583

Comment: Nothing can be added to this perfect project.

PI Response:

Thank you.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006767
Project: Quantifying EGS Reservoir Complexity with an Integrated Geophysical Approach - Improved Resolution Ambient Seismic Noise Interferometry
Principal Investigator: Tibuleac, Ileana
Organization: Board of Regents, NSHE, obo University of Nevada, Reno
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 7.0

Comment: This project seeks to map EGS reservoirs using improved ambient seismic noise interferometry.

The project investigates a relatively inexpensive seismic exploration technique, using ambient noise interferometry and methods previously used in nuclear monitoring, to map EGS favorability estimation at a scale (and depth) not yet seen in active seismic surveys in geothermal fields. The method has potential to provide information on fault dips using ambient seismic noise processing. The project also conducts a statistical evaluation, integration and synthesis of seismic and other geothermal favorability parameters.

The impact of the project, if successful, will be to provide a relatively inexpensive, easy to acquire method of mapping fractures and their properties in EGS fields, methods for which are not currently available.

Although the research shows considerable promise, the project is delayed and is therefore scored 7.

PI Response:

The start of the project was conditioned to successful submission of the final report on another DOE project on June 30. Please note that the team technical activity on this project was not the cause of the delayed start of this project.

Reviewer 23434

Score: 7.0

Comment: In the right locations, in the right settings, I think this methodology could be a useful addition to existing techniques to analyze EGS fields.

PI Response:

The results in a previous experiment, at Soda Lake, in an exploration area of a producing field , were affected by cultural noise caused by surface piping and the geothermal power plant. We are developing the methods such that this problem will be mitigated in the future, by deployment changes (for instance, depth of the sensor) and analysis method changes based on better knowledge of the useful noise field. The Dixie Valley area is ideal for testing these new methods because (1) the bulk of the suvey is outside the area of the power plant so the impact of cultural noise will be minimized, (2) the lines are perpendicular to the main road, thus useful cultural noise will likely be recorded; (3) the new methods being developed can be critically tested to evaluate the mitigation of cultural noise, and (4) the existing extensive geoscience data base developd by AltaRock (2014) is at sufficient scale to complement the high-resolution ambient seismic noise at Dixie Valley, for useful insight into potential EGS reservoir characteristics.

Reviewer 24876

Score: 6.0

Comment: Ambient noise is often used to provide monitoring of a local site using local seismicity or industrial generated noise. This approach would be an important technique for relatively low cost monitoring of EGS subsurface reservoirs. The information provided in the presentation was inadequate for determining the potential success of the project. As stated in the presentation, numerous delays have put the project 12 – 24 months behind. The information in the presentation was unclear. For example, slide 3 on the low resolution of S-waves was never adequately explained. What makes this low resolution? It was never clear what problem was caused by the power plant. How do you measure stochastic heterogeneity? Are you referring to the approach based on reflectivity and Hurst exponents? The presentation stresses the ability of the technique to delineate faults but in EGS other information is of interest, for example crack/fracture generation, fluid saturations, fluid migration, etc.

PI Response:

Because this project has not started yet, we were not able to present results of the EGS analysis. The results presented at the Peer Review meeting were for the Soda Lake project, within a month of finishing the calculations, and three months before the final report. Perhaps we have not explained enough in our presentation that the project did not start, and that the results preliminary results in a hydrothermal setting in another location, at Soda Lake. .

Each comment is addressed below:

1. Harmonic industrial noise is usually discarded in ambient noise studies, because it contaminates the Green's Functions with harmonic frequencies. This was the problem we had near the Soda Lake power plant.

2. In slide 3 we showed what we interpret as fundamental mode Rayleigh waves, as opposed to S-waves. The reason these waves characterize the subsurface at low resolution is longer wavelengths (300-2000m). The common interpretation is that a seismic phase is affected by a heterogeneity of the size of its wavelength. Relatively, a P-phase would be affected by heterogeneity tens of meters in size.

3. The stochastic heterogeneity was measured like in Chapter 6 of the attached report, and two measures were estimated, correlation length and Hurst number. As demonstrated in the Soda Lake report, the two parameters are delineating the production area in Soda Lake, at depths less than 1000m.

4. Yes, we have demonstrated potential fault delineation with the technique,because it was one of the tasks on the Soda Lake project. We have also demonstrated that the stochastic parameters have the potential to indicate fractured regions in Soda Lake. Because we use not only velocity however, spectral, entropy and stochastic parameters, we proposed to test the predictive potential of the method in an EGS environment, where these parameters are estimated up to 3 km (as opposed to 1 km) depth. Fluid saturation and migration studies using seismic analysis are beyond the scope of the DV study.

It should also be noted that the ambient seismic noise project at Dixie Valley is to define reservoir characteristics pre-stimulation. The last reviewers' comments dealt with the effects of stimulation. The Dixie Valley project is focused on defining EGS reservoir properties at the exploration stage. The technique will also be applicable to monitoring the EGS stimulation as stated by the reviewer, however this research is outside the scope of the currently planned Dixie Valley project.

Reviewer 23583

Score: 5.0

Comment: Project seeks to ascertain usefulness of applying advanced seismic techniques such as Ambient Noise Inferometry (ANI) and seismic array signal processing techniques developed for nuclear explosion monitoring program, to an active operating and potential EGS geothermal site in Dixie Valley. It is hoped that the increased resolution will positively impact the previously calculated 'favorability/trust maps' (Iovenitti). This project will benefit the exploration for EGS sites by providing higher resolution subsurface maps of supplementary seismic parameter information. If project objectives can be met, EGS program goals to characterize EGS reservoirs will be advanced.

PI Response:

The reviewer is correct in reporting that the exploration for EGS sites will benefit from higher resolution of surface maps showing the EGS reservoir characteristics.

Reviewer 29854

Score: 7.0

Comment: This project's primarily aims at evaluating a cost-effective geophysical technique, seismic ambient noise interferometry, to complement EGS resource exploration. If feasible, the technique could enable cost savings in exploration and monitoring phases compared to active source seismology and would allow imaging a greater depth. Progress is delayed by a pending report of a previous project, which should validate the passive seismic method in hydrothermal systems. It is noted that EGS environment pose additional challenges.

PI Response:

As stated in the responses to several reviewer comments above, the Dixie Valley project is designed to identify EGS reservoir characterticistics at the exploration stage. Such information will be benefical for the design of an EGS stimulation.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 8.0

Comment: The project will apply ambient noise seismic interferometry techniques, and seismic array signal processing techniques developed for nuclear monitoring to geothermal ambient seismic noise reflection surveys to evaluate, at the same scale, the usefulness for EGS exploration of seismic parameter information in comparison with information from other geophysical exploration methods.

This will be done by: 1) collect and analyze new data; 2) use seismic event waveforms from the existing EGS1 seismic surveys at Dixie Valley to investigate the possibility of extracting supplementary seismic parameter information; and 3) generate new EGS favorability / trust maps for Dixie Valley by factoring the proposed higher seismic resolution data to compliment and improve the previous investigations.

Technical feasibility: Pilot studies at Soda Lake (Tibuleac and Eneva, 2011; Tibuleac et al., 2010) and results on EE0002778, EE0005518, and OE-EERE10EE0003997 showed that the method has encouraging results for velocity model inversion, fault definition, and that other seismic parameters (attenuation and spectral properties) show property variations in the exploration areas. Thus, this technique has a high probability to be successful.

PI Response:

The PI concurs with the reviewers comments.

Reviewer 23434

Score: 7.0

Comment: By building upon knowledge in the nuclear monitoring community the research has a sound approach.

PI Response:

The PI concurs with the reviewers comment.

Reviewer 24876

Score: 7.0

Comment: The project is not far enough along to judge, adequately, the technical approach. In theory, this method should provide information on the subsurface and is also being used by the earthquake seismology community. The question is whether the interpretation techniques are significantly advanced to determine the relevant information for EGS. Future work by this project will address this issue.

PI Response:

The preliminary results from the ambient seismic noise study in Dixie Valley as reported in AltaRock (2014) and the results of the Soda lake project (attached) demsenostrate viability of the methodology to identify EGS reservoir characteristics.

Reviewer 23583

Score: 6.0

Comment: Overall quality of the technical approach is adequate. The scientific rigor is satisfactory and work elements, procedures and methods are appropriate in order to achieve project objectives. Research team is able and has necessary field equipment, processing facilities, experience and understanding.

PI Response:

The PI concures with the reviewers comment

Reviewer 29854

Score: 7.0

Comment: The project evaluates in an EGS target identification context a seismological method that is well established in other applications. Surface wave tomography based on seismic ambient noise has become widespread in seismology during the past decade, and body wave extraction has also been developed. A specific challenge identified in this project is non-uniform distribution of seismic noise sources. This is proposed to be tackled by the C3 method, which is particularly good for that purpose, although it increases the noise recording time required to reach stability of the Green's functions C3.

PI Response:

The C3 method does increase the processing time, as longer time windows will be necessary for crosscorrelations (to provide enough coda length). The recording time, however, may be actually reduced, as suggested by our investigations with using overlapping windows. We are currently testing the C3 method for the Soda Lake experiment. Upon successful parallel computing implementation, the processing time will be reduced to the point it not longer constitutes a problem.

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Seismic ambient interferometry appears to be able to characterize many properties of the subsurface, as follows.

Physical subsurface parameters measured directly: (1) P/S wave seismic velocity; (2) seismic attenuation; (3) stochastic heterogeneity; and (4) earthquake focal mechanisms.

Subsurface parameters measured indirectly include: (1) temperature/pressure at depth; (2) location and geometry of fractures/faults; (3) stress and stress drop; (4) lithology/heterogeneity at depth; and (5) potential EGS reservoir volume.

The method is relatively low-cost. If it can produce the results that the researchers claim, it will be a very useful monitoring method for reservoir creation and management, and possibly also for exploration.

PI Response:

The PI concures with the reviewers comment.

Reviewer 23434

Score: Not scored

Comment: Knowledgeable personal, good site location, and logical scientific approach are all strengths of this project.

PI Response:

The PI concures with the reviewers comment

Reviewer 24876

Score: Not scored

Comment: Ambient noise and interferometric techniques have the potential to be powerful techniques for subsurface monitoring.
The strength is that it is being explored.

PI Response:

The PI concures with the reviewers comment

Reviewer 23583

Score: Not scored

Comment: This project focuses on testing the applicability of advanced and low-cost seismic methods to EGS exploration, with the hopes that improved resolution will improve 'favorability/trust maps'. Improving spatial resolution of seismic-derived parameters useful to EGS exploration could have a positive influence on 'favorability/trust maps' to some extent. Seismic resolution is an enduring problem. This project might impact the closure of an enduring EGS knowledge gap. It is possible that results from this project would reduce costs, improve performance and stimulate key markets for EGS exploration. Stated project objectives seek to adapt advance EGS exploration techniques by applying new, to geothermal, seismic techniques to determine multiple seismic parameters to improve characterization of lithology, temperature and fault orientation. If project objectives are met, a new, low-cost method to explore for EGS reservoirs will be available. Hard to determine the progress of this project since there is some connection to the previous project that has to be resolved first. Looks like there is a possibility that the project will start next month? Because the project has not started yet, there are no results with which to determine the significance of related to project objectives. However, the potential for significant results of applying ANI and advanced signal processing techniques should be impactful if results are positive.

PI Response:

The Sodal Lake project report was submitted to DOE on June 30, 2015. Given the submission of this report (attached) a positive DOE decision has been taken on the start of the Dixie Valley project.

Reviewer 29854

Score: Not scored

Comment: This project's primarily aims at evaluating a cost-effective geophysical technique, seismic ambient noise interferometry, to complement EGS resource exploration. If feasible, the technique could enable cost savings in exploration and monitoring phases compared to active source seismology and would allow imaging a greater depth. The project evaluates in an EGS target identification context a seismological method that is well established in other applications. Surface wave tomography based on seismic ambient noise has become widespread in seismology during the past decade, and body wave extraction has also been developed.

PI Response:

The PI concurs with the reviewer's comments.

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: None identified.

PI Response:

Reviewer 23434

Score: Not scored

Comment: The PI seems to be spread thin, and this project (which is rapidly approaching its conclusion) needs to get the final data sets, sensors placed, data analyzed and published. This over extension of the researchers could result in poorer results than would otherwise be expected from the project.

PI Response:

The reason the project was delayed was related to the submission of the Soda Lake project (attached) and DOE's validation of the results. The PI and Dixie Valley project team are now free to concentrate on the new project. Additionally, the Soda Lake project provided insight to making the processing of the Dixie valley data faster and more time-effective. New approaches will be used at Dixie Valley to make the project more time-efficient,

Reviewer 24876

Score: Not scored

Comment: Delays in the project.

The presentation was not clear. Many figures and captions were unexplained

PI Response:

We expect that our responses to comments above have clarified at least the some of the issues identified above.

Reviewer 23583

Score: Not scored

Comment: The connection between project objectives and EGS program goals is needs to be stronger. ANI and advanced signal processing techniques should be looked into, but the project goal needs to be better connected to parameters of interest to EGS that directly address EGS-related subsurface problems and issues. Yes, structure is important but not as critical as permeability for EGS to succeed. A focus on exploration improvements, which are not top priority for EGS because there seems to be more EGS sites available (apriori?) and the critical EGS problems are about creating a sustainable reservoir, not finding an optimal site. Therefore, this project, unfortunately, does not impact significant knowledge gaps. A method to provide specific costs and performance savings was not presented so impact on markets is not easily estimated. Project has not started yet.

PI Response:

No EGS exploration project is available in Dixie Valley. AltaRock (2014) identified that are favorable for an EGS project but unfortuantely the ambient seismic noise survey conducted did not have sufficient resolution to provide a compartive analysis with the other non-seismic geoscience data sets which are described above. The current Dixie Valley project is designed to add the same resolution ambient seismic noise analysis as the other multiple geological and geophysical measurements in the Dixie Valley Geothermal Wellfiedl which has many suitable EGS locations. Our proposal responded directly to the EERE need to enhance “the ability to characterize, with a high degree of constraint, subsurface fractures…, stress…, and other physical reservoir properties” and to increase “the precision and accuracy of directly measured parameters.” "By integrating complementary technologies…" we seek to improve resolution from a scale of km to a scale of meters, to acomplish these objectives.

Reviewer 29854

Score: Not scored

Comment: Progress is delayed by a pending report of a previous project, which should validate the passive seismic method in hydrothermal systems. It is noted that EGS environment pose additional challenges.
A specific challenge identified in this project is non-uniform distribution of seismic noise sources. This is proposed to be tackled by the C3 method, which is particularly good for that purpose, although it increases the noise recording time required to reach stability of the Green’s functions C3.

PI Response:

The project delay has been addressed in response provide dby the PI above. Please see the above response to the C3 assesment.

IMPROVEMENTS

Reviewer 23418

Comment: None to suggest.

PI Response:

N/A

Reviewer 23434

Comment: More time spent on this work in the final days of the project should enable meaningful results to be generated.

PI Response:

We believe there was a confusion between this project and the Soda Lake project which was presented to demonstrate the advances made in the ambient seismic noise methodology.

Reviewer 24876

Comment: No suggestions at this time.

PI Response:

N/A

Reviewer 23583

Comment: The project might benefit from refocusing to demonstrate the determination of subsurface seismic parameters of interest to EGS characterization, monitoring, creation and/or operations, e.g., parameters related to permeability, flow, and/or higher temperatures, at higher resolution and at lower cost than traditional techniques. That goal would be of greater benefit to the program.

PI Response:

The current Dixie Valley project is focused on EGS characterization at the exploration stage, as opposed to production stage. The project is based on filling-in the seismic data gap identified in AltaRock (2014) by high resolution (<100m sq.) ambient seismic noise data collection and analysis at the Dixie Valley Geothermal Wellfield using virtual reflection lines up to 10km in length to estimate P/S - velocity models, attenuation, spectral and heterogeneity parameters. In addition, the usefulness of additional seismic parameters extracted from earthquake data will be assessed. The results will be calibrated with geologic/well information. Geostatistical analysis of the data will evaluate statistical correlations between the proposed higher seismic resolution information and existing high resolution non-seismic geocience (i.e., geology, magnetotellurics, gravity, magnetic, thermal models). New favorability/trust maps to identify drilling targets will be generated, factoring the proposed higher seismic resolution data. The seismic noise interferometry techniques were tested and fine-tuned by part of the Dixie Valley project team for conventional geothermal favorability and for fault identification at Soda Lake, NV (attached report). Physical subsurface parameters measured directly in this project are (1) P/S wave seismic velocity, (2) seismic attenuation, (3) stochastic heterogeneity, and (4) earthquake focal mechanisms. Subsurface parameters, measured indirectly are (1) temperature and pressure at depth, (2) location and geometry of features/faults, (4) stress and stress drop, (5) lithology/heterogeneity at target depth, and (6) potential EGS reservoir volume.   These parameters will characterize EGS reservoir characterizatization at an exploration stage.

Reviewer 29854

Comment: Reviewer did not provide comments for this criterion.

PI Response:

N/A

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005125
Project: Geothermal Resource Development with Zero Mass Withdrawal, Engineered Convection, and Wellbore Energy Conversion
Principal Investigator: Hughes, Richard
Organization: LA State University
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 6.0

Comment: Even in volcanic domains, geothermal energy often has difficulty competing against other power generation technologies because of high costs. The project proposes a geothermal generation modality tailored to the Louisiana Gulf Coast which seeks to exploit Hot Sedimentary Aquifers using “off the shelf” technologies.

The project is based around Zero Mass Withdrawal, whereby both the heat exchanger and turbine are incorporated within wellbore, and geothermal fluid circulation occurs in and out of the well.

The approach is novel, however because of the low enthalpy resource targeted, and the need for redundancy of equipment within the wellbore (maintenance would be extremely difficult); a significant lowering of LCOE is not expected from this operating modality.

Progress has been hampered by the loss of key staff.

PI Response:

Fair evaluation of what was presented. We are evaluating use of abandoned wellbores as a method for lowering LCOE and that does appear to be interesting.

Reviewer 23434

Score: 3.0

Comment: While I would love for this to be a higher score, I just failed to see the relevance of this project in a real world setting. Too high of a cost.

PI Response:

A review score of 3 seems overly harsh in our opinion. We have delivered what we proposed despite our setbacks and while the reviewer may believe the cost is too high, we have already identified an application that combines this idea with another to have a fully sustainable process.

Reviewer 24876

Score: 7.0

Comment: This project is outside of my expertise. However, the project accomplished the tasks and is on track to complete the project in July 2015.

PI Response:

Reviewer 23583

Score: 4.0

Comment: Project seeks to demonstrate technical and economic feasibility of a new and innovative custom-tailored to Louisiana subsurface conditions, in-borehole, geothermal electrical generation system that extracts energy from non-fractured, hydrocarbon-free, low enthalpy formations. This Louisiana resource was estimated to have a geothermal potential of ~80 GWe. If project objectives can be met, GTO program goals will be met because overall geothermal usage will be increased with some impact to the program's goals.

PI Response:

There is nothing to respond to here other than the score of 4 - I will again presume that our choice of an overly conservative wellbore construction cost was the issue.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 7.0

Comment: It appears that a lot of good work has been conducted or is in progress towards this project to date. This includes: (1) geological studies, including structure, temperature and permeability; (2) heat extraction; (3) wellbore energy conversion; (4) wellbore integrity; (5) geomechanical risk; (6) economic analysis; and (7) geospatial analysis.

PI Response:

Reviewer 23434

Score: 4.0

Comment: It seems like the research was focused on the goal of examining this zero mass withdrawal system, without many concerns about the engineering viability of actually running the system. Details seem well thought out, but the overall system has major flaws.

PI Response:

The reviewers first comment is incorrect. A great deal of concern about the viability of the system was appropriated. The wellbore construction and operations are new applications of existing technology and hence our belief that initial costs of such a system would start out high (which is what we provided) and would come down as experience implementing these systems is developed. We did not incorporate the liklihood that costs would come down in our analysis since we don't really know what the learning curve would be nor how many chances we would have to learn.

Reviewer 24876

Score: 7.0

Comment: This project is outside of my expertise. However, based on the slides, great care and thought were put into the mechanical, hydraulic, thermal and economic impacts of the proposed new method for heat extraction without the need for fracturing.

PI Response:

Reviewer 23583

Score: 5.0

Comment: Overall quality of the technical approach is adequate. This project is not a scientific endeavor but rather an engineering study and work elements, procedures and methods are appropriate in order to achieve project objectives. Research team is able and has necessary equipment, facilities and understanding.

PI Response:

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: The technical approach is strong, in that desktop and laboratory studies are being undertaken to provide information on the key variables that affect geothermal developments.

PI Response:

Reviewer 23434

Score: Not scored

Comment: I really like the idea, and see a need for this type of energy source.

PI Response:

Reviewer 24876

Score: Not scored

Comment: No comments at this time.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Project explores the feasibility of a very innovative geothermal energy extraction system that does not impact EGS program knowledge gaps but does significantly address known, anticipated, and significant economic challenges for expansion geothermal electrical energy production in the U.S., a clear GTO objective. As said previously, this project does not impact the EGS program nor do the activities and results impact costs nor performance, as currently designed. This project's activities might impact geothermal energy applications and markets in geothermal energy development if the costs can be reduced. Looks like project was initiated in 2011 and will end this July. Considerable work has been done but it looks like several critical tasks will not be completed in time. Initial PI left the project and the project lost ground. A one year extension was granted but the ends in July of this year. Most likely, the project is behind schedule. For example, well construction and microturbine designs are still in progress. If project reaches stated objectives the EGS program is not significantly impacted. The GTO program could be impacted but costs need to be reduced.

PI Response:

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: Little reason is given for the decision to investigate Zero Mass Withdrawal as the modality for exploitation of the Louisiana geothermal resources. Without understanding those reasons, this work appears to be an engineering novelty that will have negative impacts on LCOE.

Have the possible effects of fines migration or sanding been considered?

PI Response:

The reasoning behind a single wellbore system is two-fold. First, the well construction costs for a single lateral section are somewhat higher than a single vertical wellbore but not nearly as expensive as constructing injector/producer pairs. Second, the single wellbore system mitigates issues with seismmic events due to severe pressure and temperature changes (a clear goal of the original RFP). The well construction design includes sanding/fines migration mitigation on the producer side and is a primary reason moderate flow rates are proposed (lower flow rates mean lower completion pressure drops and lower the chances of sanding). Higher flow rates would require longer completion segments which impacts the producer side more than the injector side but would also mean the entire system would need to be longer in the target zone. Wellbore lengths from the evaluations we have done are well within the constraints of what has been done in oil and gas development but again, the impact of the downhole tools for such a system would be a concern. In addition, Louisiana reservoirs can be exploited whith these longer wellbores but it is not clear how tranferable the technology would be to other regions as we do not have that data.

Reviewer 23434

Score: Not scored

Comment: Cost, cost, cost.

Placing so much equipment downhole, where it will eventually break, is such a difficult proposition.

Use in very low temperature systems results in low energy withdrawal.

PI Response:

Agree.

Reviewer 24876

Score: Not scored

Comment: No comments at this time.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Connection to the EGS program is weak. One possible tenuous connection is that low-enthalpy, rocks in other regions of the U.S. could benefit from this technology, though the hot-dry-rock idea does not fit with this approach. Copious amounts of water with high permeability are needed. This project has significant risk. Rough estimate from the PI at the Peer Review meeting is that the system will cost ~15M per well/system that will generate 1MWe. That is very expensive compared to other technologies like PV, wind, and even nuclear. Project is very specifically focused on

Louisiana resources and requires very permeable formations and represents a new resource type, again, if the costs can be reduced. Connections to the EGS programs are nonexistent. Project is behind schedule, out of funding and several key tasks might not get completed in time. Technology maybe technically feasible but is not economically feasible.

PI Response:

As stated previously - the $15M per system is likely overly cautious on our part but the point is well taken that wells are expensive. We believe all key tasks will be completed and as stated above there are methods we are evaluating for both combining the technology with other processes or lowering the well construction cost.

IMPROVEMENTS

Reviewer 23418

Comment: The costs of the proposed Zero Mass Withdrawal modality should be benchmarked against conventional surface-based generation, with both options for flow between wells and flow between an entry and exit point of a single well being considered.

PI Response:

This is being done.

Reviewer 23434

Comment: I wouldn't recommend that the researchers spend time/effort in finding an industrial partner to try and make this happen. Ending this project in July makes sense at this point. It was a noble effort, and I think there were some good things that came from it, student knowledge and examination of a problem that does need to be solved, but this does not appear to be a method worthy of much further study.

PI Response:

We obviously disagree that it is not a method worth further study given that without really spending any effort we have been approached to continue to develop the concept.

Reviewer 24876

Comment: No comments at this time.

PI Response:

Reviewer 23583

Comment: In the remaining time, project should concentrate on a realistic cost estimate with error bars and a comparison be made with other current energy generation technology costs. Cost reduction opportunities should be identified along with associated needed research. A path forward for this technology should also be developed and delivered to GTO.

PI Response:

This is effectively what we had planned.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments
Principal Investigator: Yarom Polsky, Philip Bingham
Organization: ORNL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 9.0

Comment: This project has two parts: (1) develop an experimental capability to image/characterize fluid flow through fractures; and (2) quantify hydraulic fracture-induced stresses within geological samples at EGS representative conditions.

Perhaps the biggest difficulty with EGS development has been that we can't see what we are doing! Also, learnings have come from empirical, experience based in-ground operations that have poor control and poor instrumentation, and are very expensive. Few operations have been available for these learnings to be made.

This experimental apparatus is absolutely unique in allowing real-time investigation of fluid flow in rock samples, and visualization of in-situ strain.

For reservoir creation, this project will: (1) allow enhancement and validation of hydraulic fracture simulation codes; and (2) studies of strain during hydraulic fracture with variable pressure, temperature, and triaxial stress state will help optimize stimulation techniques.

For reservoir operation, this project will: (1) allow measurement of flow structure in fractures to improve understanding of reservoir flow; (2) facilitate development of reduced order representation of flow; (3) provide a validation tool for reservoir flow codes; and (4) provide non-invasive quantification of geochemical interactions (dissolution/precipitation) that affect long term reservoir performance.

Impact: Methods developed and measurements performed in this effort will provide a more complete characterization of physical processes that are critical to design and management of EGS.

PI Response:

Reviewer 23434

Score: 9.0

Comment: I think there is an impressive level of quality associated with this work that has widespread importance beyond just geothermal fracture flow. I think the geothermal community should be proud to have helped support this work.

PI Response:

Reviewer 24876

Score: 9.0

Comment: Fractures are key components of EGS reservoirs and their response to perturbations from production and operational processes is important for reservoir management. This project uses neutron imaging to quantify flow paths along fractures and mechanical deformation of fractured rock at elevated temperatures and pressures. The experimental approach has enabled imaging of the transport path of immiscible bubbles through propped rough/smooth fractures, mineral dissolution/precipitation and single phase flow. They have also developed a neutron imaging technique for determining local strains in a rock. This is an exciting development because it enables determination of the microscopic contributions to strain from individual minerals or mineral assemblages on macroscopic rock deformation. This was demonstrated by their results on marble and granite. The work is high quality because their method provides information and details of flow and deformation for samples under EGS pressures and temperatures. In addition, the sample size is greater than that typically used in X-ray CT which enables better coupling between microscopic-macroscopic deformation behavior. The project is on track.

PI Response:

Reviewer 23583

Score: 8.0

Comment: Project seeks to demonstrate a new and promising experimental imaging capability based on neutron radiography applied to EGS-relevant rock samples and focused on visualizing and ultimately characterizing flow through porous media and fractures of particular interest to EGS. It is hoped that this technique will provide new and/or improved capabilities versus existing laboratory techniques. This project should improve our understanding of fracture behavior thus improving our ability to control, monitor, and optimize fracture creation and thus heat transfer in EGS systems if this novel technology is somehow improved or has capabilities that current techniques do not. This is a great idea and an outstanding project with potentially high impact.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 10.0

Comment: For measuring flow, the project has developed a sample holder and specialized jet that allows samples to be exposed to a neutron scanner. Water can’t be used as it is opaque to neutrons, necessitating a process to select an appropriate contrast agent. Experiments have been designed to understand flow through fractures, and surface roughness, aperture variation and tortuosity are some of the variables investigated. High speed particle image velocimetry using neutron radiography has been demonstrated, including particle (bubble) tracking.

Hydraulic fracturing is investigated using neutron diffraction. Lattice deformations can be measured and equated to macroscopic stresses. Tests have been conducted that verify that strains can be mapped in geological material in a triaxial stress state in a pressure vessel.

PI Response:

Reviewer 23434

Score: 10.0

Comment: Examining both stress/strain and fracture flow in a high resolution/non-destructive fashion within rock fractures is an accomplishment in itself. The fact that this is available for others to come and use to examine other properties is phenomenal. Overall, think the proof is in the pudding; this is an approach that seems scientifically and technically sound.

PI Response:

Reviewer 24876

Score: 9.0

Comment: The neutron imaging approach developed by this project is an excellent method for monitoring flow paths in fracture and deformation during high pressure – high temperature experiments. The team put much effort into overcoming technical challenges and succeeded in developing a particle-tracking technique with neutron radiography.

PI Response:

Reviewer 23583

Score: 8.0

Comment: Overall quality of the technical approach is superior because the project work is sharply focused to developing imaging capabilities. The scientific rigor is outstanding because experiments are following a step-by-step approach that slowly moves towards the final goal. Work elements, procedures and methods are appropriate in achieving project objectives. So far, technical challenges have been surmounted. Instrumentation and equipment are deemed appropriate for this research. Research team is strong and has necessary facilities, expertise and experience.

PI Response:

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: Being able to visualize flow within rock samples, and also crystal strain within samples while under load, is a major advance in geoscience.

PI Response:

Reviewer 23434

Score: Not scored

Comment: High level of technical knowledge, Nondestructive, high resolution, easy to see how these techniques can be widely used in the scientific community. Very strong development and use of a methodology that can be exploited to understand fundamental gas in subsurface flow knowledge.

PI Response:

Reviewer 24876

Score: Not scored

Comment: The expertise of the team to overcome challenges and develop a working imaging system for capturing flow paths through fractures, alterations caused by reactive flow and local strain information over the entire length of the sample.

PI Response:

Reviewer 23583

Score: Not scored

Comment: Project has the potential to address many, critical and significant processes in creating, monitoring, and operating EGS reservoirs by making measurements that traditional laboratory techniques cannot make and/or decreasing costs or time needed to make these measurements. Potential measurements include: flow features and pathways of interest in permeable samples, better understand flow through fractures and the importance of fracture attributes, support validation of numerical flow models, as well as, identify crystal phases within representative geological materials, while performing sample strain mapping of induced triaxial and uniaxial applied stresses. Clearly, a technique that will allow a better understanding of fracture/flow phenomena would surely impact our ability to perform controlled reservoir creation, monitoring and operations and close an important EGS knowledge gap.

Making insitu measurements of critical fracture flow parameters would certainly bring greater insight into EGS subsurface fracture processes, and help optimize fracture creation. These improvements would undoubtedly, reduce costs, improve performance and stimulate key markets for reservoir creation, a critical cornerstone in EGS successful implementation.

Experimental apparatus has been designed, built and initial measurements and observations performed. Major technical challenges have been overcome. Initial results look promising, specifically, high-speed, neutron particle image velocimetry has been demonstrated. Progress is good.

If realized, stated objectives to develop a neutron-beam based experimental capability to image and characterize fluid flow through fractures, as well as, quantify hydraulic fracture-induced stresses within samples of EGS rock types rock and at EGS representative conditions, specifically focused on EGS fracture creation would be innovative and new, potentially helping to reach key goals of EGS; create and operate sustainably and economically, subsurface, heat transfer reservoirs.

PI Response:

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: Measuring strain can only be done spot-by-spot, and each spot requires considerable time (?90 minutes), which prohibits visualization of whole-of-sample fracturing as it occurs.

PI Response:

Reviewer 23434

Score: Not scored

Comment: Better linkage with computational fluid dynamics and geometrical modeling seems like an obvious improvement. Work with UT Austin was mentioned, so I assume there is work on going with this that the PI just didn't have time to discuss at length.

PI Response:

Reviewer 24876

Score: Not scored

Comment: “Engineered” fractures: The flow paths in induced or natural fractures should be quite different from that observed in engineered fractures.

This is more of a question: Does the resolution improve with decreasing sample size or is 100 microns related to some fundamental principle of neutron imaging?

Does this work with only specific fluids (fluorinert) or can any fluid be used (i.e. similar to EGS fluids)?

PI Response:

Reviewer 23583

Score: Not scored

Comment: Due to the expense of this technique and difficulty obtaining beam time, it may never be used as a replacement for other more traditional, high-throughput and less expensive laboratory techniques and at best will be used in very specialized situations. Not totally clear in this reviewer's mind from the data presented that these neutron techniques can improve upon existing laboratory techniques either in more precise measurements, or faster, or cheaper.

PI Response:

IMPROVEMENTS

Reviewer 23418

Comment: None to suggest.

PI Response:

Reviewer 23434

Comment: The more people know about how to access this system, the more gradual improvements the project and research in general will have.

PI Response:

Reviewer 24876

Comment: Use natural or induced fractures.

PI Response:

Reviewer 23583

Comment: At some point in the future the project would benefit from a more formal comparison between neutron radiography's emerging capabilities versus current techniques in order to both measure effectiveness and to better highlight the technique's superior capabilities.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Novel use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems
Principal Investigator: Rose, Kelly
Organization: NETL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23418

Score: 7.0

Comment: Most of the information we have about deep EGS projects to date comes from microseismic monitoring, hydraulic reservoir testing, and fluid tracers. Several new tools have been trialed in the last 5 years or so, including 4D magneto-tellurics (MT), ambient seismic imaging, InSAR, and tilt meters. Major advances in microseismic monitoring and processing have also been made.

This project develops novel uses of 4D monitoring techniques to improve reservoir characterization including temporal-spatial variation in temperature, crack volume and their effects on porosity and permeability. The monitoring techniques being evaluated include ground-based radar to complement satellite radar, MT, controlled source electromagnetics (CSEM), and gravity.

The potential impact of the project is high; it will be very interesting to see the results of the monitoring during the next stimulation at Newberry.

The project has deployed integrated surface geophysical tools (portable radar, MT, gravity) during initial hydro-shearing at Newberry EGS site in coordination with Alta Rock, and also during subsequent injection and production testing periods. Difficulties have been experienced due to weather (early and heavy snowfall) and lower stimulation volumes (leaking casing).

The project has built a 3D geological model utilizing surface geological maps, stratigraphic columns, LIDAR, well logs, seismic, gravity and magnetotelluric data.

The project has been underway for a number of years, but its progress is dependent on activity by Alta Rock, and this has been slower than everyone would have liked.

PI Response:

We agree, no comment needed.

Reviewer 23425

Score: 6.0

Comment: This project is intended to provide EGS operators with a lower-cost, surface-based system to assess temporal changes in the flow pathways and the temperature of the target reservoir. An additional goal is to identify reduction in permeability and EGS reservoir conductivity throughout the life of an EGS reservoir using only surface observations. This is an admirable goal that I suspect will be extremely difficult to achieve either in theory or in practice. This work is not complete, ending in Q2 FY16. It is unclear to the reviewer what the impact of this effort in terms of achieving its objectives will ultimately be and only a few months are available to complete this effort. The presentation showed many graphics but it was difficult to know how these related to achieving the goals of the project.

PI Response:

While there are inevitable limitations in a project with an observational window of limited duration, a key goal is to demonstrate that by coregistering key physical and chemical observations that constraints can be placed on fluid circulation pathways and the permeability and temperature of those pathways, of relevance to the timescale of the observational window. While the observational window, at present, spans months in duration, in a production setting this would be extended over the lifetime of the EGS field.

We offer one important clarification regarding the theoretical basis for the goal to "...identify reduction in permeability and EGS reservoir conductivity throughout the life of an EGS reservoir using only surface observations." First, we have always considered the 4D monitoring methods employed in this project as complimentary to monitoring methods such as microseismic, chemical tracers, pressure measurements, well temperature, pressure, and flow data, and not a replacement for them. By demonstrating the sensitivity of each method to temporal and spatial variations in fluid pathways, the necessary components of a control loop for maintaining the productivity of an EGS play can ultimately be assembled. The use of ground surface and space-based methods is intrinsically less expensive than borehole methods, and the final combination of control loop observations would likely be of reduced cost if dependence only on borehole methods can be reduced.

Regarding the justification for the theoretical basis for identifying a reduction in permeability, this is based on identification and subsurface imaging of EGS fluid pathways that change with time (i.e., 4D spatiotemporal monitoring). Once signatures of subsurface fluid can be identified from a multi-day stimulation period where water at pressure is injected deep into the reservoir, any changes associated with these montoring signatures can be compared with corresponding changes in fluid flow rate with time as measured at the wellhead and would be considered an indication of spatiotemporal changes in permeability at depth. Fluid pathways can be cut off by mineralization and re-routed. Any such short-term observations of spatiotemporal fluid pathway changes we observe can be useful for understanding long-term changes in permeability in EGS reservoirs as it is reasonable to assume much of the same processes governing short-term permeability changes also play a role in long-term permeability changes. Ideally, a long-term monitoring study is preferable for identifying long-term changes in reservoir permeablity, but practical limitations associated with a limited-duration demonstration project such as this, prevents identification of long-term reservoir-wide changes in permeablility.

Reviewer 24876

Score: 8.0

Comment: EGS reservoirs vary in rock type and structure that result in different mechanical, geochemical and hydraulic responses during operation. This project examines the use of various geophysical monitoring methods to determine the ability of each technique to sense spatial and temporal fluid distributions in the subsurface. Progress was made on assessing the sensitivity and identifying methods (field design and analysis) for using radar/satellite, magnetotellurics and gravity approaches to monitor the subsurface. The level of productivity appears to be high given the tremendous amount of data collected from 4D monitoring and the ongoing analysis and interpretation of the results. This work is very important because the results of this research will determine when EM techniques can or cannot be used to monitor subsurface fluid distributions.

PI Response:

We agree, no comment needed.

Reviewer 23583

Score: 7.0

Comment: Combining 4D gravity, MT, radar with a 3D geologic model is a big step toward total, O&G-like integration for geothermal. The O&G industry for years has integrated all collected data (including well logs and core analysis and etc.) at a play/field. The geothermal industry tends to collect and analyze individual data sets but rarely, truly integrates. The value of this integration is high and adding the time dimension brings new insight into standard techniques that could give valuable information on EGS processes. Data collection project objectives have been met, and analyses continue, and EGS program goals to characterize, create and operate EGS reservoirs will be definitely impacted.

PI Response:

We agree, no comment needed.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23418

Score: 7.0

Comment: Tracking the progress of fluids in a developing geothermal reservoir is an exciting area of development, promising much better information than microseismicity alone. This project utilizes several observation methods (including new computational facilities) that have been shown to work individually elsewhere.

Four-dimensional MT has been used to monitor hydraulic stimulation at other EGS projects. At Paralana, South Australia, it appears to have identified that injected fluid moved into the reservoir volume and created an interconnected network that markedly increased the electrical conductivity of the rock volume (Peacock et al., 2013, Case History: Time-lapse magnetotelluric monitoring of an enhanced geothermal system, Geophysics, 78/3, P.B121-B130).

InSAR has been used previously to show surface deformation in operating geothermal fields. However, work presented by Elsworth (GTP150032) suggests that in deep geothermal reservoirs subsurface strain will be more readily measurable using surface tilt meters than changes in elevation will be using radar or other geodetic methods. It would be very interesting to see if this project could compare the methods during the next stimulation at Newberry.

The project could be strengthened by the inclusion of tilt meters.

PI Response:

We agree that adding a tiltmeter array to ground and satellite radar interferometry would enhance our project. However, given that this is a heavily forested area with a surface cover comprised of unconsolidated, unstable volcanic deposits (as evidenced by the noise we observed in the absolute gravity data we collected), any tiltmeters would have to be placed in boreholes to isolate them from daily thermal and moisture expansion noise which would add considerable effort and cost to the project. In addition, Elsworth (2015 GTP) plots are theoretical predictions of tilt, strain, and vertical displacement against a (ground) noiseless, system detection threshold. An adequate analysis of the noise contribution at Newberry would require considerable effort. Even if noise was nonexistent or easily mitigated, given the unknowns associated with the fluid pathways we are trying to identify, attempts at inversion of point-based borehole tiltmeter data would be more difficult given the non-unique nature of the solution space. Quasi continuous maps of surface deformation from InSAR provide wide-area coverage to identify unpredicted/unexpected locations of subsurface volume change if they are at a level that is detectable. Although micro-tilt measurements are more sensitive and hence can detect smaller surface deformation (tilt) signals from deeper sources, isolating these tiny signals from noise and interpreting the results in terms of unique subsurface volume change sources would be extremely difficult without the InSAR data constraints. So, it would definitely be an enhancement to add a tiltmeter array (especially to mitigate the detrimental effects of snow cover) but if we had to choose one or the other, we think we chose correctly going with ground and satellite radar interferometry with tree-mounted corner reflectors used as fiducial points.

Reviewer 23425

Score: 7.0

Comment: A lot of work has clearly gone into this project and it appears that some of the field work has been more difficult than expected due to environmental conditions encountered at Newberry. Also I understand an injection at Newberry didn't proceed as anticipated which also contributed to the problems. Field work in general is very difficult to do and the results rarely seem to support the original enthusiasm. I wonder if the original idea of evaluating subsurface conditions in an EGS regime using only a surface approach that involves different methods that are somehow integrated isn't a bit simplistic given the complex relationship to detectable signals of pore/fracture flow, permeability and temperature. I agree that this project would be transformational using mainly surface techniques to assess the state of an EGS if the goals stated here could actually be realized.

PI Response:

We appreciate the recognition the impact the unexpected site, field, schedule, and weather conditions had on our project. This is intrinsic to fieldwork, yet it is essential to obtain expeimental data such as this to validate (and to develop) the theoretical models that would underpin any future EGS production control loop. A consequence of these challenges has been that more time and effort has been needed for data collection and re-deployments (particularly the need to carry out two rather than one field monitoring effort, separated by two years), with less time available for data processing, analysis, and fusion between our datasets. We agree that our goals may have been ambitions, and as this reviewer says, "Field work in general is very difficult to do and the results rarely seem to support the original enthusiasm", but we have done our best to overcome the obstacles we faced and have learned a great deal from this project even before its completion. There have already been significant advances in merging ground-based interferometric radar with satellite InSAR ground surface deformation data sets, and new methods for 4-D magnetotelluric analysis have been developed. Our present efforts include completion of the 3-D geological baseline model for Newberry, completion of the new time-dependent (4-D) magnetotelluric inversion method, and fusion with a newly completed (as this is written) 3-D density model resulting from inversion of the gravity data set. These results will be overprinted on the recorded/located microseismic cloud associated with the EGS stimulation (as provided by AltaRock Energy and collaborators), providing the most comprehensive multiphysics overview on an EGS system to-date. As such, this work will be an important guide for future comprehensive EGS studies not only at Newberry volcano, but also far more broadly.

Reviewer 24876

Score: 8.0

Comment: The scientific approach is of good quality because it compares/contrasts several different geophysical methods (level of difficulty of deployment, site considerations, etc), the data produced by these techniques and the ability to detect subsurface alterations of fluid distributions or volumetric deformation responses.

PI Response:

No response needed .

Reviewer 23583

Score: 7.0

Comment: Overall quality of the technical approach is superior and the scientific rigor is solid. Work elements, procedures and methods are appropriate in achieving project objectives. Research team is strong and has necessary facilities, expertise and experience. Research team brings years of application of MT techniques to subsurface characterization and it will be interesting to see what be detected as a change during the stimulation. In addition, and if project objectives are met, EGS stimulation could gain a new system for monitoring.

PI Response:

No response needed

STRENGTHS

Reviewer 23418

Score: Not scored

Comment: The project is introducing higher frequency recording for MT, and also better computational facilities for dealing with the larger volumes of data. It will be interesting to see whether there is an increase in resolution.

The project is introducing novel ways to try to get better resolution from satellite radar: tree coverage is an issue; the project is deploying reflectors to see if the bright spots returned from those can give better processing of the scene.

The use of ground-based radar is intriguing, as it could provide real-time mapping of changes in elevation. However, it appears to be problematic in deployment and continuous operation.

PI Response:

MT: It is good to see the recognition of the technological advances associated with the wideband magnetotelluric monitoring effort at Newberry, extending the sample rate to 4096 Hz, while also maintaining 32-bit sample resolution. This enhanced dynamic range is of considerable benefit when collecting MT data in the presence of cultural noise sources, as one would find associated with the multi-MW electrical generators used during the EGS stimulation. The improved computational facilities (a combination of NETL supercomputer times as well as updated hardware for multi-GPU massive parallel computing as provided through project support) is proving to be a singular advance in our ability to carry our rapid 3-D MT imaging, and to provide a development platform for the 4-D imaging methods now in development. The resulting technology will be broadly generalizable and of benefit to future EGS and other subsurface imaging work as well as the present project.

Radar: Yes, tree cover and snow during stimulation have been the biggetst challenges, followed by a lack of nearby high vantage point for the ground radar to image the stimualtion zone (the radar was stationed on the North face of Paulina Peak over 6 km distance from the stimulation zone which turned out to be too far away for adequate azimuth resolution). Continuous operation was not implemented during the 2012 stimulation, but it was for the 2014 stimulation after modification of the fuel supply system for the generator. In addition, a slower scan speed was used for 2014, but the large distance to the stim zone proved to be the dominant factor. The radar reflectors have been highly successful for the satellite data as about 90/100 reflectors are consistently seen in the data post installation and provide good phase change fiducials for the satellite InSAR data.

Reviewer 23425

Score: Not scored

Comment: Kelly Rose and the consortium of experts is certainly a strong point. The basic idea of using very different techniques and integrating the results through modeling. The collaboration with AltaRock.

PI Response:

No response needed.

Reviewer 24876

Score: Not scored

Comment: Access to field sites and the personnel with EM and gravity experience.

PI Response:

No response needed.

Reviewer 23583

Score: Not scored

Comment: Project directly targets key aspects of EGS goals to research processes and technologies in monitoring and operating EGS reservoirs. In particular, project aims to overcome challenges to evaluating and assessing longevity and viability of EGS reservoirs through lower-cost, surface-based measurement systems. Providing operators with information concerning temporal changes in reservoir flow pathways and temperatures throughout the life of their production and injection wells clearly and exceptionally addresses known, anticipated, and significant EGS monitoring and operations technical knowledge gaps. We just don't have low-costs techniques to monitor real-time changes in the reservoir especially between wells. This idea could help.

Using low-cost, geophysical, surface-based measurement systems to assess long-term changes in EGS reservoirs, could lower costs and possibly improve performance in geothermal energy development. Because these are surface-based measurement technologies, not borehole or seismic. In addition, providing operators with information to monitor and potentially manage the reservoir in near-real-time clearly and exceptionally addresses known and significant EGS monitoring and operations technical knowledge gaps.

Considerable progress has been made and the project is entering the final data analysis stage in 2015. For example, all surface geophysical tools were deployed during initial and second phase of hydro-shearing at Newberry EGS site and during subsequent injection and production periods/testing. Preliminary results show changes in properties and are promising. Progress is good.

Using low-cost, geophysical, surface-based measurement systems to assess long-term changes in EGS reservoirs, could lower costs and possibly improve performance in geothermal energy development. Because these are surface-based measurement technologies, not borehole or seismic. In addition, providing operators with information to monitor and potentially manage the reservoir in near-real-time clearly and exceptionally addresses known and significant EGS monitoring and operations technical knowledge gaps.

PI Response:

No response needed.

WEAKNESSES

Reviewer 23418

Score: Not scored

Comment: Perhaps the biggest weakness of this project – that progress is dependent on activity by Alta Rock – is one of its biggest strengths – which it is observing a full-scale reservoir develop.

One of the things I like about the current GTO program is that it is investing in all scales for geothermal development – from ground selection, to reservoir development, to lab-based experiments, to computational modelling. This project seeks to characterize EGS behavior at the reservoir scale.

Tilt meters measuring strain propagated from the subsurface as a result of constructional cooling appear to have a higher signal-to-noise ratio than measurements of surface elevation change by radar. It would be good to see this incorporated into the current project.

PI Response:

We agree regarding the value of GTO program's commitment to monitoring a full-scape reservoir stimulation. Being tied to AltaRock's schedule did have a big impact on our team given the needed schedule and resource adjustments, as well as the arrival of winter weather on Paulina Peak for the radar and post-stimulation and MT station maintenance needed that was hampered by deep a snowpack, both during the 2012 stimulation attempt, and during the 2014 stimulation.

Experience gained during the 2012 winter monitoring effort led us to discontinue the final phase of stimulation monitoring in 2014, for health and safety considerations, although the main phase of stimulation was successfully captured.

Regarding the use of tiltmeters, please see our response above (p. A4).

<u>Reviewer 23425</u>

Score: Not scored

Comment: Lots of measurements have been made to date using different techniques, but it remains unclear how this can be brought together in a coherent manner to be useful to decision makers and operators. The project still has a year almost and maybe this will be adequate time to achieve some of the objectives.

PI Response:

Agreed, this has been a very challenging site and the project timeline has been complicated by the industry partner's late season stimulation schedule and need for a 2nd stimulation attempt near the end of our original project period of performance. We have and continue to do our best to meet our objectives despite the impact of the delayed stimulation and its relatively small volume have had on the time available for fusion of data sets and the reduction in signal-to-noise ratio for our primary observational data sets. Despite this challenges, we are optimistic of meeting our primary project goals.

<u>Reviewer 24876</u>

Score: Not scored

Comment: No comments at this time.

PI Response:

No response needed.

<u>Reviewer 23583</u>

Score: Not scored

Comment: Not sure this integration technique with these measurements will help with practical monitoring and operational issues. Signal is very small and interpretation is difficult especially for 4D data. If MT, gravity, and radar changes are seen in the reservoir how will these be interpreted because there are several possibilities? Seems difficult to say lower costs when the budget is fairly large. Not clear how the data integration will be done. Is there going to be a formal joint inverse technique or is it going to be 'plot on top' method used in the past where each data set is piloted on top of the others?

PI Response:

As commented above, we faced many unexpected obstacles in the execution of this project. We are working hard to process the data we collected and this will be an "overlay/coregistration" approach to combining the disparate datasets and view joint inversions as follow-on work. This far we are in the middle of data processing and connot comment yet on combining datasets. Having said this, the data returned from this project is of enormous value and in many ways unique, driving the development of new analysis methods that will have broad applicability to spatio-temporal monitoring of subsurface fluid migration.

IMPROVEMENTS

Reviewer 23418

Comment: The next phase of stimulation at Newberry could include ambient noise seismic surveys (i.e. the method of Tibuleac) and deployment of tilt meters (i.e. method of Elsworth GTP150032). These would significantly complement the MT and radar (respectively) of this project.

PI Response:

Since the microseismic array (MSA) has adequately located the stimulation-related microseisms, the ambient noise surveys might help with the identification of subsurface structure and possibly spatio-temporal changes in fluid pathways, but adding ambient noise seismic surveys would not help to better locate the microseisms other than by providing an incremental improvement to the underlying velocity model. This might slightly improve the microseismic locations, although the microseismic cloud is already quite well constrained.

We address the tiltmenter recommendation above (p. A4), but not that Elsworth (GTP150032) is not an actual data collection effort using tiltmenters, it is only a theoretical detection study irrespective of real data noise sources.

In addition to tiltmeters, other methods related to our primary data sets, such as seismoelectric methods, and sel potentials, could also play a complementary role in identifying aseismic fluid pathways. One important aspect of this project is that by providing alternative methods that are sensitive to the presence and absence of fluids, the potential exists for identifying where fluids have migrated along already permeable pathways that may permit fluid circulation without detectible seismicity.

Reviewer 23425

Comment: Possibly more modeling earlier on in the project would have helped in the deployment and data acquisition stages. Also having a backup plan when the Newberry injection didn't work out would have been a good idea although I recognize that such backup plans are scarce when there are so few EGS sites available.

PI Response:

We would have liked to have been able to do more predictive modeling early on in the project, but instrument acquisition and "shakedown", site permitting, and deployment planning activities consumed more time than anticipated. Since deployment of the ground radar was dependent on having a high vantage point where the stimualtion zone is visible, source modeling would not have changed the location for the radar monument on Paulina Peak (closer peaks did not have a line-of-sight to the stimulation zone, and considerable efforts were expended in site visits to other locations that overlook the stimulation zone), nor would it have had any impact on the TerraSAR-X and Radarsat-2 satellite tasking. Every effort was put into obtaining the most frequent data possible before, during, and after stimulation, but arrival of snow prevented post-stimulation radar data collection.

Reviewer 24876

Comment: Need parallel processing capability for analyzing the 4D data.

PI Response:

Agree. In addition to procuring increased high-performance computing capability for this project (utilizing eight NVidia Kepler K80 GPUs with a total of 39,936 GPU cores) , we also have accounts on, and have developed an efficient 3-D MT inversion procedure on NETL's supercomputer, a fast computational platform we are using to develop the 4-D MT imaging code.

Reviewer 23583

Comment: Of benefit to the project would be an answer to this question: What is the connection between estimating temporal-spatial variation in temperature, crack volume, and their effects on porosity and permeability, and improving reservoir longevity especially given this EGS site and short data set?

PI Response:

As mentioned above (p. A2) our goal in this project is to identify spatiotemporal changes in fluid pathways and relate those changes to corresponding spatiotemporal changes in permeability of the reservoir. These changes when observed over a relatively short time period compared to the expected lifetime of a geothermal reservior, are nontheless expected to provide insights into the long-term behavior of EGS reservoirs because the same crack mineralization or other method of fluid pathway closure should also be occuring at longer timescales. We believe that these processes occuring at the timescales we are observing, should be the same mineralization processes occuring during the life of the reservoir. Therefore, by studying our shorter-duration datasets, we expect to extrapolate these processes to long-term EGS reservoir performance estimates. This will provide important information on the relative sensitivity of the various surface and satellite based methods, in contrast with and in combination with borehole methods, ultimately guiding the approach that one would adopt in designed a production control loop to maximum the longevity and production of an EGS reservoir.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: SURGE: Sedimentary Geothermal Feasibility Study
Principal Investigator: Augustine, Chad
Organization: NREL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23444

Score: 6.0

Comment: Large areas of the US have sedimentary basins with sufficient temperatures at depth to produce geothermal energy. Many of these areas are near population centers that could greatly benefit from geothermal electricity generation. However, several formations have sufficient heat but permeability too low for productivity, thus they require permeability enhancements be used. If these types of formations could be sufficiently stimulated to add to the overall geothermal resources, new areas would be available for energy production. Consequently, advancing our understanding of formations and permeability enhancements in these geologic regimes is in line with the goals and missions to address knowledge gaps to aid in, and to increase, geothermal energy production.

Accomplishments focus on modeling of reservoirs by including various stimulation techniques to enhance permeability. Initially developing analytical models for basin analyses followed by numerical models has led to some advances in knowledge but for highly idealized systems. Results of well spacing, configuration and productivity as well as thermal breakthrough times are useful for model refinement and identifying key aspects for the suggested system. Preliminary cost structure analyses lay the foundation for additional work. Delays in licensing and model validation are not uncommon. Adequate progress has been made with respect to stated goals.

PI Response:

Reviewer 29854

Score: 9.0

Comment: The project goal is to evaluate the feasibility of geothermal projects in sedimentary reservoirs. The key challenge is their relatively low permeability; hence the feasibility of permeability enhancement and their expected performance in terms of reservoir productivity evolution need to be assessed. If realized, this capability to exploit low-permeability sedimentary reservoirs would significantly expand geothermal energy. The current phase of the project has identified promising technologies and basic requirements for the commercial viability through reservoir modeling. Permeability requirements are stringent but reasonably achievable through the enhancement techniques evaluated in the project. The team has started a field validation in the Wattenberg field and is in a good position to lead a demonstration project if warranted.

PI Response:

Reviewer 23568

Score: 6.0

Comment: The PIs have addressed a risky potential resource, namely, deep, low-permeability sedimentary basins and have obtained numerical modeling results. Their results, in my view, however, say that the likelihood that an oil-and-gas, hydraulic-fracturing approach to exploiting low-permeability, deep sedimentary basins for significant geothermal resources is a very long shot. Nothing wrong with funding the project. The studies needed to be done. But look at what was found. Permeabilities of hundreds of millidarcies are required. Hydraulic fractures 50-meters high are required. The nature of research is that the results do not always point the way to an economic or technically feasible approach to adding to geothermal capacity. The next planned step in the project is to examine the role of heterogeneity. The only situation in which I could see heterogeneity being important is if the basin contained isolated patches of high-permeability lenses or fractures because then the technological question would be whether or not they could be linked up through engineered fractures. But I would be creating a project that is not the one being reviewed.

The project achieved its goals: (1) "Analyze the feasibility of developing commercial sedimentary geothermal projects" and (2) "Evaluate well productivity enhancement options and determine the techniques and technologies required. " They have 'Analyzed' and 'Evaluated' but did not obtain, through no fault of their analysis, the impact hoped for, namely, "A project that demonstrates through reservoir modeling and detailed analysis that low-permeability sedimentary geothermal systems can be enhanced to produce geothermal electricity commercially would greatly expand the size of the sedimentary geothermal resource potential." (Quotes from Project Summary)

PI Response:

We disagree with several of the conclusions Reviewer 23568 drew from the study and would like to carlify a few points.
1.) It is correct that we found that permeabilities of hundreds of millidarcies (mD) would be requierd for some of the reservoirs modeled, but point out that this is for a simple system consisting of a doublet of vertical wells. Numerical modeling showed that well enhancement techniques can increase the productivity of wells by a factor of roughly five. Another way to interpret this result is that well enhancement techniques can decrease the permeability requirements for a system by a factor of five, to roughly 100-200 mD, maybe less depending on the system attributes. This greatly reduces the formation performance requirements and should increase the number of sedimentary formations that could be candidates for geothermal development. This result shows the value and potential of continued study of well enhancement techniques in sedimentary systems.
2.) The comment about 50-m high hydraulic fractures being required appears to imply that creating such fractures would be difficult. Fractures hundreds to thousands of feet (hundreds of meters) in length are typically created in shale formations. These fractures typically extend through the height of the formation (10-100+m). In fact, the transition to another formation is often cited as the reason that fracture height stops growing in shale formations, indicating that fractures extend the height of the formation.
3.) The study of the role of heterogeneity is to determine how much real world issues, such as variations in permeability, degrade reservoir performance from the idealized situations initially modeled. Although not presented in the Peer Review, our initial work shows that heterogenities have little impact on reservoir performance as long as the scale of the disturbances is small compared to the reservoir size - the disruptions average out. Large lenses that the reviewer mentions would actually be detrimental becaucse they would encourage a short-circuit in the reservoir, acting much like a large fracture that channels flow.

4.) We disagree with the reviewers final conclusion, that through "no fault of [our] own" the project did not show the impact hoped for. Demonstrating improvements in reservoir lifetime and a factor of 4-6 times improvements in well productivity is a large impact in our opinion. We could have done a better job conveying the importance of that result and its impact on permeability requirements for the system. A analysis showing the number or size of systems that would be made commercially viable with this improvement would quantitatively show this impact, but was not in the scope of the study, but would be an area for future research.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23444

Score: 6.0

Comment: There is much literature on modeling reservoirs and controlling parameters in sedimentary systems that does not appear to have been consulted. Understanding previous work and developments may have saved time and effort. Beginning with analytical solutions to a model is useful but it is unclear why new analytical models need to have been developed. That said, validating numerical models by analytical is a cautious and necessary step. A highly idealized system of parameters provides a starting point. Using reservoir modeling programs that have been validated and are widely available may have facilitated a more realistic assessment of the system or provided a better starting point for additional code development. Sensitivity analyses of parameters should be completed to identify those likely controlling parameters for focus such as permeability, in addition to the time step and grid size. Clearly stating the dimensions of the numerical model (2D, 3D) facilitates understanding of the results. Analyses would benefit from a thought experiment on how an added dimension to the system would impact stated results and what could be modeled to understand these complexities found in the real world. Once the primary controlling factors are understood, modeling to an actual geothermal system is appropriate.

PI Response:

A new analytical model was not developed. The analytical model is based on the work of Gringarten (1979). The purpose of the analytical model was to understand the relationship between key parameters such as well spacing, matrix permeability, flow rates, reservoir lifetime, etc., and to identify reservoir characteristic requirements (such as minimum permeability or required well spacing, given other constraints) for commercially-viable sedimentary projects.

As noted by the reviewer, the analytical model was also used to validate the numerical model. STARS CMG was the commercial software package used. It is a well-known and widely used software program. Still, the model required validation to ensure that the impact of numerical model parameters such as grid spacing (which can lead to numerical dispersion), boundary effects, and time steps were adequate to reduce numerical errors to the point where the numerical model results match analytical results. The impact of numerical model parameters on the modeling results is illustrated in Slide 9 of our presentation, which shows how changing grid block spacing impacts the thermal breakthrough time predicted by the simulations. The analytic model results greatly facilitated model validation.

Sensitvity studies were carried out for both the analytic and numeric model. Time prevented presenting most of the numercial model results. These detailed results are discussed in the publications noted on the last slide of the presentation. The scaling rules in the analytic model were also observed in the numerical modeling sensitivty runs.This gave us further confidence in our results as we moved from the simple vertical well doublet case to modeling well enhancement techniques such as a horizontal well.

We should have been more clear on model dimensions. Vertical well doublets could be modeled in 2D, but the well enhancement techniques all required 3D modeling.

Reviewer 29854

Score: 8.0

Comment: The project involved reservoir modeling and analysis of technological options.
The modeling plan included a balanced use of analytical and numerical approaches. An analytical model of a canonical configuration was developed to provide insight into controlling parameters and a benchmark problem for numerical methods. The error convergence of the thermal simulations as a function of grid size seemed slow, which suggests opportunities to improve the computational performance of the numerical method (e.g. using higher order algorithms).

The numerical reservoir models were used to evaluate performance (thermal breakthrough time) of permeability enhancement techniques for different well and fracture configurations, including the effect of reservoir heterogeneity. Horizontal well with longitudinal fractures were found to be most favorable, achieving productivity enhancement factors near 5. Cost analysis was conducted to assess economic viability. A specific case study is being developed, in the Wattenberg field, Colorado.

PI Response:

Reviewer 23568

Score: 6.0

Comment: The technical approach was a careful step-by-step process. First, Gringarten's parallel plate, analytical model and then 4 numerical modeling scenarios were considered. The best-case scenario was found to be the case of a horizontal well intersected by multiple, vertical hydraulic fractures. It is that best-case scenario that was achieved with 50-m high fractures that led me to question the practicality of sufficient enhancement in this geothermal environment.

As part of the numerical work, the PIs discovered that they needed to use a fine spatial grid because of the large time-scale differences between advective versus diffusive heat transport. I wondered if the PIs have looked into numerical methods for managing the time-scale differences. There might be a reasonable approximation to avoid having to go to very small spatial scales.
I wondered also if geochemical effects -- precipitation/dissolution -- might significantly alter the results.

PI Response:

As mentioned in our response above,fractures hundreds to thousands of feet (hundreds of meters) in length are typically created in shale formations. These fractures typically extend through the height of the formation (10-100+m). Given the experience in the shale industry, we don't feel that fractures that extend the height of the formation are technically infeasible.

We did not look at geochemical effects as it was out of the scope of our study. We feel that is a second-order effect that requires study at a later date once the primary questions are answered.

STRENGTHS

Reviewer 23444

Score: Not scored

Comment: Proving a path forward to extract geothermal energy from untapped reservoirs that occur over large geographic areas is strength of the work. Completing an initial assessment of well placing and density provides a first order approximation to the cost and productivity and thus, the likelihood of this resource being developed.

PI Response:

Reviewer 29854

Score: Not scored

Comment: The project goal is to evaluate the feasibility of geothermal projects in sedimentary reservoirs. The key challenge is their relatively low permeability; hence the feasibility of permeability enhancement and their expected performance in terms of reservoir productivity evolution need to be assessed. If realized, this capability to exploit low-permeability sedimentary reservoirs would significantly expand geothermal energy. The current phase of the project has identified promising technologies and basic requirements for the commercial viability through reservoir modeling. Permeability requirements are stringent but reasonably achievable through the enhancement techniques evaluated in the project. The team has started a field validation in the Wattenberg field and is in a good position to lead a demonstration project if warranted.

The project involved reservoir modeling and analysis of technological options.

The modeling plan included a balanced use of analytical and numerical approaches. An analytical model of a canonical configuration was developed to provide insight into controlling parameters and a benchmark problem for numerical methods.

The numerical reservoir models were used to evaluate performance (thermal breakthrough time) of permeability enhancement techniques for different well and fracture configurations, including the effect of reservoir heterogeneity. Horizontal well with longitudinal fractures were found to be most favorable, achieving productivity enhancement factors near 5. Cost analysis was conducted to assess economic viability. A specific case study is being developed, in the Wattenberg field, Colorado.

PI Response:

Reviewer 23568

Score: Not scored

Comment: Even though it is a negative result from a programmatic perspective, the strength of the project is that we now know not to pursue deep sedimentary basins.

PI Response:

We disagree with the reviewers conclusion that the project had a negative impact from a programmatic perspective. As stated in our response in the "Impact of Research…" seciton, demonstrating improvements in reservoir lifetime and a factor of 4-6 times improvements in well productivity is a large impact. We should further point out that the well enhancement configurations studied were our initial configurations. The configurations are not optimized in terms of fracture or lateral horizontal well length (in terms of performance or cost) nor designed specifically for the systems studied. Further improvement from optimized well enhancment design is possible. As is, the project demonstrated the potential to increase well productivity (or conversely, lower reservoir permeability requirements) by a factor of roughly 5 over using vertical wells. Gringarten (1979) further showed that well configurations, such as a 5-well "star" pattern, in a large field, could further increase recovery rates and/or decrease well spacing requirements - another area we have not studied. Given the large areal coverage of sedimentary basins, well configurations are feasible (and are use in oil recovery currently). Further, it points to a geothermal system that can scale up in size over broad areas once demonstrated, and take advantage of learning to reduce costs over that scaling up period.

Our conclusion from the study to date would be that given the reservoir requirements for producing large volumes of fluid over long periods of time, GTO should only be explore deep sedimentary basins if the system design includes the well enhancement techniques. Combining the information on analytical model results from Slide 7 and the cost analysis results form Slide 8 with the productivity enhancements in Slide 11, the results point to systems that could be created for <$8,000/kW in formations with sub-100 mD average permeabilities. Referencing the figure from Kirby 2012, this could include a large number of sedimentary formations reaching considerable depths, up to 5 km.

WEAKNESSES

Reviewer 23444

Score: Not scored

Comment: A more thorough literature review would familiarize the team with the vast amount of information available on Darcy flow, controlling parameters, assumptions that are reasonable, as well as the constraints on the reservoir modeling outcomes. While useful to begin with an idealized system of isotropic and homogeneous permeability as an end member case, permeability is one of the key controlling factors on flow in porous media. Testing the models with heterogeneous permeability that is anisotropic within layers, as well as in layered systems would provide a more realistic system analyses because many of these formations consist of fine grained minerals that align perpendicular to the stress fields. Sophisticated reservoir models exist which could serve as a guide for future studies.

Clarity on how the enhancements were actually developed would be useful.

The cost analyses did not incorporate the cost of the enhancement techniques.

Clarify why an oil and gas company would want to invest in this technology given that the price return is likely limited.

PI Response:

We agree that heterogeneous permeability that is anisotropic within layers is more realistic and should be the next step in these studies. The are our planned next steps. We started with idealized systems to develop understanding of what the major controlling factors are, and to test the technical and economic feasiblity - if it doesn't work in the idealized case, it's not likely to work when complexity is added.

The business model, especially in the case of an oil and gas company as the primary investor, needs development. However, the sedimentary system does not require oil and gas investment, just their technology such as extended reach horizontal wells and fracture creation. Oil and gas service companies would likely be willing to lend their services for sedimentary geothermal sysetms (for a fee, of course).

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23568

Score: Not scored

Comment: The weakness of the project is that the project might have started with scenarios of the permeability structure of real, deep sedimentary basins with some architectural feature that could be exploited via engineered fracturing. For example, might there be a deep, overpressured basin deposited in a fluvial environment whose high-permeability sand lenses could be turned into a productive reservoir via strategically induced hydraulic fractures?

PI Response:

Our approace was to start with the simplest system we could imagine and add complexity, to understand the factors and parameters that control system performance, cost, and electricity generation potential. Starting with a complex system begs the question of which complexities to include (or exclude). Likely we'd pick a system and model it's complexity, but our focus was on general sedimentary systems. The system the reveiwer describes could be studied if it were of interest and showed geothermal potential. From the description, geopressured formations in the Gulf of Mexico seem a likely fit. Some of the authors have studied these systems in the past (ex. Esposito and Augustine, 2014,"Results of Reservoir Modeling of the Operation and Production of a Recompleted Gas Well in a Geopressured/Geothermal Reservoir in the Wilcox Formation, Texas, for Electricity Generation." SPE Journal, SPE-169902-PA, http://dx.doi.org/10.2118/169902-PA).

IMPROVEMENTS

Reviewer 23444

Comment: see the above section on weaknesses.

Improve the conceptual model of the system, including permeability. The models do not include any chemical reactions between fluids and reservoir minerals, which may be beyond the scope of the project. However, using another geochemical modeling program, one could assess if these reactions would be important for a given thermal regime and provide constraints on fracture healing/sealing. Review the literature on modeling studies to guide future models and to evaluate controlling parameters.

PI Response:

Reviewer 29854

Comment: The error convergence of the thermal simulations as a function of grid size seemed slow, which suggests opportunities to improve the computational performance of the numerical method (e.g. using higher order algorithms).

PI Response:

Reviewer 23568

Comment: It would be useful to get a geologist's perspective on what deep, low-permeability sedimentary basins are really like.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: SURGE: Completing Horizontal Geothermal Wells
Principal Investigator: Augustine, Chad
Organization: NREL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23444

Score: 6.0

Comment: Direct application of advanced technology currently deployed in the oil and gas industry to geothermal system development reduces costs and the time required for development and testing directly addressing GTO mission and goals. Horizontal drilling and fracturing techniques are a mature field in the oil and gas segment. Application of these techniques to geothermal energy development may potentially allow many more fields to be developed for commercial use.

First order approximations of the viability of the approach, using previously developed algorithms, industry stimulation models and idealized geologic parameters demonstrates that several mitigating factors of a more realistic system need to be taken into account. Initial analyses is completed for the casing design, pressures and cements required for cycling and for isolating zones. Although the injection completion design for horizontal wells is developed, it comes prior to full geothermal system analyses. The determination that commercially available oil and gas equipment will withstand the temperatures and cycling in geothermal systems is an important outcome as is the development of the casing design and completion techniques. Original milestones have been attained although some are restricted to identification of technologies. One presentation at the Stanford Geothermal meeting is minimal over a two year period.

PI Response:

The goal of the project has been to determine if there are any significant impediments for applying unconventional resource development technology and procedures to enhanced geothermal systems. In that respect, nothing has been found that with some modifications, can be used.
Regarding the one paper, the project has only been ongoing for one year and that a second paper is slated for the GRC 2015.

Reviewer 29854

Score: 9.0

Comment: The project examines if permeability enhancement technologies and techniques available from the oil and gas industry can be transferred or adapted to enhanced geothermal system, in particular completing horizontal wells with multistage hydraulic stimulations. The project developed requirements, designs and identified existing technological capabilities. Casing profile designs for horizontal EGS well were developed too. EGS environments were found to be near the operation limits of available commercial equipment, pointing to opportunities for more R&D.

PI Response:

Agreed

Reviewer 23568

Score: 7.0

Comment: Many people have expressed the idea that the geothermal industry can ‘borrow’ technology from oil & gas. So talk is cheap. This project actually examines the’ nuts and bolts’ or should I say ‘plug and perf’ of that technology transfer. To be sure, this is a ‘paper’ study in terms of the specifications for casing, connections, and stage isolation techniques. The results are encouraging, albeit at the margins of the specifications. A particularly important consideration is the thermal cycling that the connections experience between the cold water injection and the hot water production. Yet, in the end, there will be no substitute for real world experience and/or experiments under geothermal reservoir conditions.

PI Response:

Agreed. A follow on finite element model is being developed to determine the thermal cycling issues. This study will have benefits to not only this project, but also to geothermal development in general.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23444

Score: 5.0

Comment: The technological transfer of materials and designs from the oil and gas industry to the geothermal industry provides a foundation for understanding the materials but not necessarily the system. The scientific approach here needs to begin with a well characterized geothermal system in order to develop well designs and to use computational modeling to predict fracture spacing for an EGS system and to identify appropriate completion techniques and technology. Understanding the heat source helps to predict the lifetime to the system, necessary to justify the cost of these EGS wells. Using generalities of the Newberry system extracted from logs is a good start but verification and validation of the parameters should follow. Use of commercial software for predicting fracture creation is only as good as the code and the input data. The regional stress field is needed to understand fracture orientation and anisotropy; and lithology is needed to understand fracture spacing. Using highly idealized systems, with large through going fractures that intersect three wells, as shown, rarely occurs in nature. The approach used to model fractures incorporated (unrealistically) idealized fracture sizes that needs to be revisited as well as using a code that incorporates real rock properties. Thus, it is highly suspect that hydrologic zones can be isolated based on such modeling. Moving from the generic models of fracture creation to the real rock system is difficult and not insignificant. How an actual EGS system is to be developed needs to consider fracture size, spacing, interconnectivity, reactivity between fluids and rocks as well as the use of proppants. If these variables cannot be evaluated, at a minimum, conceptual models of how these parameters affect the system should be included. The well design, completion techniques, well casing and cement seem detached from the actual geothermal system.

PI Response:

This project is taking a stepwise approach to developing EGS, looking at system components in order of development, starting with horizontal drilling (studied by Sandia/Baker Hughes previously), well completion for zonal isolation in horizontal wells (Year 1, bulk of Peer Review presentation), fracture creation (Year 2 - current work), production well drilling and completion (covered a bit in Year 2), and circulation (outyears). Our team understands that these components work together as a system, and we are anticipating the impact of future activities as much as possible while focusing on the task at hand. This was the driver behind performing some basic fracture modeling to understand how the stimulation process will impact the well and completion design. Regarding the idealized fractures, it was understood that the model chosen was limited. However, the goal was to determine the order of magnitude for fracture stimulation pressures and rates. Plus, it was free. We understand that the fracture modeling we did was rather simplistic, but gave us a ballpark idea of what sort of pressures the completion design would be required to withstand. Later studies (Year 2) will tackle fracture cration (for example) in depth with more sophisticated software (Mangrove, from Schlumberger).

It is understood that this is a general study of the applicability of unconventional resource technology to EGS. Until a specific site is chosen and characterized, no detailed work can be done. As for the well design, until actual specifics can be incorporated, the design necessarily must be general. Plus, the design is based on unconventional resource wells and would not look like a typical geothermal type completion.

Reviewer 29854

Score: 8.0

Comment: The requirement and design phases followed a logical flow, based on available software. Three zonal isolation techniques from petroleum industry were considered. These have not been field tested under conditions typical of EGS environments, hence the necessity to proceed with an approach based on simulations. Challenges were identified in modeling fracture system evolution with commercial software.

PI Response:

In the FY15 program, a better fracture model has been identified and is currently being applied.

Reviewer 23568

Score: 6.0

Comment: While the investigation of specifications for horizontal well equipment was straightforward, I am less sure about the past and future work to "(1) Model Creation of fracture system with commercial software and 2.Intersecting the fractures by drilling." Using the Newberry well logs for fracture characterization is good in the sense that it is a real field, but it is perhaps not representative of large, granitic batholiths. Besides fracture characterization, information on stresses is also critical and there is no mention in the presentation or summary of how that parameter will be dealt with. On the other hand, a lot of emphasis is being placed on obtaining the appropriate software, but little discussion of criteria for selection or mention of consideration of critical inputs such as the stress field in the reservoir. I am not sure generic modeling will serve much purpose. Overall, there is the question of rationale for, and justification of, the simplifying assumptions that will be made in terms of the applicability of model results to assessing the development of EGS.

PI Response:

The reviewer's comment that the critical inputs for fracture modeling were not discussed is reasonable. Given the limited time for the peer review presentation, we focused on work completed and were not able to commit much time to future plans and methodology. The fracture modeling task is still underway, but will focus on identifying the parameters, such as stress field and rock properties, that control fracture behavior. Unlike previous studies, we will also focus on the properties of the fracture fluid, such as viscosity, to determine how they influence fracture behavior. The goal is to be able to engineer and control fracture creation, given the rock environment, rather than predict how fractures will grow. By its nature, this study requiereds some "generic modeling" rather than focusing on a certain system.

STRENGTHS

Reviewer 23444

Score: Not scored

Comment: Validating that commercially available equipment developed for the oil and gas industry can be directly applied to an EGS system overcomes some technological and financial barriers. In addition, using the oil and gas approach to well stimulation, completion techniques and well casings saves time and cost. Technological transfer of knowledge and materials from one sector to another facilitates geothermal energy production.

PI Response:

Agreed

Reviewer 29854

Score: Not scored

Comment: The project examines if permeability enhancement technologies and techniques available from the oil and gas industry can be transferred or adapted to enhanced geothermal system, in particular completing horizontal wells with multistage hydraulic stimulations. The project developed requirements, designs and identified existing technological capabilities. Casing profile designs for horizontal EGS well were developed too. EGS environments were found to be near the operation limits of available commercial equipment, pointing to opportunities for more R&D.

The requirement and design phases followed a logical flow, based on available software. Three zonal isolation techniques from petroleum industry were considered. These have not been field tested under conditions typical of EGS environments, hence the necessity to proceed with an approach based on simulations. Challenges were identified in modeling fracture system evolution with commercial software.

PI Response:

Noted earlier.

Reviewer 23568

Score: Not scored

Comment: Good idea to give industry a jump start on using oil & gas technology, if they have been hesitant. Yet, I would guess that industry would want proof in the pudding, so the next step is a small field demo.

PI Response:

Let's get started.

WEAKNESSES

Reviewer 23444

Score: Not scored

Comment: Application of these techniques to an actual geothermal system is largely lacking. Developing the system/methodology based on idealized fractures that are usually long and wide (100s m) is largely unrealistic. The behavior of the fractures is a function of the regional stress field in addition to the rock properties. Determining the likelihood of fluid-rock reactions for fracture sealing or the ability of fluids to dissolve the rock matrix is essential for evaluating transfer of technology and the EGS system lifetime. Fracture modeling of an actual geothermal system would facilitate verification and validation. Identifying barriers to success, uncertainties and limits of the models improve the results because critical analyses add confidence.

PI Response:

This process is recognized and is the focus of some of FY15's goals.

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

No comment.

Reviewer 23568

Score: Not scored

Comment: There is insufficient awareness of geologic context, especially the stress field. Also, there seemed to be little critical due diligence of capabilities and limitations of the software that is being chosen. Also, I worry about the problem of getting a Master's level student for the modeling. This is not plug and play but requires some sophistication in understanding the goals and significance of input parameters.

PI Response:

Using the Altarock data gave the modelers some grounding in the realities of geothermal systems, limited as it is. Future work should be done to directly measure these properties to input into the latest fracturing models.
As for a master's student, the model for the FY14 project was actually done by a PhD student as a summer project. He had taken the graduate level stimulation course offered at Mines the previous semester, the software company's short course, and is working on his dissertation in a related field. The Master's student working on the project is being mentored by Dr. Azra Tutuncu, an expert in fracture modeling. Using a Master's student is not the fastest or most efficient means of completing the research, but is the nature of the NREL/CSM collaboration. It does have the added benefit of educating future geothermal researchers.

IMPROVEMENTS

Reviewer 23444

Comment: See approach and weaknesses. Most relate to modeling of the fractures, validating fracture models, using realistic input data for the geologic system, and critically analyzing the results for applicability and uncertainties.

PI Response:

Noted

Reviewer 29854

Comment: Reviewer did not provide comments for this criterion.

PI Response:

No comment.

Reviewer 23568

Comment: The modeling of creating fractures needs to be ground truthed in some way. At least use an oil and gas case history for that purpose, even if it is missing the temperature aspect.

PI Response:

Noted. The team is considering that for FY15.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Imaging Fault Zones Using a Novel Elastic Reverse-Time Migration Imaging Technique
Principal Investigator: Huang, Lianjie
Organization: LANL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23444

Score: 7.0

Comment: The ability of subsurface techniques to image steeply dipping faults has the potential to identify previously unknown fault systems that may impact geothermal resources, reservoir production and/or lifetime estimates. If successful, the proposed work could reduce risk and provide improved data for use in conceptual models of resource exploration, development and productivity addressing goals of the GTO mission. The new algorithms and techniques have improved significantly the signal to noise ratio when tested on a synthetic dataset. Thus, elected objectives have been attained.

Substantial delays occurred earlier in the implementation of this project because the company did not keep/have pre seismic data needed for the study. DoE GTO provided additional funding yet it took another ca. year. As of January, a PO was issued. Thus, the project falls short of the original milestones but new milestones have been created. Development of the 2D and 3D techniques is underway and appear to be successful based on testing using synthetic data.

Numerous publications and presentations have resulted from the algorithm development providing evidence of accomplishments in imaging enhancements.

PI Response:

Thank you for your comments and understanding. The delay was out of our control. We will complete the project within the budget.

Reviewer 29854

Score: 9.0

Comment: The project goal is to improve the efficiency of geothermal exploration by developing the capability for seismic imaging of steeply dipping faults, which may control flow paths and reservoir confinement. This addresses a limitation of conventional seismic migration techniques, typically used to image sub-horizontal reflectors. This new capability has the potential to reduce geothermal exploration and development costs. The team has made steady progress on development of 2D techniques and setting the building blocks for 3D modeling.

Project productivity includes software, 5 peer-reviewed articles published and 7 conference abstracts presented.

PI Response:

Thank you for your comments. We have developed a suite of novel reverse-time migration methods to greatly improve our capability to directly image steeply-dipping fault zones.

Reviewer 23568

Score: 7.0

Comment: Seismic reflection imaging is good at imaging subhorizontal layers as well as offsets of the layers. Faults connecting the layers are inferred. The goal of this project is to obtain direct images of the faults in the same sense as imaging sedimentary layers. The geothermal reason for attempting to image subvertical faults directly is that such faults are often conduits of flow in the geothermal plumbing system. Therefore, direct imaging can be an important tool in exploration for geothermal fields. The PI encountered delays in obtaining pre-processed seismic data from the Soda Lake geothermal field, so the proof of the pudding is still to come. The PI has published a number of journal and conference papers, so the productivity has been high in a scientific sense. The fact that the algorithms require a super computer is a concern in terms of implementation by the geothermal industry. It does not have as much access to massive computational resources the way the oil industry does.

PI Response:

Our algorithms can also be implemented on GPU computers that are much more affordable and may be suitable for geothermal industy's applications.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23444

Score: 6.0

Comment: The series approach follows a logical order from obtaining a preprocessed dataset for a geothermal site, developing new algorithms for the velocity model and migration resulting in improved signal to noise ratios with testing on synthetic datasets and an ultimate application to a complex geothermal system. To date, algorithm testing is restricted to 2D synthetic data that may not capture the noise in real 3D datasets. Testing the algorithms on 'real' data needs to be included or on a noisier dataset. Demonstration of feasibility should follow. Other methods for algorithm validation could be considered. Adding a discussion of confounding factors to data interpretation and image processing would be useful as would a clear discussion of uncertainties. Having a strategy to release the new code for more widespread use should be included. Rigor to the algorithm development is high, testing appears to be weaker.

Initial problems with obtaining the dataset hampered progress. Having agreements from all participants ahead of time is a necessary condition to later success. This aspect of the study might be improved by better oversight. From the documentation, the personnel involved in the project are unclear.

Carefully thinking through a broad spectrum of risks would be useful to ensure success rather than stating "there is no risk".

PI Response:

We have developed and impletemented our algorithms in 3D and will test the 3D imaging capability with noisyg data. Our remaining tasks will mainly focus on field data applications.

The project is delayed because the data processing company Geokinetics did not keep a copy of pre-processed seismic data and re-processing of Soda Lake seismic data was delayed for various reasons out of our control. DOE GTO provided funds to cover the seismic data processing cost in June 2014. After receiving the funds, LANL obtained a quote from Geokinetics to process the data. However, Geokinetics did not want LANL to start the subcontract paperwork until a data processor Geokinetics assigned to do the work went back to work from his sick leave. LANL contacted Geokinetics one to twice a month since then, but the assigned data processor still could not work by September, 2014. Then LANL started to obtain quotes from other companies rather than waiting for Geokinetics, and started the subcontract paperwork for Vecta to process the seismic data in early October, 2014. The purchase order (PO) was ready to be signed before the 2014 Christmas holiday break. At that time, LANL found out that Vecta was not in the Governments System for Award Management (SAMS). It took two months for Vecta to establish a profile at SAMS, and LANL was then able to issue the PO to Vecta on 01/27/2015. Vecta started processing the 3D-3C Soda Lake seismic data in February, 2015, and delivered processed data in May, 2015. LANL is now working on the processed data, and will complete all remaining tasks within the budget.

It is crucial to test our new algorithms on field seismic data to demonstrate the practical applicability.

<u>Reviewer 29854</u>

Score: 9.0

Comment: The research plan involves two components: advanced elastic waveform tomography with enhanced resolution on model discontinuities to obtain improved velocity models, and elastic reverse-time migration method for seismic imaging of steeply-dipping fault zones. The project includes a number of technical advances in inversion and imaging methods and optimization of forward wave propagation simulators.
The validation so far is shown for 2D synthetic data, including additive noise. It may be useful to develop synthetic tests for the imaging methods that include more realistic “noise” in the form of speckle induced by scattering due to unmodeled small-scale heterogeneities in the velocity model.

PI Response:

Thank you for your suggestion. We will test the robustness of our algorithms to the scattering noise from small-scale heterogeneities.

<u>Reviewer 23568</u>

Score: 9.0

Comment: The PI has innovated and successfully implemented a reverse-time migration algorithm. The algorithm and associated numerical schemes have been validated successfully for 2D synthetic examples and developed for 3D. Achieving this goal in 3D required several numerical innovations as well. As discussed above, the 2D validation did not include the kind of noisiness associated with geologic heterogeneity. That might be necessary when looking at the Soda Lake data.

PI Response:

Thank you for your comments. We will test the 3D algorithm for noisy synthetic data.

STRENGTHS

Reviewer 23444

Score: Not scored

Comment: Developing new algorithms to dramatically enhance the signal to noise ratio on seismic datasets will significantly reduce the need for arbitrary interpretations to detect and locate steeply dipping (and other) subsurface faults. As such, this technique could be valuable to many sectors of industry (geothermal, fossil fuel, etc.). Improved location of faults potentially reduces risk by more clearly identifying these key geologic features.

PI Response:

Thank you for your comments.

Reviewer 29854

Score: Not scored

Comment: The project goal is to improve the efficiency of geothermal exploration by developing the capability for seismic imaging of steeply dipping faults, which may control flow paths and reservoir confinement. This addresses a limitation of conventional seismic migration techniques, typically used to image sub-horizontal reflectors. This new capability has the potential to reduce geothermal exploration and development costs. The team has made steady progress on development of 2D techniques and setting the building blocks for 3D modeling.

Project productivity includes software, 5 peer-reviewed articles published and 7 conference abstracts presented.
The research plan involves two components: advanced elastic waveform tomography with enhanced resolution on model discontinuities to obtain improved velocity models, and elastic reverse-time migration method for seismic imaging of steeply-dipping fault zones. The project includes a number of technical advances in inversion and imaging methods and optimization of forward wave propagation simulators.

PI Response:

Thank you for your comments.

Reviewer 23568

Score: Not scored

Comment: The strength of the project is in the innovation of a new time-reversal migration scheme and its computational implementation for large amounts of seismic reflection data.

PI Response:

Thank you for your comments.

WEAKNESSES

Reviewer 23444

Score: Not scored

Comment: Please refer to approach. Original plans that did not adequately access the availability of the data did not allow the project to achieve its original milestones. Using only 2D synthetic data for model testing and validation may be inadequate to evaluate the algorithms as much of the noise, interferences, etc. are missing yet those may be of paramount importance in actual geothermal systems. Adding additional validation techniques, including uncertainties and a discussion of the above is needed to enhance confidence in results. A plan for dissemination of the code for wider use by the geothermal community should be included.

PI Response:

We were initially told by our industy collaborator that the data were available, but the data processing company did not keep a copy of the processed data. Thank you for your suggestions. As we mentioned above, we will test our 3D algorithms with noisy synthetic data.

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

N/A

Reviewer 23568

Score: Not scored

Comment: More geologic reality could have been incorporated in the synthetic examples. An example was presented with noise in the sense of recording noise, but the real issue will be geologic 'noise.'

PI Response:

The geologic model used to test our algorithms were built based on the geologic features found at the Soda Lake geothermal site and the geologic interpretation of seismic data processing results of 3D Soda Lake seismic data. The model was provided by our indutry collaborator. We will test our algorithms using noisy data suggested by the othe reviewer as mentioned above.

IMPROVEMENTS

Reviewer 23444

Comment: Elucidated under weaknesses; identifying barriers to success, uncertainties and limits of the models improve the results because critical analyses add confidence.

PI Response:

Thank you for your comments.

Reviewer 29854

Comment: Validation was presented for 2D synthetic data, including additive noise. It may be useful to develop synthetic tests for the imaging methods that include more realistic “noise” in the form of speckle induced by scattering due to unmodeled small-scale heterogeneities in the velocity model.

PI Response:

Thank you for your suggestion. We will test our algorithms using the scattering noise as mentioend above.

Reviewer 23568

Comment: If the Soda Lake inversion is successful, then there is nothing to improve. If, however, it fails, then the PI needs to go back to gradually increasing the geologic complexity of his synthetic examples to learn how to deal with real 3D scenarios.

PI Response:

Field data applications are always challenging. Seismic migration needs seismic inversion and velocity-model building results to provide higher-resolution images. We will address the challenges in applying our algorithms to field data.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Stochastic Joint Inversion for Integrated Data Interpretation in Geothermal Exploration
Principal Investigator: Mellors, Rob
Organization: LLNL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23444

Score: 6.0

Comment: High validity methods to locate resources and reduce risk and costs of associated with geothermal energy development and exploration help to minimize significant market barriers. Overcoming such obstacles will also help to reduce energy cost, potentially expedite development of resources and facilitate discovery of new resources. If such a numerical method could be developed to explicitly target new producing wells, the geothermal industry would be transformed.

Several forward models/codes have been tested and successfully linked in series, with inversion techniques following. Code development is rarely straightforward such that time has passed between initial development and final code development (codes are rarely ever complete). Field data has been gathered and inverted, although more clarity on what type of field data has been used would be beneficial. Validation of matching temperature and permeability seems minimal. Milestones have largely been met. A publication per year is average and sufficient. Additional work relating to the actual geologic system and matching parameters is needed. There does not appear to be any 'risk assessment' component as stated in the objectives. The peer reviewed publication on efficient optimization of well placement is a highly relevant result.

PI Response:

The risk assessment is derived from the posterior probability results and unfortunately we did not make that clear. We will provide more clarity on the tpye of field data in the final publication and we appreciate the reviewer pointing this out. We did present a comparison of the observed and matched temperatures but as the underlying permeability is not known, we could not provide a measure of the match.

Reviewer 29854

Score: 9.0

Comment: The project aims at improving the efficiency of geothermal resource exploration, including expected cost reductions during exploration (number of wells) and improved decision-making based on more accurate risk assessment. Progress is outstanding. Development of the method and computational framework was completed on a pilot prospect case, then tested and improved on a second prospect. Some challenges were efficiently addressed with solutions not anticipated in the original proposal.
Project products include software, peer-reviewed publications and conference presentations. Method developed for sensitivity analysis can be readily adopted by other teams working on stochastic inversion.

PI Response:

Reviewer 29852

Score: 7.0

Comment: The project was well presented by the PI. It appears that all goals were met and all tasks were completed. The impact of this project on geothermal energy development may unfortunately quite minimal due to the complexity of the develop joint inversion technique. No direct mechanism has been developed for users to apply the highly technical method. The two presented examples indicate that high-level knowledge will be needed to operate a complex hybrid of NUFT and geophysical model for prospect evaluation. Not sure if that can be done without an open source. A web service is not going to do the trick. I would not recommend spending $$ on that.

The productivity was moderate. In total, 3 peer reviewed papers will have been published. Not bad, not great. The novel aspect of this project, in my opinion, could have led to several more papers.

PI Response:

Yes, transitioning to external use is a challenge. We had a choice between creating a simple and easily transferable code or a more complex code that pushed state-of-the-art. Essentially, we are researchers and not professional code developers so we elected to test the limits of what was possible which would allow others to buld on the experience. The idea for a web-service was based largely off the example of the National Atmospheric Release Advisory Center, which also has complex models but allows a web-based input that is sucessfully used (see https://narac.llnl.gov/narac_web.html). Simply making the existing code open-source is probably insufficient as a fair amount of expertise is needed to operate the code at present.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23444

Score: 5.0

Comment: To improve prospect evaluation, a series of models are linked where the output of one model is used as input for the next model in the series. These models follow a conceptual model for an idealized geothermal system with scarce geologic data to produce a possible range of solutions. Testing the model on an idealized system allows problems to be identified and solved as well as validation to occur prior to testing the model on 'real' data is an appropriate and rigorous approach.

To match temperature profiles of a 'real' geothermal system, an idealized system was modeled. Minimal geologic complexity was incorporated; length and width of a single fault and isotropic permeability of 'key' layers. Permeability is likely to be anisotropic and variable, factors that control the fluid and thermal distribution in a system. Because the temperature source is not specified, but there is a constant bottom temperature boundary condition, results that 'match' the temperature profile with the fault are suspect. Few geothermal systems are simply driven by basal heat flux. Incorporating more realistic heat sources would improve the outcomes. There is a non-unique solution to the thermal field results. It is well known that initial and boundary conditions coupled with permeability are key controlling factors on fluid and heat transport. Incorporating more realistic geology would improve confidence in the modeling. Models modeling models are awash with uncertainties. Identification of these would benefit the overall approach.

Elucidating boundary and initial conditions are paramount as these control much of the outcome. One can produce a highly precise but inaccurate model. Identifying whether the thermal field is in the prograde or retrograde stage is key to development of a hydro/geothermal system. Therefore understanding the heat source is important - whether or not one can match the current thermal profile.

Risk assessment is an objective but what is presented does not account for the various steps in an actual risk assessment. Adding this information would bring the mathematics back to geothermal energy production and well drilling.

PI Response:

Geothermal systems are highly complex but initial exploration efforts are often focused on a conceptual model that is highly idealized (see Cummings, 2009). Our efforts were focussed on developing the capability to test this conceptual model rather than a highly-detailed reservoir model. In our two test cases at Superstiton Mountain and Hawthorne, we were not modeling models; rather we were testing existing idealized cross-sections developed by the Navy Geothermal Program.We do recognize that our treatment of the heat source is simplified but now that the code is developed, we can implement more complex and realistic source if the data is available. The MCMC technique provide an alternate way to estimate uncertainty and hence risk and Monte Carlo methods are frequently used in the petroleum industry although this route was not fully explored our current implementation.
Cummings, W. Geothermal resource conceptual models using surface exploration data, 2009, 34th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-187.

Reviewer 29854

Score: 8.0

Comment: The Bayesian approach to the multi-data joint inversion problem has a very solid basis and employs state-of-the-art tools. The geophysical data comprises DC and MT resistivity and geological constraints are included. Parameters constrained by the inversion are permeability, conductivity and geometry. The overall framework is flexible and in principle could be extended to other datasets, if computationally feasible.
The approach starts with the formulation of a clear hypothesis to be tested through the Bayesian inference framework. This level of focus on real geothermal performance metrics drives efficiently the integration of multiple datasets, in contrast to an approach where each geophysical technique would be driven by independent resolution concerns.
Systematic sensitivity analysis is critical to support probabilistic decision-making, but it can be computationally expensive or even intractable. The reduced-order-model approach adopted in this project is a smart and original solution to address this challenge. Results were presented that demonstrate how such model reduction encapsulates the effect of the small-scale complexity of the real Earth, e.g., a coarse-grained description seems sufficient for the specific decision-making purposes. It would be interesting to compare this “empirical” coarse-graining approach to mechanically consistent homogenization.
In the first case study presented (Superstition Mountain) the method answered a first order (binary) question: the presence of a fault zone is arguably required to explain the data. At a finer level, the results did not seem to show a significant information gain from prior to posterior distributions of permeability. This, however, is not a weakness of the method but of the dataset. This may indicate opportunities to improve the experimental design in follow-up studies, and the Bayesian framework developed in this project could be an essential building block to achieve optimal experiment designs.
The software transfer model could be developed some more.

PI Response:

Yes, the software transfer model can be improved and we would like the opportunity to do so.

Reviewer 29852

Score: 8.0

Comment: The approach of the team, using a combination of THMC and DC resistivity modeling, is solid. Both examples were expertly researched. The problem is with expanding the approach to anywhere else without direct involvement of the team. This appears to be a nicely executed academic research project with limited practicality for others.

PI Response:

Correct. We are evaluating ways to expand the concept, now that it is proven, to a more widely useful project. Nevertheless, we believe that we have shown a possible path forward which will aid others.

STRENGTHS

Reviewer 23444

Score: Not scored

Comment: Developing methods and algorithms to maximize the use of limited data for geothermal prospecting is an important advancement to facilitate decision making and risk reduction. Integrating a variety of numerical methods, optimizing information saves time and computational overhead.

PI Response:

Reviewer 29854

Score: Not scored

Comment: The project aims at improving the efficiency of geothermal resource exploration, including expected cost reductions during exploration (number of wells) and improved decision-making based on more accurate risk assessment.

Progress is outstanding. Development of the method and computational framework was completed on a pilot prospect case, then tested and improved on a second prospect. Some challenges were efficiently addressed with solutions not anticipated in the original proposal.

Project products include software, peer-reviewed publications and conference presentations. Method developed for sensitivity analysis can be readily adopted by other teams working on stochastic inversion.
The Bayesian approach to the multi-data joint inversion problem has a very solid basis and employs state-of-the-art tools. The geophysical data comprises DC and MT resistivity and geological constraints are included. Critical parameters constrained by the inversion are permeability, conductivity and geometry. The overall framework is flexible and in principle could be extended to other datasets, if computationally feasible.
The approach starts with the formulation of a clear hypothesis to be tested through the Bayesian inference framework. This level of focus on real geothermal performance metrics drives efficiently the integration of multiple datasets, in contrast to an approach where each geophysical technique would be driven by independent resolution concerns.

Systematic sensitivity analysis is critical to support probabilistic decision-making, but it can be computationally expensive or even intractable. The reduced-order-model approach adopted in this project is a smart and original solution to address this challenge. Results were presented that demonstrate how such model reduction encapsulates the effect of the small-scale complexity of the real Earth, e.g., a coarse-grained description seems sufficient for the specific decision-making purposes.

PI Response:

Reviewer 29852

Score: Not scored

Comment: The novel joint inversion approach is well described in two Applied Energy journal papers. A major strength is that the approach allows for adjustments in properties during the process, after establishment of an initial geologic model. The team has shown creativity by imposing a Reduced Order approach, when needed, and by incorporating faults.

PI Response:

WEAKNESSES

Reviewer 23444

Score: Not scored

Comment: See above comments in Approach. The assumed flow, based on a constant thermal bottom boundary condition, is likely unrealistic for most geothermal systems. Using isotropic, homogeneous permeability provides boundaries to the flow and thermal field but likely will not help target specific wells because of the producing zones may be unique. A continuous, single, through going high permeability fault may be unrealistic also. Parameters used commonly vary with pressure and temperature although they are modeled as constant.

Because each geothermal system is unique, identifying the critical parameters that are needed as input would strengthen the applicability of this methodology to other systems. A clear statement of what new has been learned about geothermal prospecting based on this research would be beneficial. Including uncertainties and unknowns that may minimize applicability of this methodology to other areas enhances the confidence in the proposed method.

PI Response:

The sensitivity study was intended as a step towards identifying critical parameters.

Reviewer 29854

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 29852

Score: Not scored

Comment: The major weakness is that the work is not transferable. I'm quite familiar with joint inversion and it's difficult to see how this approach is useable by others without knowledge of complex programs like NUFT. I'm afraid that this nice applied research will be completely forgotten in a few years.

PI Response:

We will do our best to avoid this result. As the key aspects are already published and have already been cited, it is hopeful that others can build upon it. With a well thought-out interface, it is possible to make complex programs and processes simple. But developing user-friendly interfaces is not trivial and requires a significant investment.

IMPROVEMENTS

Reviewer 23444

Comment: See weaknesses. Rethink the conceptual geologic framework for modeling. Identify key inputs that must be known to enhance targeting the prospects. Once the data has been matched, clearly state how to site a well. Provide a thorough assessment of how variable parameters affect the system response, identify barriers to success, elucidate uncertainties and identify bounds for when the models can be used. These data improve results by adding confidence.

PI Response:

This is a clear exposition of what we would like to do next in this project, if funding was available.

Reviewer 29854

Comment: It would be interesting to compare the “empirical” coarse-graining implied by the reduced-order-model approach to mechanically consistent homogenization.

In the first case study presented (Superstition Mountain) the method answered a first order (binary) question: the presence of a fault zone is arguably required to explain the data. At a finer level, the results did not seem to show a significant information gain from prior to posterior distributions of permeability. This, however, is not a weakness of the method but of the dataset. This may indicate opportunities to improve the experimental design in follow-up studies, and the Bayesian framework developed in this project could be an essential building block to achieve optimal experiment designs.

The software transfer model could be developed some more.

PI Response:

Yes, we agree on the software transfer model aspect.

Reviewer 29852

Comment: A recommendation is to have the PIs meet with GTO staff to see if the method can be disseminated to the community without having to resort to suggested web service, which would be instant failure and a waste of money.

PI Response:

We are pursuing ideas on how to take the next steps. While examples exist of useful web services (see the NARAC example above), it may not be the optimal method.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Identifying High Potential Well Targets with 3D Seismic, and Mineralogy
Principal Investigator: Mellors, Robert
Organization: LLNL
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23444

Score: 4.0

Comment: Developing methods to locate zones of elevated temperature and permeability have the potential to reduce risk, lower cost of drilling by minimizing unproductive wells, and lower the overall LCOE cost. If new geothermal prospects could be identified, these methods would contribute to the development of new geothermal resources. As such, the study directly impacts the programmatic mission and goals.

Accomplishments and results are difficult to access because of the propriety nature of the presentation. Some relationships are purportedly found between seismic attributes and geothermal productivity but it is unknown if these are new finds or confirmation of what was already known. Examples of attributes with no key do not appear to be correlated to the wells based on the color scheme. The high permeability zone clusters overlap with other attributes making the uniqueness of any of these solutions difficult to access. Results are primarily focused on calculating attributes. There does not appear to be integration with the ‘, and mineralogy' portion of the title unless those data represent the nameless attributes.

PI Response:

We regret that we could not present the full dataset due to the proprietary nature of the datasets. The work is still in progress and was subject to funding delays. At the time of the preparation of the peer review materials in early 2015, the results were primarily only attributes and extensive comparsion with geologic and mineralogy had not yet been conducted. This is currently in progress. We agree that the high permeability zones do overlap with other zones, which makes this a challenging problem. We do not fully understand the comment "unknown if they are new finds or confirmation of what was already known", as we are not clear on 'what is known' relating attributes to permeability in geothermal areas. There are proven studies from the oil and gas industry that use a similar process. The mineralogy data referred to is proprietary analysis of well cuttings. Strictly speaking, the mineralogy is not an attribute; rather it is a known factor to which the derived seismic attributes are compared. It may be that we did not fully explain the underlying process and analysis which caused some confusion on the part of the reviewers.

Reviewer 29854

Score: 7.0

Comment: Mapping of high productivity zones through original analysis of seismic data, adapted from proven techniques in the petroleum industry, to reduce risk and cost of exploration.
Progress is reasonable, albeit preliminary, given the funding delays.

PI Response:

A fair assessment.

Reviewer 29852

Score: 6.0

Comment: It's very difficult to assess this project due to the associated NDA. The described methodology makes sense although the use of attributes may not be simple to transfer from petroleum reservoirs to geothermal applications. Numerous challenges need to be overcome. The PI's presentation was rather vague with numerous references to the NDA. In my opinion, this project should not have been reviewed in this format.

PI Response:

We understand the difficulties of the reviewer and regret the constraints of the NDA.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23444

Score: 5.0

Comment: Beginning with well-developed and tested techniques for the oil and gas industry provides a useful starting point. Testing these techniques on a field case where high productivity geothermal zones are known and mapped is an essential step toward validating the applicability of this methodology. Comparing attributes from the 3D seismic with 'other' unspecified attributes in high productivity zones provides a basis for application of the methods. However, there are many confounding factors in 3D reflection and its relationship to geothermal zones. Several of these factors are specified; several are not and should be. If the productive zones are near vertical or sharply dipping, they cannot be adequately resolved. Decisions as to how one determines the cause (geologic) of the reflections need to be developed and presented. For example, there are numerous causes for acoustic slowness, what decisions cause it to be determined that it is fractures, not fluid or another factor. The density crossplot provided has a huge scattering of data, stating that it is a linear relationship defies the data for the gray dots. More thorough analyses of data correlations should be completed accounting for all of the geologic variables (fluid, composition, lithology, mineralogy, fractures, etc.). A quantitative measure of a seismic characteristic remains an inference. Placing bounds on these inferences is important. A discussion of the resolution and spatial limitations to the features identified should be included specifically addressing the scale of the features to be identified. Resolution of meters may be excellent but does that resolution capture the necessary detail required for citing a well.

Although the title has ', and mineralogy' tacked onto the end, it is unclear how this data is being incorporated into the data analyses.

It is very difficult to access the rigor of the approach because of the proprietary data. Consequently, the numerical score was decreased.

PI Response:

The reviewer raises some good points regarding the geometry and geology of the reflections. We did not mean to imply that the density crossplot was linear but rather to demonstrate that a relation ship did exist and that it was not completely random. We note that while it would be useful to include all geologic variables, values for these variables are only known in a few places with limited accuracy and we are hampered by available data. Placing bounds and errors is important and is part of the ongoing work.

Reviewer 29854

Score: 8.0

Comment: The goal is to identify zones of high temperature and high permeability zones by seismic attributes and combinations thereof, extracted from 3D seismic reflection surveys. These attributes are argued to be more sensitive to subtle material changes (lithology, fracture characteristics, attenuation) associated to geothermal productivity. Their relation to relevant physical parameters is derived through a data-driven neural network approach. Relations between seismic attributes and physical properties include waveform coherence and its relation to fracture distribution. The approaches and tools are well developed in petroleum industry. The pilot study in Raft River leverages existing 3D seismic reflection datasets. The statistical validation process is well planned. Challenges are anticipated, including different attribute signatures, geological complexity and acquisition challenges in geothermal versus petroleum exploration contexts. In-house and commercial codes are used, the former having the advantage of transparent control on the data processing. Dissemination of results is limited by proprietary data, but methods and workflow will be made available.

PI Response:

It is a good summary.

Reviewer 29852

Score: 6.0

Comment: It's not clear what the quality of the research is due to the NDA. Based on Mellor's reputation, I have no doubt that solid science has been applied. However, the reviewers have not been presented with the right info to make a decent evaluation.

PI Response:

As stated above, we regret the limits of the proprietary agreement. However, it was a necessary conditon in acquiring access to several million dollars of seismic data and well data.

STRENGTHS

Reviewer 23444

Score: Not scored

Comment: Developing methods to detect higher permeability zones that might serve as production zones for geothermal energy is strength. Using techniques developed for the oil and gas industry and repurposing these techniques to geothermal systems saves time and potentially can lead to new discoveries. Using neural networks is a powerful technique if appropriately constrained and applied.

PI Response:

Yes, neural networks are useful but we also recognize that appropriate constraints must be imposed.

Reviewer 29854

Score: Not scored

Comment: Mapping of high productivity zones through original analysis of seismic data, adapted from proven techniques in the petroleum industry, to reduce risk and cost of exploration.

The goal is to identify zones of high temperature and high permeability zones by seismic attributes and combinations thereof, extracted from 3D seismic reflection surveys. These attributes are argued to be more sensitive to subtle material changes (lithology, fracture characteristics, attenuation) associated to geothermal productivity. Their relation to relevant physical parameters is derived through a data-driven neural network approach. Relations between seismic attributes and physical properties include waveform coherence and its relation to fracture distribution. The approaches and tools are well developed in petroleum industry. The pilot study in Raft River leverages existing 3D seismic reflection datasets. The statistical validation process is well planned. Challenges are anticipated, including different attribute signatures, geological complexity and acquisition challenges in geothermal versus petroleum exploration contexts. In-house and commercial codes are used, the former having the advantage of transparent control on the data processing. Dissemination of results is limited by proprietary data, but methods and workflow will be made available.

PI Response:

Reviewer 29852

Score: Not scored

Comment: Research idea is novel and may have a potentially high payoff. The reduced risk and savings in locating high temp and high perm zones are tempting.

PI Response:

Yes, it is high-risk but also high-payoff.

WEAKNESSES

Reviewer 23444

Score: Not scored

Comment: The lack of clarity on confounding factors that may produce the seismic signals/attributes should be discussed and evaluated. Key geothermal parameters are not specified. While using an already obtained dataset is strength, having that be proprietary minimized impact and confidence in the results. Mineralogy does not appear to be incorporated into the project (although it could be a nameless attribute).

PI Response:

As mentioned above, mineralogy is included but was not extensively discussed as we have not fully include the data. It would be compared with the attributes rather than being an attribute itself.

Reviewer 29854

Score: Not scored

Comment: Progress is reasonable, albeit preliminary, given the funding delays.

PI Response:

Reviewer 29852

Score: Not scored

Comment: The NDA is major weakness. It is not clear how gained knowledge (either "good" or "bad" will be transferred to the public.

PI Response:

Further presentations on the process (but not details specific to the geothermal system) will be made at public conferences.

IMPROVEMENTS

Reviewer 23444

Comment: See weaknesses and approach. Validate these methods on other systems to test for utility of methodology. Include mineralogy if it is part of the study. Refrain from overstating the results - e.g. location high temperature zones; it is very difficult to unambiguously determine that a reflection/impedence is caused solely by high temperature.

Include a discussion of the spatial resolution of the 3D seismic and its relationship to the scale of the geothermal system.

Do not have the major conclusions of the project be proprietary. A clear reason why this is proprietary when funded by public dollars should be included.

PI Response:

The discussion of the spatial relationship is a good one that was not made clear in the report and presentation. We would like to test the methodolgy on other systems but would like to focus on this area first. The agreement is that the process will be public but not details specific to the prospect.

Reviewer 29854

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 29852

Comment: No suggestions.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005513
Project: Time-lapse joint inversion of GEOphysical Data and its application to gEothermal prospecting - GEODE
Principal Investigator: Revil, Dr Andre
Organization: Colorado School of Mines
Panel: Reservoir Fracture Characterization & Fluid Imaging

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23444

Score: 8.0

Comment: Determining the current groundwater flow paths can be useful for locating permeable zones and contributes to understanding and characterization of the overall geologic system. Building accurate geologic models of the geothermal system decreases risk and potentially lowers cost. Thus the project addresses market barriers and knowledge gaps. Application of these technologies to two geothermal areas can be used to validate (or not) the methodology and provide new insights into the geology of the areas.

Accomplishments to date have had a significant impact on providing new techniques for data inversion that potentially lead to an improved understanding the geologic features of one study area. Acquiring a variety of geophysical data and combining these data improved subsurface geology ultimately resulting in a new geologic cross section that inferred additional faults in the area, potentially elucidating the flow paths for hot spring fluids. Such contributions add to the understanding of the geothermal system and the fundamental geologic controls on the system. Using these data should improve 3D thermal and flow modeling by improving the accuracy of the subsurface geology.

The relationship between the 3D tomography of Stromboli and this study is unclear. Reasons for why it was done are missing. Integration of this aspect of the research should be improved.

Productivity appears to be excellent; quality of the geophysics is also excellent. Geophysical interpretations seem to lack input by a geologist with knowledge of the geologic complexities of the area and have not been validated by geologic approaches. In addition, the UTM coordinates on the images/figures presented are NOT those from the Pagosa Springs area - making this reviewer question what exactly was done and presented and where it was done.

While it is common practice to overstate conclusions, a geothermal system cannot be understood based on a few parameters i.e. faults. To locate potential geothermal wells requires understanding of the entire geologic system involved through space and time, including identification of the heat source in addition to the flow path and the major faults in the area. The range bounding fault has been known for some time. One single time snap shot of the system is useful but it is insufficient. The data presented is useful but care must be taken not to extrapolate beyond bounds.

Several peer reviewed publications denotes substantial results, progress and productivity.

PI Response:

The work on Stromboli was done (at a no cost for DOE) because we add the opportnity to image in 3D the hydrothermal system of volcano both using gravity and electricl resistivity tomography. This was unique opportunity to work on this kind of object that is fairly well-know and therefoe can be considered as a natural laboratory to experiment new imaging techniques. Regarding Pagosa Springs, the UTM coordinates should be the correct one (there were double-checked duirg the work done at Mines nd during the submission of the manuscript).

Reviewer 29854

Score: 8.0

Comment: This project has advanced the capabilities of geophysical methods for geothermal prospecting. In particular it advanced ground water flow imaging to improve the efficiency of resource exploration, development and management. Two application cases were considered, leading to improved characterization of the plumbing system in Pagosa Springs, and to recommendation of injection on a fault zone in Jersey Valley.
Productivity indicators include 11 articles, a Nishida award from the Japan Geoscience Union, software made available and documented in specialized articles in computational journals and books.

PI Response:

Reviewer 23568

Score: 4.0

Comment: The title is “Time Lapse Joint Inversion of Geophysical Data….” The impact of this project is stated by the PI to be to:

- Decrease of the costs of drilling through better characterization of targets
- Better management of existing fields through time lapse geophysics."

These generalities would appear to be realized in a proposed case history study according to the following statement from the Project Summary: “The work requested by ORMAT at Jersey Valley was to obtain an idea of the hydrogeology of the area and to provide a location for the reinjection of the warm water. The Jersey Valley power plant is producing 10 to 15 MW and is currently limited in its production by the availability of permeable aquifers to re-inject the produced water. Unfortunately, Jersey Valley is currently experiencing a 4 years drought and all the springs (hot and cold) have dried out (see figure below at 4 years interval). The self-potential profile in the valley itself is currently flat indicating no base flow. Hopefully we got very good gravity and MT data that are currently used to assess the geometry of the sedimentary infilling of the valley.” I ended up confused by this paragraph because it was not clear if the change drought precluded making a hydrogeologic model or not. One would think that change in recharge would be a good stressor for model validation. But I gathered from the last sentence that no model of the hydrogeology of Jersey Valley has been completed and this project has only three months to go before it ends. One PI died in January 2015 and the presenting PI seemed to be making his exit to France. The Summary says that in May/June 2015, the following will be accomplished “(4) Final attempts to produce a geological model and a hydrogeological model consistent with all available geophysical data (SP, MT, gravity) and geological knowledge of the area. “ It does not sound very promising to me.

PI Response:

No comment here. I think the referee does not realize what has been made and has probably no bckground in geophysics and the state of the art in geophysics applied to geotehrmal systems. We apologize that Mike Batzle hd to pass away during the course of the project and that for personal reasons, I have to "exit" (what a poorly chosen word) to France.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23444

Score: 7.0

Comment: The technical approach is appropriate and follows a stepwise linear path moving from data acquisition, data manipulation, to testing of geophysics to other areas. Coupling geological data with imaging data is an essential component, although there does not appear to be a geologist working on the project. USGS currently has been working in this area mapping the surface geology, this data could be useful.

No information is presented on sensitivity or resolution of the various geophysical measurements or associated uncertainties, with respect to the geologic data/information nor to the spatial scales needed for identifying key geothermal features. For example, geologic facies are shown but these are likely clumped groupings. No data was presented on if the groupings determined by geophysical techniques match the well logs and if so, to what spatial scale. Evaluating the non-uniqueness of the solutions/interpretations should be included. For example, what are other explanations/processes for high self-potentials? A more thorough analysis of cause and effect as well as uncertainties adds confidence to the interpretations. Information on the groundwater flow model would have been useful as it is unclear why a steady state model would be used. Combining these data lead to suggested target wells - although the regional geology needs to be evaluated.

While targeting likely faults is useful, that is only one component of a multidimensional system. Describing how this fault data fits into the remaining portions of the systems (heat source, etc.) would enhance the outcomes. Discussion of limitations provides bounds needed by the geothermal sector.

PI Response:

The referee made very good points and we agree with him. We are devoting a lot efforts (see our papers) to come with an idea of the uncertinty and uniquess issue of the solution. We have two papers in rpess in Geophysics focusing on this issue. regarding the heat regime at Jersey Valley, our input information is realy too scarce at this point, but we agree with the referee that it will need to be incrporated into the modeling.

Reviewer 29854

Score: 8.0

Comment: The project addresses the combination of active and passive geophysical methods. It also integrates geological expertise into geophysical data inversion, for instance by parameterizing models through level sets to facilitate the imposition of geological constraints. It also incorporates petrophysical constraints for each material facies and constraints on the statistics of spatial heterogeneity of material properties via parameterized variograms, a very flexible approach.

A method to combine geophysical attributes for the characterization of flow paths was developed.

The self-potential method was demonstrated as an appropriate geophysical method to image shallow ground water flow, with implications on guiding strategies for water reinjection.
Some of the methods still need to be extended to 3D.

PI Response:

Thanks.

Reviewer 23568

Score: 6.0

Comment: Given the objective of using time lapse joint inversion for better characterization of reservoirs, the technical approach seemed to be reasonably consistent. "Our goal was to develop new methods to better jointly invert geophysical data and to include prior geological information in the inversion of the geophysical data (geologically constrained inversion). The idea was also to validate these new techniques at different scales including a volcano (Stromboli) and both Jersey Valley (NV) and Pagosa Springs (CO)." The work itself, however, was kind of scattershot. One example seems to be a joint inversion of a geological cross section with geophysical data in which a fault is magically added to a prior geological section on the basis of low electrical resistivity where the fault was drawn. A synthetic 2D model that was to show the identification of 4 facies on the basis of knowing their petrophysical properties was a second example. Third, an SP map was shown of Jersey Valley where a negative anomaly is supposed to show downward flow in a regional adjacent to the mountains where no other corroborating evidence is presented. Finally, mention is made of the uninterpreted 1210 gravity stations, and 221 MT stations along 18 profiles that were discussed in my review of project impacts. Of the 4 examples, only Stromboli has a time lapse aspect and that is hardly a U.S. geothermal target.

PI Response:

I mentionned during my talk, Jersey Valley is known for its scarsity of data. We hve done our best with the available data and the one we gathered. ALL the data available to us have been jointly interpretated, so I have a hard time to understand the last two sentences.

STRENGTHS

Reviewer 23444

Score: Not scored

Comment: Providing enhanced techniques to image subsurface geology is a first step to a more complete understanding of subsurface environments in geothermal areas. The improved techniques have a range of uses, for active systems. Substantial data collection has occurred that will add to the understanding of at least two active geo/hydrothermal systems. Integration of multiple techniques improves the likelihood of arriving at an accurate interpretation.

PI Response:

We agree.

Reviewer 29854

Score: Not scored

Comment: This project has advanced the capabilities of geophysical methods for geothermal prospecting. In particular it advanced ground water flow imaging to improve the efficiency of resource exploration, development and management.

The project addresses the combination of active and passive geophysical methods. It also integrates geological expertise into geophysical data inversion, for instance by parameterizing models through level sets to facilitate the imposition of geological constraints. It also incorporates petrophysical constraints for each material facies and constraints on the statistics of spatial heterogeneity of material properties via parameterized variograms, a very flexible approach.

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Two application cases were considered, leading to improved characterization of the plumbing system in Pagosa Springs, and to recommendation of injection on a fault zone in Jersey Valley.

Productivity indicators include 11 articles, a Nishida award from the Japan Geoscience Union, software made available and documented in specialized articles in computational journals and books.

PI Response:

Thanks

Reviewer 23568

Score: Not scored

Comment: While I was negative about the diffuse results, I acknowledge that there were half a dozen scientific papers, several of which are in good journals.

PI Response:

Thanks at least for this positive assessment. I think the referee shoukd define what he means by "good journls" Most of our papers are published in journals with very high impact factors.

WEAKNESSES

Reviewer 23444

Score: Not scored

Comment: While several new geologic features/faults were interpreted from the geophysical data, none were verified by surface exposures nor by other geologic measures/data/parameters. Having a geologist working together with the geophysicists would provide confidence that the interpreted geologic features actually exist. Information on spatial scales of resolution should be included and related to the spatial scale of features tested. Uncertainties on all analyses should be included. Care should be taken to explicitly state what interpretations are based on what data. Understanding of the plumbing system for Pagosa Springs involves more than identifying faults, such a discussion would benefit the overall outcome and minimize over interpretations of data.

PI Response:

This is incorrect. We hve been working with the geologist of ORMAT (as discussed in the report) and the model agrees of course with the outcrops. Same for Pagos Springs (we worked with the geologist of the Denver Museum of Nature and Science).

Reviewer 29854

Score: Not scored

Comment: Some of the methods still need to be extended to 3D, which may rise computational challenges.

PI Response:

We agree. All the technique we have developed can be easily extended in 3D for the more advances approaches. With the appropriate computer power, there is no problems there.

Reviewer 23568

Score: Not scored

Comment: While there was some scientific output, the work did not impact geothermal reservoir characterization very much.

PI Response:

We disagree.

IMPROVEMENTS

Reviewer 23444

Comment: Suggestions are included in weaknesses and approach. In any figure/image, the data should match the title. UTMs provided on the images for Pagosa Springs are not from that area. This lack of attention to detail undermines confidence it the results and outcomes of the study.

PI Response:

I will double check the UTMs for Pagosa Springs but the work has been done there. I cn provide the reports for the field camps of geophysics. Since everthing was reported in Google Earth, the UTMs coordinates are correct. Something weird here.

Reviewer 29854

Comment: Reviewer did not provide comments for this criterion.

PI Response:

NA

Reviewer 23568

Comment: The project is finishing. There is not much room to improve the project now.

PI Response:

NA

Reservoir Modeling Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002761
Project: Recovery Act: THMC Modeling of EGS Reservoirs - Continuum through Discontinuum Representations: Capturing Reservoir Stimulation, Evolution and Induced Seismicity
Principal Investigator: Elsworth, Dr. Derek
Organization: Pennsylvania State University
Panel: Reservoir Modeling

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23425

Score: 8.0

Comment: This effort is broad in representing THMC effects with the goals of capturing an understanding of reservoir stimulation, reservoir evolution and the relationship of MEQ to EGS operations. The work appears to have benefited from collaborations involving LBNL and AltaRock. The work seems to have been performed methodically including the development of process couplings, some chemical models, stimulation models and production models. It is quite apparent that a lot of work has been done during the course of this effort as evidenced in part by the list of publications and presentations. Both the presentation and Summary cover an impressive list of topics. What is more difficult to understand is how decision makers and EGS operators can best access the body of knowledge and understanding that has been created during the course of this project. My understanding is that some of the new results (e.g., models) that have emerged from this work may get incorporated into the couplings of different codes such as FLAC, TOUGHREACT and PFC3D.

PI Response:

The codes of FLAC_TOUGHREACT are nominaly available but not supported by us for their use. We consider our effort more focused on developing then using coupled codes to unravel key processes that are relevant to EGS rather than being "code developers." But they are available. We do not plan to commercialize them.

Reviewer 23450

Score: 6.0

Comment: The project goal is to model the evolution of porosity, permeability and heat transfer area in such pressure-sensitive fractured reservoirs using Thermal, Hydrological, Mechanical and Chemical (THMC) models. The early time response is influence by the stimulation and late time response has more induced seismicity.
Innovative research and experimental testing coupled with field data.
Ambitious effort,

- Difficult to keep all code development progressing
- History matching different datasets will require a learning curve, what are the priority HM variables?

Can this be simplified by select grouping of dimensionless variables?

- Can a commercial operator afford collecting sufficient data sets to fully use the code?

- Presented data sets show partial matches to select data sets, promising
- How much early data is required for confidence in forecasting and engineering a system?
- Stress field, anisotropy in permeability , rock lithology and properties
- Code user friendliness

The project proposes to examine key THMC process couplings to extend the understanding and use of distributed parameter reactive-chemical models. Goals achieved seem reasonable to the task. Experimental and field data from Newberry is helpful in evaluating the utility of the THMC models.
The project funding of $1.6 M seems rather large for the work presented.

PI Response:

The project funding was $1.1 with in-kind match for the remainder. The project has supported 3.5 Ph.D. students and work on continuum and discontinum models, flow transport and seismicity.

Regarding dimensionless parameters, the crucial ones for project viability and induced seismicity are those in Gan and Elsworth, JGR, 2014b.

Reviewer 23479

Score: 8.0

Comment: Background: Note that initial project start / end date were 1/2010-12/2012; extended by no-funds extension to 6/2015.

This is ongoing work, at albeit at relatively late stages, and its entire impact is difficult to assess. However, based on the track record of scientific communication, the work is helping to define and improve the state-of-art.

PI Response:

Reviewer 29851

Score: 8.0

Comment: The project's objectives are important to the broader GTO's mission and goals as it targets the core challenge of effectively engineering and sustaining the EGS reservoir.
The project aims to develop knowledge in the THMC couplings that are critical to successful EGS design, production and sustainability. This knowledge will be a useful outcome from the project and builds towards future studies.

The knowledge gained has the potential to remove barriers to successful design and implementation of a working EGS as well as be able to design better cost efficiencies. The work performed in this project is contributing to the community's library of analysis, understanding and tools. The project aims to transfer this knowledge through educating students.

The tasks are well conceived with the core objectives and milestones of the project progressing well.
The results are significant in terms of the project's technical objectives and goals with the majority of these being accomplished. The objective of developing discontinuum models is the weakest accomplishment, although good work has been done here.

The quality of the technical accomplishments, results, and progress is high.

The work has been productive with notable accomplishments made in: developing the knowledge of THMC couplings as planned; playing a role interpreting field data from the Newberry demonstration project using numerical and laboratory experiments, and; developing how measurements from the field are theoretically related to changes in the rock and reservoir properties.

The achievements are significant within the community as evidenced by the number and quality of technical publications. There are no apparent reasons why the project cannot be completed as proposed.

PI Response:

We, also, are disappointed by the partial derailment of the discontinuum analysis, but have a workaround available from the final work on the project that we are excited can say something about alternative methods of stimulation - partly inspired by involvement of Elsworth in the "Future of EGS" committee and by the analysese completed by Golder and Itasca in that endeavor.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23425

Score: 8.0

Comment: The technical approach seems reasonable involving identifying the modes of porosity, permeability and fracture surface evolution which is followed by developing THMC models which are then verified by EGS demonstration projects such as Newberry. It appears that two favorable Go/No-Go decisions were made during the course of this work. Technical approach over all seems quite strong. It remains unclear to this reviewer regarding how far the effort got in making the necessary couplings as well as incorporating new permeability evolution effects into a usable framework for decision makers and operators.

PI Response:

Reviewer 23450

Score: 7.0

Comment: The presented data showing the use of the THMC model for select experimental and observational data sets is very intriguing. Application to larger, field scale and commercial data sets would be the next test of code utility, functionality, and predictability.

Examination of the coupled physical, mechanical and chemical processes in the laboratory and application to a field site is a very good technical approach allowing testing of hypothesis and the ability to model and match field behavior. The rock mechanics experiments provide insight to the various modes of rock failure. The results are intriguing for what they can and cannot explain about MEQ at Newberry and the effects of mineral content, frictional stability, and frictional strength. Also the linkage of MEQ to evolved permeability is very insightful. The mathematical formation and implementation into a THMC code is used to test both experimental lab data and field scale data.

PI Response:

Application to a field site will likely occur separately under the GTO comparison project - just beginning.

Reviewer 23479

Score: 9.0

Comment: This project proposed to couple two different Itasca Consulting models, PFC3D and FLAC3D, with TOUGHREACT. In that context, the novelty lies in (1) the development of lumped-parameter models for couplings such as pressure solution and dilation, (2) interfacing these process models with TOUGHREACT-PFC3D/FLAC3D, and comparing discontinuum (PFC3D) and continuum (FLAC3D) approaches.

The work with PFC3D was never brought to full completion, and the project has been redirected somewhat. Recent emphasis has been on interfacing this work with results of the Newberry stimulation experiments.

PI Response:

See above regarding workaroudn for discontinuum models.

Reviewer 29851

Score: 7.0

Comment: Numerical modeling analyses have different technical approaches that can be used to better understand how changes in rock and reservoir properties affect the efficiency and sustainability of an EGS. This project aims to use both continuum and discontinuum numerical approaches to examine the key processes and apply the knowledge gained to the Newberry case study. This approach is appropriate within the project's objectives and resources.

The approach is well designed, based on years of technical experience with the PI, and is an extension of established knowledge and technology developed and tested in previous work. The approach has been well managed in the project tasks and executed to plan.

PI Response:

STRENGTHS

Reviewer 23425

Score: Not scored

Comment:
* PI with broad knowledge of EGS challenges
* Support from graduate researchers
* Collaboration with LBNL experts on TOUGHREACT

* Strong presentation/publication record
* Validation of models using field observations

PI Response:

Reviewer 23450

Score: Not scored

Comment: A good test of the model is to examine the behavior of a created hydraulic fracture during pressure depletion and progressive loss of fracture half-length, as observed in a number of Bakken-type shale plays.
A large number of publications, presentations, and intellectual property licenses have come from this effort, providing good technology transfer.

PI Response:

Reviewer 23479

Score: Not scored

Comment: The PI is a leader in the field of rock mechanics and fluid flow + transport in fractured rocks. He and his lab have an impressive record of sustained progress in this arena – for instance, the Taron and Elsworth work ca. 2010 defined the then-current state-of-art.

The list of publications and presentations is impressive.

PI Response:

Reviewer 29851

Score: Not scored

Comment: The combination of high-quality laboratory experiments, field data and numerical modeling is commendable. The focus on using microseismic data to interpret permeability is a good approach and should be built upon in future work. The use of the modeling tools to find new qualified approaches to engineer an EGS, e.g. through experimenting numerically with different well configurations, is an excellent step and is the future approach the community should take to help make EGS successful.

PI Response:

WEAKNESSES

Reviewer 23425

Score: Not scored

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23450

Score: Not scored

Comment: good project

PI Response:

Reviewer 23479

Score: Not scored

Comment: N.A., though it would have been nice to see the discontinuum model fully completed, e.g. with the originally proposed TOUGHREACT-PFC3D coupling.

PI Response:

Agreed.

Reviewer 29851

Score: Not scored

Comment: The original project objectives aimed to develop discontinuum models. Although some good results have been achieved, I don't believe this has worked out as well as hoped.

PI Response:

Yes, regrettably - but a workaround has allowed us to get much of what we hoped from this.

IMPROVEMENTS

Reviewer 23425

Comment: Maybe a clearer roadmap to realizing benefits of this research would be helpful. It is difficult to identify big achievements obtained from this research.

PI Response:

Reviewer 23450

Comment: Can parametric runs be made and dimensionless groups arranged to create type curves that capture the inter-related processes in a graphical format. Such type curves may assist the simulation engineer in selecting the first order parameters to model. In an operating field context, such type curves may provide interpretive or diagnostic ability without to run complex and CPU intensive codes.

PI Response:

Certainly this is used in Gan and Elsworth, JGR, 2014b, at least for the interplay of flow and hear transfer, but it is not clear (to me) exactly what these dimensionless groups may for the interconnection between the other (nonlinear) process couplings.

Reviewer 23479

Comment: Please see comments in other sections.

PI Response:

Reviewer 29851

Comment: The researchers could improve their work by building on the discontinuum approach that they've used to better understand how the discrete fracture network (either natural or engineered) effects the creation and longevity of an EGS. Perhaps improvements could focus on the differences observed in sensitivities between the discontinuum and continuum approaches and how chemical coupling plays a role in the effectiveness of discrete fractures in the reservoir (as the THM algorithms in discontinuum modeling are relatively mature).

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002757, GO18194, GO18196
Project: Recovery Act: Development of a Geomechanical Framework for the Analysis of MEQ in EGS Experiments (GEYSERS). Analysis of Geothermal Reservoir Stimulation using Geomechanics-Based Stochastic Analysis
Principal Investigator: Ghassemi, Dr. Ahmad
Organization: The Board of Regents of the University of Oklahoma
Panel: Reservoir Modeling

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23425

Score: 8.0

Comment: Prof. Ghassemi presented three different projects funded by GTO. The primary project he presented involved developing a geomechanical framework for analyzing micro-earthquakes associated with pumping during EGS experiments. Progress on all three of his projects appears to be affected by the administrative problems that he has encountered in transferring GTO support between Texas A & M University and the University of Oklahoma. The reviewers understood that this multi-year novation process has been very difficult and remains uncompleted as of this review. This presents a major problem for this reviewer as work has evidently been interrupted for at least two years which appears to be beyond the control of Prof. Ghassemi. Even though the project should have concluded by now, the work is still in its early to mid-project stages. I can therefore only evaluate it is a mid-project review.

What Ghassemi and his group have done to this point appears to be highly credible from a technical perspective. He is performing a variety of rock-mechanics experiments to determine parameters that will go into his geomechanical framework model that is intended to explain observed seismicity during pumping operations at Newberry. Understanding how pumping affects seismicity as well as interpreting what the seismicity means in terms of producing permeability is potentially a very important end result of this project. Therefore, I have given the project a high rating.

My understanding is that after completion of the novation process that Prof Ghassemi should have enough remaining funds to complete the project deliverables.

PI Response:

We appreciate the encouraging remakrs and do plan to complete the projects and provide useful results for the geothermal community.

Reviewer 23450

Score: 9.0

Comment: It is unclear exactly which project(s) were to be reviewed. The presentation on three projects was very interesting and showed scientific and programmatic interrelation with each other. I liked these projects, how they intermeshed, and the way the results were presented.
Modeling fracture initiation and propagation is an interesting endeavor; the presented experimental results are very interesting, lots of good data measurements that can be used in modeling. The modeling results showed very good correlation with measured data and provided mechanistic insights into fracture initiation and propagation.

Understanding the mechanism of MEQ is a key issue in all injection projects, geothermal, hydrocarbon, waste disposal. This research is providing insight into this problem with field data sets from Newberry and the NW Geysers HTR. Understanding the mechanisms by which injection and injection duration may trigger MEQ is critical to public acceptance of injection projects in general, not just geothermal or EGS.
What are the special techniques developed? Applied more multi-stage tools, conducted poro-elastic measurements, and modeling of fracture initiation and propagation in different stress regimes (tensile, shear, and tearing).

No program budget information was provided, it is difficult to comment on productivity, however, the volume of work presented is valuable.

PI Response:

We value the reviewers' consideration of the circumstances and do appreciate the difficulty of reviewing these projects in such a short period of time. We did our best to communicate the most important points and our progress under the circumstances. I have compiled a list of our related publications to date, to provide some basis for judgement while emphasizing that completion of the projects would result in a higher level of productivity as we prefer not to published work that is not completed.

I would also like to point out that the students who took part in these projects are all employed in energy sector with some in the geothermal community. And this itself is a very positive impact of these projects.

Reviewer 23479

Score: 6.0

Comment: Background: This review package includes 3 statements of work: (1) geomechanics-based stochastic analysis of injection-induced seismicity via porothermoelastic FEM; (2) MEQ studies in the context of the Newberry EGS experiment; and (3) 3D modeling of fracture clusters in geothermal reservoirs.

The two peer-review project summaries seem to relate mainly to SOWs (2) and (3); perhaps (1) and (3) are both included in the second summary?

Collaborators include Nick Davatzes (Temple) and AltaRock.

Given the long project timeline (2009-present) and the generous funding (~$2.6M in Federal funds), the list of publications and presentations is not particularly strong. For instance, no papers related to SOW (2) have yet been published in peer-reviewed journals. However, considerable work related to SOWs (1) and particularly (3) appears in the PI's C.V. The PI attributes delays, in part, to project-contract difficulties among DOE, TAMU, U. Oklahoma, and Temple (see 1st project summary, p. 4; 2nd project summary, p. 6, presentations). Yet nearly all of the money seems to have been spent.
Delays and lack of productivity with respect to SOW (2), in particular, have limited the potential impact of this work.

PI Response:

The money has not been spent. One project has $480,000 left. Another has $90,000 left and the third should have $45,000 left. Anyone remotely familiar with supervising students is aware of the impact lack of these funds would have on a PI and students, particularly when multiple PIs have to integrate their works. The reviewer need not use the PIs CV for publications related to the projects, we have provided an updated list below. The records show that the publication record for these projects is indeed superior.

The projects did start in 2009 but transfer issues have been disruptive causing delays in finalizing work and hence preventing more publications to be completed Having said that, the three projects have yielded a total of 11 Journal publications and 24 conf. papers. This would be considered impressive to most people considering the difficult circumstances. In addition, we have 2 papers under review and the completion of project will yield at least 5 more journal papers bring the total to 18.

Project 1.

1. Li, Y., Wang, J. Jung, W., Ghassemi, A. 2012. “Mechanical Properties of Intact Rock and Fractures in Welded Tuff from Newberry Volcano," Proc. 37th Stanford Geothermal Workshop, January 30 - February 1, 2012.

2. Wang, J., Jung, W., Ghassemi, A. 2012. “Deformation and Failure Properties of Newberry Welded Tuff from Geo-N1 well.” , Proc. 46th U.S. Rock Mechanics / Geomechanics Symposium, Chicago, IL. June 24-27.

3. Cladouhos, T., S. Petty, G. Foulger, B. Julian, and M. Fehler (2010). Injection Induced Seismicity and Geothermal Energy, GRC Transactions, 32, 1213-1220.

4. Fetterman, J.D. and Davatzes, N.C. (2011) Evolution of Fracture Porosity in the Newberry Volcano Geothermal System, Oregon, USA: Feedback between deformation and alteration. Geothermal Resources Council Annual Meeting, San Diego, CA. 7 p.2012:

5. Davatzes, N.C., Hickman, S., * Fetterman, J.A., Cladouhos, T.: Newberry EGS Demonstration, USA: Overview and Structural Analysis. International Geothermal Congress, Freiburg, Germany, May 23, 2012.

6. Wang, J., Jung, W., Li, Y., Ghassemi, A. 2015. Rock Mechanical Characterization of Newberry Tuffs. Geothermics (to appear).

Our injection tests and integration activities should generate 2-3 journal more publications, bringing the total to 4 Journal and 5 conf. papers. .

Project 2:

1. Zhang, Z. Ding, J., Ghassemi, A., Ge, X., 2015. A hyperelastic-bilinear potential for lattice model with fracture energy conservation. Engineering Fracture Mechanics. 142, 220–235.

2. Zhang. Z., Peng, S., Ghassemi, A., Ge, X. 2015. Lattice bond cell modeling of dynamic hydraulic fracture. Proc. 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA.

3. Gao Q., and Ghassemi, A. 2015. Hydraulic Fracture Design in Heterogeneous Formations. The 5th International Conference on Coupled Thermo-Hydro-Mechanical-Chemical (THMC) Processes in Geosystems: Petroleum and Geothermal Reservoir Geomechanics and Energy Resource Extraction. Salt Lake City, Utah.

4. Huang, K., Ghassemi, A. 2015. Modeling 3D thermal fracture propagation by transient cooling using virtual multidimensional internal bonds. Int. J. Num. Anal. Methods. Geomech. (under review).

5. Tarasov, S. and Ghassemi, A. 2014. Self-similarity and scaling of thermal shock fractures. Physical Review E 90 (1), 012403-1-6.

6. Huang, J., Ghassemi, A. 2013. Simulating geomechanical evolution of fractured shale reservoir using a poro-viscoelastic constitutive model. Proc. 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, USA.

7. Huang, K., Zhang, Z., Ghassemi, A. 2012. Modeling three-dimensional hydraulic fracture propagation using virtual multidimensional internal bonds. Int. J. Numer. Anal. Meth. Geomech. DOI: 10.1002/nag.2119.

8. Zhang, Z. Ghassemi, A. 2010. Simulation of Hydraulic Fracture Propagation near a Natural Fracture Using Virtual Multidimensional Internal Bonds. Int. J. Num. Anal. Methods. Geomech. DOI: 10.1002/nag.914.

9. Huang, K., Ghassemi, A. 2012. Modeling 3D Thermal Fracturing Using Virtual Multi-dimensinal Internal Bonds. Geothermal Resources Council 2012. Reno, Nevada. Sept. 30-Oct.

10. Min, K.S., Zhang, Z., Ghassemi, A. 2010. Hydraulic Fracturing Propagation in Heterogeneous Rock using the VMIB Method", 35th Stanford Geothermal Workshop, Stanford University, California, USA.

11. Min, K.S., Zhang, Z., Ghassemi, A. 2010, Numerical Analysis of Multiple Fracture Propagation in Heterogeneous Rock induced by Hydraulic Fracturing. 44th ARMA Conference, Salt Lake, Utah, USA

12. Min, K.S., K. Huang, Ghassemi, A. 2011. A Study of Numerical Simulations of Mixed-Mode Fracture Propagation in Rock. Proc. 36th Stanford Geothermal Workshop, Stanford, California, USA.

13. Huang, J., and Ghassemi, A. 2011. Poroelastic analysis of gas production from shale. 45th ARMA Conf., San Francisco, California, USA.

14. 13.Min K.S., Ghassemi A. 2011. Three-dimensional numerical analysis of thermal fracturing in rock. 45th ARMA Conf., San Francisco, California, USA.

Remaining work for this project will results in 2 more journal and 1-2 conf. papers bringing the total to 7 Journal and 10-11 Conference papers..

Project 3:

1. Safari, A., Ghassemi, A. 2015. 3D Thermo-poroelastic Analysis of Facture Network Deformation and Induced Micro-Seismicity in Enhanced Geothermal Systems, Geothermics (in press).

2. Jafarpour, B., Tarrahi, M., Ghassemi, A., 2015. Integration of Microseismic Monitoring Data into Coupled Flow and Geomechanical Models with Ensemble Kalman Filter. Water Resources Research (in press).

3. Verde, A., Ghassemi, A. 2015. Modeling injection/extraction in a fracture network with mechanically interacting fractures using an efficient displacement discontinuity method. Int. J. Rock Mech. (in press).

4. Verde, A., Ghassemi, A. 2015. Fast multipole displacement discontinuity method (FM-DDM) for geomechanics reservoir simulations. Int. J. Num. and Anal. Methods in Geomech. (in Press)

5. Wang, X. and Ghassemi, A. (2012), "A 3 D Thermal-poroelastic Model for Geothermal Reservoir Stimulation". Proc., 36th Workshop on Geothermal Reservoir Engineering, Stanford University.

6. Wang, X. and Ghassemi, A. (2011), "A Three-Dimensional Stochastic Fracture Network Model for Geothermal Reservoir Stimulation". Proc., 36th Workshop on Geothermal Reservoir Engineering, Stanford University.

7. Lee S. H. and Ghassemi, A. (2011), "Three-Dimensional Thermo-Poro-Mechanical Modeling of Reservoir Stimulation and Induced Microseismicity in Geothermal Reservoir", Proc. 36th Stanford Geothermal Workshop, Stanford, CA

8. Ghassemi, A., X. Zhou. (2011), A three-dimensional thermo-poroelastic model for fracture response to injection/extraction in enhanced geothermal systems. Geothermics, 40 (1), 39-49.

9. Lee S. H. and Ghassemi, A. (2010), "A Three-Dimensional Thermo-Poro-Mechanical Finite Element Analysis of a Wellbore on Damage Evolution", Proc., 44nd US Rock Mechanics Symposium, Salt Lake City, UT

10. Lee S. H. and Ghassemi, A. (2010), "Thermo-poroelastic Analysis of Injection-Induced Rock Deformation and Damage Evolution", Proc., 35th Stanford Geothermal Workshop, Stanford, CA

11. Lee S. H. and Ghassemi, A. (2009), "Thermo-poroelastic finite element analysis of rock deformation and damage", Proc., 43rd US Rock Mechanics Symposium, Asheville, NC.

12. Akbarnejad-Nesheli, B., and Ghassemi, A. (2009), "Undrained Poroelastic Response of Berea Sandstone and Indiana Limestone to Confining and Deviatoric Stress Change." Proc., 43rd US Rock Mech. Symp., Asheville, NC June 28th – July 1, 2009.

13. Tarrahi M., Jafarpour B. (2012), "Inference of Permeability Distribution from InjectionInduced Discrete Microseismic Events Using Kernel Density Estimation and Ensemble Kalman Filter", Water Resources Research, (in review).

14. Tarrahi M., Jafarpour B. (2011), "Inference of Geothermal Reservoir Properties from MicroSeismic Events with Ensemble Kalman Filter", American Geophysical Union Fall Meeting, December 2011, San Francisco, USA.

Completion of the project should yield 2 more papers bring the total to 7 (5+2) Journal and 9 conf. papers.

Reviewer 29851

Score: 5.0

Comment: This review covers three projects managed by Dr. Ahmad Ghassemi (PI), currently at the University of Oklahoma and formerly at Texas A&M University. All three projects have parts that are important to the broader GTO's mission and goals as they target the core challenge of understanding the physical processes acting in an EGS reservoir.

All three projects have been significantly affected by the move of the PI from Texas A&M to Oklahoma.
Some of the activities performed in the projects would contribute to the community's library of analysis, understanding and tools if the project tasks are allowed to be completed.
Some of the results achieved so far are significant in terms of the three project's technical objectives and goals; however the projects are clearly incomplete, significantly behind schedule and suffering from a lack of funds, resources and focus. The key question for the DOE, in my opinion, is how to get the best return on investment from these three projects moving forward.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23425

Score: 7.0

Comment: Experiments are being used to obtain data necessary to develop the required framework needed for a geomechanics model capable of explaining the occurrence of MEQ at Newberry. However, it is unclear exactly what this model will look like when completed. Will it be a report that uses the measurements to explain the microseismic observations or will it be a computer model, which incorporates the measured parameters, that predicts MEQ as a function of the pumping parameters? How we get to something useful for the EGS work at Newberry would seem to benefit from better definition as it appears a bit vague to this reviewer. Part of this vagueness may be due to the lack of maturity of the work owing to the interruptions in funding.

PI Response:

Yes, th einterrucption have prevente dthe PIS from integrating wthir work. The plan is to have a "geomechanical/geologicall workflow" for interpreation of MEQ associated with stimulation and more effective stimulation design,

Reviewer 23450

Score: 9.0

Comment: As a reviewer, I appreciated the applied combination of experimental measurements under different loading conditions and using these measurements to model the fracture initiation and propagation. The agreement between the experimental and modeling results was very good, and more importantly, the combined approach allowed insight into the physical processes involved. This approach then applied to a field test at Newberry and interpret the observations and measurements taken.

The presentation of the rigorous mathematical relationships and physics involved was very helpful in understanding the inter-relationships between experimental results and modeling when applied to real data sets. This is critical in demonstrating understanding of the key processes involved.
Would like to seem more projects like this.

PI Response:

Reviewer 23479

Score: 8.0

Comment: The most novel element of SOW (1) is the use of stochastic inversion to match observed microseismicity. SOW (2) focuses on lab measurements and experiments on core from The Geysers and Newberry: air permeability, electrical conductivity, vp and vs, magnetic susceptibility, acoustic emissions, etc.) as a basis for understanding the role of poromechanical properties in MEQ generation. SOW (3) is to develop a 3D numerical model, WARP3D, for simulating multiple fractures and fracture clusters. (Note: WARP3D is visible online, but not associated with this PI, TAMU, or Oklahoma, except on DOE websites...)

PI Response:

Reviewer 29851

Score: 6.0

Comment: The technical approaches outlined by the project's objectives are justifiable and have merit; however I question whether some of the targets were achievable with the available resources. These targets can clearly no longer be achieved without re-organization of the funding and having this effectively delivered to the PI in his new position.

The projects appear to have been executed well and delivered some good results up to the point that the PI moved universities and funding problems came into play. If the projects are allowed to continue in some capacity then I recommend a review of the remaining tasks be performed to examine if the three projects can be synthesized in some cost-effective way, so as to bring them to a successful conclusion.

PI Response:

STRENGTHS

Reviewer 23425

Score: Not scored

Comment: * Ghassemi and his students are traditionally strong and productive performers
* Ties to experiments and field results will help in keeping the theoretical aspects of model development on track

PI Response:

Reviewer 23450

Score: Not scored

Comment: The combination of experimental results, modeling of the physical processes, and applying this understanding to interpretation of field data sets at The Geysers and Newberry EGS locations. This combination is a key strength of these projects and demonstrates an advance in the state-of-the-art in fracture modeling in a complex geologic environment.

PI Response:

Reviewer 23479

Score: Not scored

Comment: (1) A solid list of products and accomplishments related to SOWs (1) and (3), including for instance examples of the Virtual Internal Bond approach and seismicity-permeability inverse model currently in press in Water Resources Research.

(2) Work related to SOW (2) that, although incomplete, has already influenced the ongoing development of the TOUGHREACT-ROCKMECH model.

PI Response:

Reviewer 29851

Score: Not scored

Comment: The PI should be commended for having some very good ideas for researching the fundamental processes operating within an EGS reservoir and developing tools that would assist with EGS design and sustainability. These ideas did produce some significant results in the early parts of the projects.

PI Response:

WEAKNESSES

Reviewer 23425

Score: Not scored

Comment: * The nature of the geomechanical framework seems a bit vague

* Major delays in transitioning support to Univ of Oklahoma have really impeded progress on this project

PI Response:

Reviewer 23450

Score: Not scored

Comment: Well thought out and executed research program.

PI Response:

Reviewer 23479

Score: Not scored

Comment: The obvious weakness is the long delay of certain elements. However the PI owns up to this issue and intends to bring all of the work to a satisfactory conclusion.

PI Response:

Reviewer 29851

Score: Not scored

Comment: The organizational and funding problems caused by the PI's move between universities produces a significant risk that all three of these projects will not reach conclusion as planned.

PI Response:

IMPROVEMENTS

Reviewer 23425

Comment: Better definition of the nature of this geomechanical framework would be quite helpful.

Completion of the novation process will provide a much better outcome of this effort with apparently no further input of GTO support to complete the work.

PI Response:

Reviewer 23450

Comment: Comments (Recommended Critique Length: 500 words)

Provide more support for projects such as this. Very well executed research project.

PI Response:

Reviewer 23479

Comment: Please see comments in other sections.

PI Response:

Reviewer 29851

Comment: In order to capture the best return on investment from these projects, in terms of both DOE funding provided so far and the work that has already been achieved, then a comprehensive review of the three projects should be performed. This review should focus on synthesizing the plans through to completion and providing sufficient funding for the PI to pull together the results so far into a meaningful package and achieve the remaining goals that the DOE feels to be of continued benefit to the community.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: ARRA THMC Modeling
Principal Investigator: Sonnenthal, Eric
Organization: LBNL
Panel: Reservoir Modeling

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23425

Score: 9.0

Comment: A coupled THMC model of EGS processes is a very ambitious goal that nevertheless should be attempted. Sonnenthal and his colleagues, using a TOUGH-based code (TOUGHREACT-ROCMECH), are likely to have significant success in ultimately developing a well behaved version of their code that can be applied to understanding how the observed chemistry and mechanical signatures, such as micro-earthquakes, can be related to each other to achieve a better understanding of the complicated processes that determine the output and longevity of an EGS regime. The use of the multiple-interacting continua (MINC) model for THM seems novel and appears to be a valuable addition to the goal of a well-coupled THMC model.

The rating of "9" given here is based more on the potential of this research for improving our understanding rather than what it has already achieved for understanding EGS. This is only reasonable as it takes significant time and effort to develop useful codes that can have high impact for addressing important problems. Sonnenthal and his group appear to be well on their way to doing this.

PI Response:

Reviewer 23450

Score: 5.0

Comment: The concept of coupled THMC modeling has intrinsic appeal to the modeling community, especially when designing an EGS system. Unfortunately, the modeling has not yet reached an a priori predictive ability, the holy grail of EGS modeling. The results presented were very interesting, but are the result of many modeling iterations.

The THMC modeling used the TOUGH-REACT code. My largest critique of this family of codes is that it is nowhere near commercial standards for technical productivity. Adding to the problem multiple and over lapping data sets, technical productivity will suffer. Clearly, TOUGH-REACT is a research/academic code, with advantages and limitations. Perhaps, future productivity could be enhanced to rewrite the code to commercial standards.
While THMC coupling provides for more complex physical and numerical interaction, it is unclear if this provides better answers or just more complex code to history match larger data sets. There is modeling argument to be made for simple models of understood physics (T and M) and stand-alone models for (M and C) rock mechanics and rock/water interactions. Certainly, effective modeling of TMHC is a multi-disciplinary activity.

PI Response:

Reviewer 23479

Score: 9.0

Comment: This project represents a concerted effort to enhance THMC modeling capability such that it can usefully address EGS environments, which are characterized by large, transient gradients in stress, temperature, and chemistry. TOUGHREACT, which has long been the main option for THC modeling, has been extended to meet these challenges. More recently, TOUGHREACT-ROCKMECH has been developed, so that the complete package now includes the “M”, for mechanics. The primary previous option for simulating high-temperature reactive transport + rock mechanics was to couple TOUGHREACT with a commercial rock-mechanics package, i.e. TOUGHREACT-FLAC. The emerging TOUGHREACT-ROCKMECH package will provide an open-source option for THMC simulation.

The PI teams’ dedication to sharing and documentation guarantees availability and use of TOUGHREACT-ROCKMECH. The extensive list of publications to data is impressive, and documentation plans are well-developed.

PI Response:

Reviewer 29851

Score: 8.0

Comment: The project’s objectives are important to the broader GTO’s mission and goals as it targets the core challenge of effectively engineering and sustaining the EGS reservoir.
The project develops and tests numerical modeling procedures that aid investigation of the mechanisms of EGS design, production and sustainability. The knowledge gained and the tools produced through the developments will be a useful outcome separate from any other work. The project also builds knowledge towards future studies.

Numerical modeling analyses have the potential to remove barriers to successful design and implementation of a working EGS as well as be able to design better cost efficiencies. There are different methods of attacking this problem with the approach taken in this project being a continuum approach. The work performed in this project is therefore contributing to the community’s library of analysis, understanding and tools.
The tasks are well conceived with the core objectives and milestones of the project progressing well.

The results are significant in terms of the project’s technical objectives and goals with the majority of these being accomplished to date.

The quality of the technical accomplishments, results, and progress is high.

The work has been productive with notable accomplishments made in developing the TOUGHREACT-ROCMECH software and coupling, and then testing the approach on field data from the Newberry demonstration project.

The achievements are significant within the community as evidenced by the number and quality of technical publications. There are no apparent reasons why the project cannot be completed as proposed.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23425

Score: 9.0

Comment: Up to this stage of development, the approach seems highly appropriate. Using a known code such as TOUGH is a good starting basis for this effort. Modeling systems similar to those observed in the field (e.g., Newberry) is a demanding way to approach the problem. It is often the case that there is a lack of the right kind of data with which to compare the results of modeling. This group is well tied to the data which is a big plus for this effort.

PI Response:

Reviewer 23450

Score: 5.0

Comment: The work at Newberry Crater was very well presented, though the history matches are good, there is still residual error, suggesting the geologic context is poorly understood or additional processes may be present.
The TMHC codes seem to have very long CPU run times, limiting their application in a commercial setting, does the PI have any plans to develop numerical algorithms to assist in the history matching process, empirical algorithms, or other techniques to speed up problem numerical solutions.

Clearly, to accomplish the over-arching goal of EGS reservoir creation and management, more numerically robust tools are needed, as well as heuristic approaches to history matching data. Can parametric runs be made and dimensionless groups arranged to create type curves that capture the inter-related processes in a graphical format. Such type curves may assist the simulation engineer in selecting the first order parameters to model. In an operating field context, such type curves may provide interpretive or diagnostic ability without to run complex and CPU intensive codes.

Modeling field scale data using THMC models is an intriguing concept, is there sufficient geoscience data sets available to history match? Data collection is expensive, especially in an economically depressed environment, what data are needed to use THMC models and what data is nice to have but not critical? And finally, would a commercial enterprise collect such a data set or would program assistance be required?

PI Response:

Reviewer 23479

Score: 8.0

Comment: This is a systematic effort to improve the THMC-modeling capability of a widely used software package (TOUGH2 family) such that it is able to simulate EGS experiments. Milestones are clear and have generally been met, with perhaps a couple of excusable exceptions. ("Excusable" because the PIs are continually pushing the frontiers of both hydrothermal modeling and computational resources.)

PI Response:

Reviewer 29851

Score: 9.0

Comment: The quality of the technical approach is high. It uses a continuum approach, which means that the properties of the rock mass are averaged across the volume of the cell size that is used. This approach is appropriate within the project's objectives and resources.

The approach is well designed, based on years of technical experience with the PI, and is an extension of knowledge and established technology developed and tested in previous work. The approach has been well managed in the project tasks and executed to plan.

PI Response:

STRENGTHS

Reviewer 23425

Score: Not scored

Comment: Strengths:

* Strong code (TOUGH) on which to base new, more sophisticated codes.

* Broad expertise of the team in geothermal problems (chemistry, mechanics and thermal regime)

* Close ties to a real EGS system which provides needed observations for model validation

PI Response:

Reviewer 23450

Score: Not scored

Comment: The TOUGH-REACT family of codes has been used for several decades for a large number of problems with a large installed academic user base and has been well tested. As such, it is an appropriate platform for additional development.

The robust and routine application to a real world sites and data is a larger concern. The limited PetaSim interface provides some benefit to engineering productivity; additional steps should be support in this area.

PI Response:

Reviewer 23479

Score: Not scored

Comment: The PI team and their associates have a long record of accomplishment in this arena and are fully capable of continuing to advance this technology. They have nurtured a wide network of academic and industry collaborators.

PI Response:

Reviewer 29851

Score: Not scored

Comment: The project uses established techniques developed over many years with an experienced PI. It validates numerical modeling results against field data from an EGS demonstration site. The approach is shown to accurately model the flow measurements during the Newberry stimulation.

PI Response:

WEAKNESSES

Reviewer 23425

Score: Not scored

Comment: In the context of what could reasonably be done to date at the level of support provided, I could not identify obvious areas of weakness. Of course, I do have a few suggestions for the future.

PI Response:

Reviewer 23450

Score: Not scored

Comment: The match of the Newberry data shows promise, however there are problems with match uniqueness, what additional data would be required to remove the non-uniqueness issues.
The long CPU run times is clearly an issue in the long term, future research should include a component to develop techniques to speed up run times by at least an order of magnitude.

PI Response:

Reviewer 23479

Score: Not scored

Comment: Please see "Improvements" section.

PI Response:

Reviewer 29851

Score: Not scored

Comment: The success of an EGS site depends on discrete natural fractures, and the ability of the reservoir and fracture set to be engineered through hydraulic stimulation for optimized flow. The success of a particular site therefore depends on a relatively small number of discrete features, their interaction with the well bore, and how these features can be put to best use. Although fractures are not explicitly modeled within the approach used here, discrete features can be implemented by using zones of heterogeneity within the calculation mesh. The modeled region of increased permeability (rock disturbance) in the model results does not appear to match well with the microseismic measurements from the field stimulation that are a direct response of disturbed rock.

PI Response:

IMPROVEMENTS

Reviewer 23425

Comment: When the TOUGHREACT-ROCMECH code is sufficiently robust, it would be advisable to consider adding or linking with an uncertainty quantification capability, such as LLNL's PSUADE suite of codes, which would allow for evaluating the impact of uncertainties in the independent variables that define the EGS regime. PSUADE also allows automated parameter ranking and sensitivity studies that are important for determining the parameters that matter most in developing EGS exploration programs and infrastructure design models.

PI Response:

Reviewer 23450

Comment: If this technology is ready, efforts should be made to transfer this technology to the private sector for use in a real world environment and make TOUGH more user friendly.

This would require setting commercial standards for program I/O, graphical pre- and post-processors, and such. The program kernel would be maintained.

PI Response:

Reviewer 23479

Comment: A longer and more intense stimulation of the Newberry well might provide considerably more knowledge and understanding. However, even in the absence of more optimal testing, it is important to extend the associated simulations to consider longer times and higher injection rates. The later-time injection rate of about 8 kg/s is still about 10 times less than the rate required for commercial viability. Are higher flowrates likely to be achievable? Note for instance that thermoelastic effects may become important at later times, helping to enhance injectivity.

PI Response:

Reviewer 29851

Comment: It would be beneficial to perform greater study of the differences between the models and microseismic measurements. This could perhaps be done with use of improved heterogeneity within the model to test whether reasonable rock structure could play a role in the microseismic locations and affect the estimates of permeable zones.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Support of the DOE GTO Model Comparison Activity
Principal Investigator: White, Mark
Organization: PNNL
Panel: Reservoir Modeling

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23425

Score: 8.0

Comment: This effort is very much needed if we expect to use codes as a means of doing diagnostics and predictions relevant to EGS. This comparison study represents an important approach to validating modeling codes and determining what types of problems pertinent to EGS are particularly challenging from both a modeling and computational perspective. The novel concept of having "champions" for problems allows experts in a range of THMC problems to propose and provide technical support in developing benchmark problems that represent significant and challenging aspects of EGS. The use of a community approach to solving problems is a group approach to getting a "right" answer to a particular problem. The community can then determine if outlying solutions are either in error or, on the other hand, may be the correct result.

PI Response:

No response.

Reviewer 23450

Score: 4.0

Comment: The project budget of $1.84 million is one of the larger DOE funded projects with a number of researchers. This budget seems rather large for a code comparison study, lots of piling on.
Is there a need for a code comparison? Apparently, the rise of THMC codes and more detailed problems has the modeling community concerned that models do not provide reliable answers or that since there are no analytic solutions available, a code comparison is required to determine where the numerical consensus is.

How many different codes are involved? The codes involved are from the different R&D activities by DOE so there are several different codes and variants of the TOUGH code. The codes provide different platforms and numerical techniques to solution, using these various codes tests the mathematics and coding implementation of complex physical processes.

Are analytic solutions available for comparison? No.

This is primarily to compare the answers of several research groups to each other and determine the group goodness of fit and outliers. I like the interactive nature of problem solution posting and the use of ISO standards for code comparison.

However, how will this improve a priori predictions/confidence in numerical simulation? Perhaps the answer lies in developing more robust simulation tools and to greatly improve the user simulation interface to expand the commercial use of simulation.

The PI should be complemented for under taking the task of herding cats.

PI Response:

Advances in modeling coupled processes over the last 35 years since the code comparison study in 1980 to include geomechanical and geochemical processes associated with enhanced geothermal systems, suggested that it was time for a new look at the computer codes being applied across the spectrum of field project. One strength of this project is the diversity in numerical simulation approaches and number of experts participating, resulting in a large budget to fund the project. The suite of benchmark problems served to identify the current capabilities of the U.S. codes. The challenge problem suite will hopefully demonstrate the ability of both the codes and expertise of the participants in tackling field-scale problems.

Reviewer 23479

Score: 8.0

Comment: This work influences ongoing code-development efforts by members of the consortium. It is still at relatively early stages – less well-developed than similar code-comparison efforts worldwide – so that the ultimate impact is yet to be determined. However the project structure encourages ongoing communication among various developers, which doubtless has immediate, albeit less tangible benefits.

The workplan is well-developed, progressing from benchmark solution / benchmark publication (in the open literature) to challenge solution / challenge publication (in the open literature). The emphases on making data available (at the appropriate time) and open-literature publication are appropriate and important to the eventual impact. The eventual impact will also depend upon whether a long-term, sustainable community forum emerges, analogous to (for instance) the SCEC/USGS rupture code verification project (http://scecdata.usc.edu/cvws/).

PI Response:

No response

Reviewer 23404

Score: 8.0

Comment: This project represents a significant collaborative effort in which "codes" are exercised on the same set of thermal mechanical hydrologic chemical problems. This sort of work is vital to success of the EGS program development. There is a diverse team of analysts (world class) working the problems, and this will benefit the GTO in the long run. The codes are complex with many parameters which can be varied.

PI Response:

No response

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23425

Score: 8.0

Comment: The general organization and execution of this effort has been highly successful overall. The PI suggests that if he could do this over he would have tried to get more international participation. Given the European involvement in EGS, this suggestion makes sense especially as it would not seem to cost GTO. The collective or community approach will work often and may be the most reasonable approach given available support as long as the personal objective of the modelers does not become to simply get the same result as others, which may still be the wrong result.

PI Response:

No response

Reviewer 23450

Score: 6.0

Comment: The use of ISO standards and an online collaborative interface makes a lot of sense and enhances the mechanics and credibility of code comparison.

The different approaches to implementing the numerical code by different organizations and authors assists in a robust family of codes to compare. If differences are found in the different problem solutions, it is unclear how this would be resolved; as an outlier, bug in the code, problem interpretation and implementation issues, etc.

Further discussion would be helpful.

The accepted, final numerical solution should be recast in terms of dimensionless groups to create graphical type curves containing a large number of solutions.

PI Response:

Resolving differences in simulation results have been the responsibility of the submitting organization. The participants have generally been very supportive of discussing simulation results that appear to be outliers. These discussions have lead to changes in some of the simulators or changes to input files and re-submissions of problem solutions. In other cases the submitting organizations have chosen to support their solutions.

Reviewer 23479

Score: 10.0

Comment: The THMC models used (or under development) for EGS simulation must rank among the most complex scientific software developed to date. These models are intended to address problems that extend well beyond the scope of the closed-form analytical solutions typically used to test or validate numerical simulation tools. Thus comparison between the results of independently developed simulators, exercised on carefully defined sample problems, is an essential step. This has been well-recognized by other Earth-science communities that rely on similarly complex models. For instance, a Google search on “gcm model comparison“ yields >500,000 results, and the earthquake-science community has a well-defined SCEC/USGS rupture code verification project (http://scecdata.usc.edu/cvws/). Such an effort has not been made in a geothermal context since 1980, when the USDOE sponsored an exercise involving the first generation of multiphase flow models. It is timely in light of the recent (2009-present) resurgence of geothermal-code development, which involves a much more complex generation of models.

PI Response:

No response

Reviewer 23404

Score: 8.0

Comment: The group of analysts developed a systematic approach to comparing complex numerical methods. They have developed a series of problems which are being solved. Each problem emphasizes a portion of real problems which should be addressed in some aspect of modeling an EGS system. The problems are generally complex. They have developed the means to post results for comparison in relatively short time frames, and they use an accepted "standard" to compare results. At some point these folks should tie their analyses to well constrained real data.

PI Response:

No response

STRENGTHS

Reviewer 23425

Score: Not scored

Comment: I originally had doubts about taking a collective (majority) approach to benchmarking exercises intended to evaluate (compare) the models and numerical approaches used by codes to solve complex problems. However, the outcome to date appears to have mostly achieved the objectives of this effort and comparing a significant number of different codes running the same problem appears to be a strength even if known analytical solutions to problems of interest are in short supply. Involving people with technical expertise from a variety of backgrounds to develop problems also appears to be a strength. A third strength is the regular meetings and discussions that the PI has to keep people updated on progress. A fourth is the use of VELO for archiving solutions and keeping people up-to-date.

PI Response:

No response

Reviewer 23450

Score: Not scored

Comment: Lots of support from the modeling community.

PI Response:

No response

Reviewer 23479

Score: Not scored

Comment: Strengths of this ongoing effort include the substantial DOE commitment ($1.8M), community involvement, and the engagement of PIs who have been involved in previous, successful code comparisons.

I also applaud the decision to go beyond “benchmarking”; to define a set of more ambitious challenge problems that represent, not what we expect the models to be able to do now, but rather what we hope they can do in 2020.

PI Response:

No response

Reviewer 23404

Score: Not scored

Comment: Key strength of this effort are:

- the diversity of participants: university, industry, national laboratory
- diversity of numerical approaches- different numerical approaches, solution schemes, platforms, etc, attempting to model the same physics.
- frequent open communications--I see this as extremely valuable. exchange of ideas
- frequent posting of results in an open sharing manner

PI Response:

No response

WEAKNESSES

Reviewer 23425

Score: Not scored

Comment: While I think the effort achieves what it sets out to do, that is, compare the results of codes, there still remains some uncertainty regarding whether the right answer is obtained. This is a difficult objection to address when problems are extremely complex and involve multiple couplings between processes. However, it would be useful to include parts to problems that, where possible, have analytical solutions that the codes can be compared against as well as against each other. More complicated/realistic problems could be built upon the simpler analytical problems. I believe this approach has been attempted only occasionally in formulating problems for this exercise.

PI Response:

For two of the benchmark problems analytical or approximate analytical solutions were generated by the participating organization and communicated via GTO-Velo and the weekly teleconferences.

Reviewer 23450

Score: Not scored

Comment: It is unclear if sufficient field geoscience data sets available for full testing and validation of the complex codes being developed and tested. It is key that this technology be transferred to the commercial sector by the development of user friendly, commercial quality interfaces to the different simulators.
A least one comparison problem should have an analytic solution for comparison with the numerical results.
Elaborate on statement ‘rebuild confidence in numerical simulation’, I fully agree. What are the steps being taken, outside of a code comparison exercise? The lack confidence in numerical simulation has several issues and not necessarily related to whether several codes can have the same of similar answer.

PI Response:

Fenton Hill has been chosen for the Challenge Problem Suite for its richness of available data.

Reviewer 23479

Score: Not scored

Comment: I am disappointed to see little evidence of international involvement. For instance, the CSMP++ model developed by a European consortium (http://stephan-matthai.com/CSMP_info2.htm) is in some respects the most sophisticated model of this kind, and has been the basis for high-level publications in journals such as Science, Nature, and JGR. Shouldn’t CSMP++ be exercised on these problems?

PI Response:

International participation will be sought during the Challenge Problem Suite.

Reviewer 23404

Score: Not scored

Comment:
- lots of participants--perhaps too many?
- at some point DOE needs to be thinking of downselecting/specializing/honing skills.
- this is not a weakness of the project, this is a suggestion to DOE
- analyses need to be analyzing some real problems using real data.

PI Response:

No response.

IMPROVEMENTS

Reviewer 23425

Comment:

* Possibly have a separate class of problems with analytical/quasi-analytical solutions that codes can be compared against.

* Increase foreign participation as possible.

PI Response:

International participation will be sought during the Challenge Problem Suite.

Reviewer 23450

Comment: Need industry participation with industry based codes for a fuller comparison of research and industrial code capabilities.

PI Response:

Itasca was a participant in the Benchmark Problem Suite.

Reviewer 23479

Comment: Seek additional international involvement, for instance, the CSMP++ consortium and OpenGeoSys (Potsdam). Might it be possible to use the IGTP as a vehicle to enhance international participation?

PI Response:

International participation will be sought during the Challenge Problem Suite.

Reviewer 23404

Comment: move on to solving problems with real data sooner as opposed to later--this is where the proof of performance will be--code comparisons are nice, but working on real data from real problems will serve the purpose of improving and focusing modeling technologies AND it will have the added benefit of having modelers really look at data being collected and when and where it is collected and the type of information being collected.

....and some of that info may be fed back to data collectors and its value evaluated in a different manner.

what can be meaningfully measured and what can be meaningfully analyzed?

what is important to know?

what gives you 90% of the answer?

is that enough?

PI Response:

Fenton Hill has been chosen for the Challenge Problem Suite.

Supercritical Carbon Dioxide and Working Fluids Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Active Management of Integrated Geothermal CO_2 Storage Reservoirs in Sedimentary Formations
Principal Investigator: Buscheck, Tom
Organization: LLNL
Panel: Supercritical Carbon Dioxide/Working Fluids

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25423

Score: 10.0

Comment: This is a Phase II project focused on using multiple fluids (brine, CO_2, N_2) for geothermal energy production and storage within sedimentary formations. Two milestones are overdue as a consequence of personal circumstances of the PI. This is a management issue that the PI and Project Officer appear to have under control. However, during the presentation, the PI provided clear evidence of progress by showing a detailed, engineering-style process flow diagram and elements of a techno-economic analysis. The PI performed numerical calculations using the NUFT flow and transport code and the USDOE GETEM code; the PI presented key results from these calculations in support of the engineering diagram and techno-economic analysis. Key features that were illustrated were net power, parasitic loads, storage of bulk and thermal energy, and storage of CO_2. These are important datasets for the project and represent significant preliminary results.

Metrics of progress include two patents, one journal article, eleven conference papers, four additional conference presentations, and awards for presentations. These are important and significant measures of success. Although probably outside the scope of the project, the PI reported that conversations have begun regarding commercialization; this is also a sign of productivity.

The potential impact of implementing the system is very large, which is why I give it a high score. However, while this particular project is nearly complete, the overall system is still in the concept stage and has a long way to go.

PI Response:

We agree that potential impact of our system is large. We also agree that the project is still in the concept stage and that it has a long way to go. Given the magnitude of the potential impact our system can have on the CO_2 storage, geothermal energy and energy storage sectors, we believe that additional funding to advance it to commercialization is worthwhile.

Reviewer 29855

Score: 5.0

Comment: This project aims at a fairly large reservoir for integrating the use of CO_2 in the reservoirs. The impact of this research is marginal. The system analyzed is highly idealized. Circular geometries with impermeable rocks on all sides in unlikely in realistic wells. The schemes proposed for the use of CO_2 and other fluids is complicated.

Accomplishments do not address economics yet. Other storage schemes such as compressed air have been analyzed and results presented in the literature. The research team does not compare such schemes with their own methods. It is not clear what the ultimate goal of this research is. Is it for carbon capture? Or is it the geothermal development. The researchers claim more-efficient circulation, but do not establish how that is achieved.

Results and progress are acceptable. Thermal storage is not likely to be viable because of degradation of temperature in the storage reservoir. Results are derived for a highly idealized geometry for the reservoir. All storage schemes seem to allow about 5% improvement in day-time power production. Economics are yet to be analyzed.

PI Response:

The ultimate aim of this project is for deployment in large reservoirs because we want to eventually deploy a system that addresses industrial-scale CO2 capture, utilization, and storage (CCUS). It is too early to judge whether the impact of our research is marginal. We have received interest from potential industrial partners. Only after testing our system in the field will it be possible to judge whether or not the impact of our research has been marginal. We agree that the circular modeling geometries are a simplification and intend to, pending further funding, address more realistic geometries through more detailed 3-D modeling. We did not assume that impermeable rocks are on all sides. We assumed an impermeable caprock and bedrock, and assumed a reservoir compartment of effectively infinite radial extent. A major challenge with CO2 capture and storage (CCS) is that most potential storage reservoirs have a finite compartment size. In other words, real reservoirs are not of infinite radial extent, as was assumed in our modeling analyses. If we had assumed a finite reservoir compartment size, our approach would have been more effective with regards to storing pressure and utilizing that stored pressure. At the time of the presentation, we had not published economic analyses of our approach. However, detailed techno-economic analyses of our system will be available once our submitted Geosphere Journal paper is published. The submitted paper is titled "Multi-Fluid Geo-Energy Systems: Using Geologic CO2 Storage for Geothermal Energy Production and Grid-Scale Energy Storage in Sedimentary Basins". The ultimate goal of our system is to make CCUS economically viable and commercially attractive at industrial scale by virtue of successful geothermal energy and/or energy-storage deployment. We disagree with the comment that we have not demonstrated more-efficient fluid recirculation. The thermosiphon effect has been well documented in our papers as well as in other papers in this field. Through computer simulation, we have demonstrated how the thermosiphon effect, along with storing pressure in our multi-well-ring approach could result in more efficient fluid circulation. To prove that this works, it will ultimately require prototype testing in the field. We also disagree with the comment concerning degradation of thermal energy storage. The large quantities of thermal energy that could be stored will result in high round-trip efficiencies. Pending further funding, we intend to compare our approach with compressed air energy storage. We also intend to extend our approach to improving how compressed air energy storage could be deployed.

<u>Reviewer 29852</u>

Score: 7.0

Comment: This project ends this FY and this review opportunity seems to be a bit late in the overall process. The PI claims to have achieved many goals and to have met many objectives. The project presentation, although well done, gave the impression that there was a lack of focus with too many applications, approaches, and details. The project's next steps seem to be commercialization and/or a staged pilot test. Based on what was presented today, it was not clear what component of this project would be part of such a pilot test. In principle, the benefits of this application, especially when applied to relatively low temperature sedimentary basin environment, can be substantial. However, there are many doubts whether this will ever be done due to the apparent complexities of the method.

PI Response:

We understand why the reviewer sees our system as being very complex. The issue is probably in how we have presented our approach, rather than the approach itself. On first principals, it is simple: configure the rings of wells to conserve pressure and CO2 working fluid, thereby deriving the greatest benefit from injecting CO2 to drive fluid recirculation. From an operational point of view, is designed to be adaptable, which could allow it to be deployed in different ways depending on local constraints and conditions. We plan to develop a stepwise commercialization approach that breaks the integrated system down into its basic components, which could be tested in a prototype project in the field.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 25423</u>

Score: 5.0

Comment: I am not an engineer. However, as defined and implemented, this project appears to employ a suitable technical approach.

That said, the flaws and issues that I describe in the following sections impact the score that I gave for this section.

PI Response:

We appreciate that the reviewer sees our research to date demonstrating a suitable technical approach.

<u>Reviewer 29855</u>

Score: 6.0

Comment: The reservoir geometry selected for analysis is highly idealized. Patents and many publications present results of their analyses. Whether such results are relevant to realistic cases is questionable.
The goal for this project is complicated by combining schemes for carbon sequestration, CO2 used for compressed energy storage, and further for thermal energy storage. It is not clear which of these schemes is likely to be most economically viable. Further these approaches must be compared to extensive set of results on compressed air energy storage and other storage schemes.

The goals should be simplified to address one thing at a time.

PI Response:

We appreciate the need to simplify the goals, which is one of the reasons we are in the process of developing a step-wise commercialization plan. Each step will address simpler and more focused goals. A key activity is acquiring data from related power systems that can help validate our techno-economic estimates.

Reviewer 29852

Score: 6.0

Comment: The approach seemed to be all over the place, including allowances to reduce environmental risk by using brine for consumption and the option for applications with limited water use. The primary focus of application in lower temperature sedimentary basins was quickly lost due to the many tangents this project seems to have moved on. It appeared that the team somehow lost focus and tried to take on too much. Although many conference proceeding papers were published, the number of peer-reviewed papers was rather small. Insufficient for a project of this magnitude.

PI Response:

This project involved a discovery process of a brand-new evolving concept, which was progressively documented in a series of conference papers. This project was executed over a four fiscal-year period. The total funding was about 0.8 FTE for two years; averaged over four years, it worked out to be 0.4 FTE per year. Because the project occurred over nearly four years, it was presented at many conferences, which was not ideal because it diluted the resources applied to peer-reviewed papers. After our Geosphere paper (submitted June 1) is accepted, we will have published two peer-reviewed papers, which in addition to two US patent applications, is a reasonable output for a total of 1.6 FTE of effort. The Geosphere paper, once published will show that our project has evolved into a well-conceived, systematic, focused approach to integrating CO2 storage with geothermal energy production and energy storage. That paper shows how using brine to produce water can reduce environmental risk by limiting reservoir overpressure.

STRENGTHS

Reviewer 25423

Score: Not scored

Comment: The project provides a holistic approach to geothermal energy in sedimentary systems. It combines technical and economic analysis, something most projects do not do. It has been productive in terms of disseminating information, as documented by conference proceedings and talks.

PI Response:

We appreciate the reviewer's comment.

Reviewer 29855

Score: Not scored

Comment: It is difficult to identify key strengths in this complicated scheme.

The team's collaboration with the Ohio State University, University of Minnesota, and ETH Zurich adds some credibility to this work.

PI Response:

We believe that once our Geosphere paper is published, the key strengths of our project will be apparent.

Reviewer 29852

Score: Not scored

Comment: The idea of storage under the lower temperature conditions is very attractive. It will potentially open up multiple sites in the US for the application. The use of the NUFT and economic software seems to be expertly done, with interesting outcomes.

PI Response:

We appreciate the reviewer's comment.

WEAKNESSES

Reviewer 25423

Score: Not scored

Comment: As described below, we learned during the Q&A session that the PI used brine efficiency curves in the engineering modeling. This is a critical link in the approach and a sensitivity analysis or some other analysis of the significance of this assumption is warranted. But it begs the question, what other simplifying or important assumptions have been made? Have these assumptions been clearly defined for the Project Officer and documented for the project? Has the significance of these assumptions been assessed? If it hasn't already been performed, some sort of process analysis is needed to ensure the veracity of the design.

This is an Enhanced Geothermal Systems (EGS) project that addresses the use of mixed fluids as the working fluid. A subtle aspect of geologic carbon sequestration permeates this project. This is not a bad thing, given the title and focus of the project. But I was looking for, and could not find, information regarding the impact of the state of the geologic carbon sequestration community on this EGS system. In other words, if geologic carbon sequestration does not become a reality, what is the impact on this EGS system? If CO2 is not being stored as part of mitigating climate change, is this geothermal system still economic? The same question applies to the price of CO2 in the context of its use as a process fluid in the oil and gas industry. Does CO2 as a commodity in the oil and gas industry affect this EGS system? These questions must be addressed as part of the techno-economic analysis.

PI Response:

We appreciate the reviewer's observations. A strong case can be made that widespread CO2 capture and storage (CCS) will not happen unless economically viable uses for this storage be developed. The overall goal of our project is to develop CO2-enabled geothermal energy production and grid-scale energy-storage applications to make it economically attractive to store large quantities of CO2. Besides the economics of CCS, the other major obstacle for CCS is the concern that injecting enormous quantities of CO2 will result in unacceptably high overpressure in the storage formation, leading to risks such as induced seismicity and CO2 leakage. Our Geosphere paper, which is in review at the time of this response, describes and analyses how our approach can be effective manage/limit reservoir overpressure, while generating water. So, the end products of our study can significantly contribute to addressing the two biggest challenges facing CCS: (1) unacceptable economics and (2) unacceptable risks driven by reservoir overpressure. By generating water, our approach can address a third obstacle for CCS deployment, which is the water intensity of the post-combustion CO2 capture process.

Reviewer 29855

Score: Not scored

Comment: The research aims to do too many things with CO_2, including sequestration, storage (both energy and thermal) all at the same time. The effort is frazzled, with no clear-cut goal. It is not yet clear which approach is projected to be economical. No comparison of highly-studied energy storage schemes under the DOE's storage program is provided. Economic assessments are available for all these from DOE.

The geometry used for the analyses is idealized. It is not clear how the results will change with more realistic reservoir geometries. The presenter suggested that this system can work better with N_2 instead of CO_2, in which case this effort has nothing to with CO_2 per say in terms of sequestration.

PI Response:

Our Geosphere paper, which is in review at the time of this response, presents our approach to CO_2-enabled geothermal energy production and grid-scale energy storage in a systematic, clear-cut manner. Because of limited resources, we decided not to continue studying N_2-enabled geo-energy systems during the last 18 months of our project. However, N_2-enabled systems have the potential of dove-tailing with CO_2 systems because of a promising new approach for efficiently generating pure streams of CO_2 involving pressurized oxy-fuel combustion, which requires pure oxygen as part of the inlet gas. Such power systems rely on an air-separation unit (ASU) to generate pure oxygen. The current thinking is to discard the nearly pure N_2 generated by the ASU. Therefore, with oxy-fuel power systems, N_2 will be available as a free byproduct. The CO_2 generated by the oxy-fuel power plant could be used for CO_2 enhanced oil recovery (CO_2-EOR). Currently, there is a shortage of CO_2 at a price that CO_2-EOR projects are willing to pay. Our N_2-enabled approach could provide a synergistic integration opportunity if oxy-fuel power systems become commercially attractive. The commercial value of oxy-fuel power systems could be enhanced if our approach is proven in the field.

Reviewer 29852

Score: Not scored

Comment: As stated before, it was difficult to detect a clear focus in the presentation. A lot was going on with numerous tangents and derivations. It was hard to imagine how a potential pilot test, apparently the next goal of the team, would look like. The complexity will likely limit interest of investors and increase the timescale before the technology can be used.

PI Response:

Our Geosphere Journal paper, which is in review at the time of this response, lays out our approach in a clear, focused manner. We are currently working with a start-up company in the development of a step-wise commercialization plan. We are also working closely with venture capital advisors who are helping us develop our commercialization plan, business model, and martketing strategy, and in identifying potential investment partners.

IMPROVEMENTS

Reviewer 25423

Comment: As defined and implemented, this is an engineering design project. Scheduling delays aside, the PI appears to have made progress on the key elements that were projected for the project. The project is slated to end July 2015. As such, my comments on the scientific and technical approach are not going benefit the PI very much. However, for his benefit regarding commercialization efforts, and for the benefit of the Project Officer, I provide the following comments.

This project describes a very idealized system. In effect, it is an engineered system superimposed on a simplistic natural system. How has the PI addressed, or will the PI address, the geologic processes and complexities that implementation will have to overcome? Examples of processes and complexities to consider are scaling, subsurface heterogeneities, lateral facies changes in a sedimentary system, reactions of sedimentary minerals with mixed fluids, brine acidification and carbonation, and water-rock interactions. When asked about this aspect, the PI provided a vague answer about reactive transport modeling. Reactive transport modeling is a necessary, but not a sufficient, approach to implementing an engineered system in a natural setting. This issue must be considered more deeply and more fully, it is a potential “deal killer”.

During the Q&A session we learned that the PI used brine efficiency curves in the engineering modeling. This seems to be a critical link in the approach. Has a sensitivity analysis or some other rigorous evaluation of this reliance on efficiency curves been performed? In other words, have the assumptions inherent in the use of these curves been evaluated?

Other recommended improvements are stated in the weaknesses section.

PI Response:

We agree with the reviewer's comments and appreciate their advice. We also agree that our project was largely implemented as an engineering design concept. We also agree that it was analyzed as an idealized system, which was done in order to focus on engineering questions about how to implement our system. In order to move closer to potential commercialization, it will be necessary to address questions concerning detailed geologic processes, heterogeneities, and complexities. Given the size of the potential commercial investment in our system, such studies will be imperative, so the financial risk is properly managed. As we conduct those more detailed scientific studies, we will continue to look to improving our conceptual design, with an eye to making it less vulnerable to potential "deal killers". When resources allow, we intend to dive more deeply into the details of our modeling approach, such as brine efficiencies. To date, one of the ways we have validated our brine efficiencies is to cross-check them with our GETEM analyses, which are discussed in our Geosphere Journal paper, which was in review at the time of this response.

Reviewer 29855

Comment: The project goal must be simplified and stated clearly. It is either the sequestration or energy storage that is main factor.

Economics for energy storage must be analyzed and compared to other methods such as CAES.

PI Response:

It is not necessary that the goal be either sequestration or energy storage. Our synergistic approach is designed to make CO_2 sequestration economically viable and commercially attractive by successfully integrating it with energy storage. Because of the societal demand for both CO_2 sequestration and energy storage (which will enable greater penetration of intermittent renewable energy), going after both targets is more strategic than focusing on either one or the other. Moreover, the synergy simultaneously helps with the economics of CO_2 sequestration and energy storage. We are in the process of analyzing the economics our energy storage approach and in comparing it against other technologies, such as CAES.

Reviewer 29852

Comment: The project will be completed this year. Hopefully a few more peer-reviewed manuscripts will appear in the literature.

PI Response:

We submitted a manuscript to Geosphere Journal on June 1. At the time of this response, it is still in review.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geothermal Energy Production Coupled with CCS: Heat Recovery Using an Innovative High Efficiency Supercritical CO2 Turboexpansion Cycle
Principal Investigator: Freifeld, Barry
Organization: LBNL
Panel: Supercritical Carbon Dioxide/Working Fluids

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25423

Score: 3.0

Comment: The PI developed an induced seismicity plan and monitored for induced seismicity. The project determined "low seismicity" despite large injection volumes of CO_2. This is a valuable contribution.

The PI installed and collected data for a short-term use of CO_2 as a working fluid in a geothermal system. A wide range of data was collected. According to project documents, the overarching objective was to demonstrate a natural thermosiphon using CO_2 as a working fluid. The fieldwork was done and the data was collected. This is an important accomplishment. The data was not interpreted and the project therefore not completed. This is a major failure and this is the reason I assigned a low score.

PI Response:

Reviewer 29855

Score: 3.0

Comment: No significant impact can be foreseen as the basic premise of the approach to use CO_2 thermosiphon is not established.

This project aims to establish a thermosiphon system with natural circulation of CO_2 in an existing field with EOR Operation. For a thermosiphon, some facts must be established first. 1. a thermosiphon is a closed system consisting of vertical and horizontal legs of pipes with vertical pipes generally a lot longer than the horizontal legs. 2. the vertical legs should have varying thermal condition such that one leg provides the heat and the other removes heat. 3. The system must be a closed loop. None of these conditions are met in the current experiments conducted and reported.

Perhaps, the title for this work should remove the words "thermo-siphon" and "natural convection."

It is not at all clear that the system is closed. The flow out of F3 well may be what is being vented from EOR operations.

As one in the audience Pointed out, there were no tracers used to assure that what was injected in F1 was really the CO_2 gas that came out of F3. No results were presented stating that the data obtained is extensive and that further work is necessary to "process the data." When the basic premise that this system is a thermosiphon that is closed has not been established, no value can be added by processing the data.

There are no models to show that the thermosiphon would work in this case and assess the potential flow rates. Such a model can be readily done with CFD software to establish what can be expected. In the reviewer's opinion, there is a lot that has not been done to establish the basic premise of the experiments.

To claim that the experiment was a "success" is simply not true. The fact that this experiment is a valid effort must be established first.

No progress can be expected from a flawed experiment.

PI Response:

Reviewer 29852

Score: 8.0

Comment: First field demonstration of CO_2 use to mine heat. This is a truly impressive accomplishment because a wealth of data has been obtained in the process that should be used to test and verify simulators. The PI presented the material expertly and with enthusiasm.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25423

Score: 3.0

Comment: The assessment of induced seismicity was performed according to standard practice and appears to have been well executed. The field test of CO_2 in an EGS system was deployed according to protocols that appear to be reasonable, but one cannot tell if it was successfully implemented because the data has not been finalized and interpreted. For this reason, I scored the PI low in this category.

PI Response:

Reviewer 29855

Score: 3.0

Comment: The approach is highly flawed and inadequate. One must start with a CFD model of the closed thermosiphon system to evaluate what can be expected at the site. Then, the fact that the thermosiphon system is closed at the site must be established by doping and measuring in and out flow rates. Then differing conditions on the vertical legs must be implemented to make sure the flow goes down on the cooled leg and upward on the hot leg. None of this was done based on the presentation provided.

Instrumentation provided appears adequate. But any interpretation of the data is likely to be highly controversial and invalid. Further efforts in this effort must be curtailed at once. Basic precautions to establish the validity of the experiments were not done.

PI Response:

Reviewer 29852

Score: 8.0

Comment: The technical approach is sound, based on what was provided in the Project Summary. It was not clear from the presentation. The PI could have done a better job describing the history of this project with a short description of the tasks. All project tasks are logical, including the sequence in which they were completed. Interestingly, a task to model the application and compare with the predictive modeling of Task 1 was not included in this project.

PI Response:

STRENGTHS

Reviewer 25423

Score: Not scored

Comment: The strengths are the field deployments of two important systems: a system to measure induced seismicity and a field experiment of CO2 as a working fluid for EGS. The former appears to have been successful, but final data was not delivered to assess the success of the latter.

PI Response:

Reviewer 29855

Score: Not scored

Comment: I do not find any strengths in this effort.

PI Response:

Reviewer 29852

Score: Not scored

Comment: A field test of heat production using CO2 has been successfully completed, including the demonstration of a geothermal thermosiphon. A remarkable accomplishment by this team as so far only theoretical approaches have been published. The test has led to the collection of a unique set of pressure, temperature, and mass flow (density) data that should be used for modeling purposes.

PI Response:

WEAKNESSES

Reviewer 25423

Score: Not scored

Comment: According to the project documents (the project summary): “Analysis and interpretation of field data acquired at the Cranfield, MS thermosiphon test using T2well/TOUGH2 coupled reservoir/well mass and heat transport simulations.” was due in September 2014. However, according to other project documents (the PowerPoint): 1) Future work is required to interpret the voluminous data collected during the field campaign; and 2) Proposal Submitted to DOE for processing and interpretation of data collected - Possible continuation of project effort in FY16. Finally, according to the third set of project documents (the SOW), the preliminary interpretation of the data is due June 2015 and the final report due September 2015.

This conflicting information suggests to me that the project ran out of money after the fieldwork was completed but before the data was interpreted. The failure to deliver the promised analysis and interpretation constitutes management failure on the part of the PI. Technically this is a management issue between the Project Officer and the PI, and I am tasked to comment on the scientific and technical aspects. But a critical portion of the project was not delivered (i.e., the data analysis and interpretation), and we were shown raw data without interpretation. How can I comment on this major portion of the project when the work was not done? No explanation was offered, just a statement that more work/money is needed (heedless of the commitment to deliver the work product). Thus I deem this to be a major weakness in the project.

The summary documents are incomplete. For example, no information for the Technical Accomplishments is provided in the Project Summary; the original instructions are listed. Information in other portions of this document is perfunctory at best. This indicates poor preparation for the meeting by the PI. The reviewers and the review process are worthy of the PI’s best effort. The PI has done fine work previously on other projects, but not on this project and not in preparing for the review.

PI Response:

Reviewer 29855

Score: Not scored

Comment: As already mentioned, the validity of the experiment is in question. It is impossible to establish this validity now that the experimental effort has been completed. No further analysis is likely to improve the validity of this effort.

It is not clear whether there were other earlier reviews conducted on this effort to address the missing evidences for the thermosiphon. Reviews of the proposed experiment and approaches could have avoided some serious flaws in this effort.

PI Response:

Reviewer 29852

Score: Not scored

Comment: In the presentation, the initial predictive modeling in Task 1 was only briefly mentioned. I would have been of interest to find out more details how the modeling data were used to design the experiment. That aspect was not clear at all. Based on some of the PI's answers to the reviewer's questions, there were some discrepancies between the predictive modeling and the field data but this aspect was not presented in any detail. I believe this was a missed opportunity to receive some information what the focus should be of future modeling exercises.

PI Response:

IMPROVEMENTS

Reviewer 25423

Comment: The major improvement needed is the final data analysis that was not delivered needs to be performed.

Regarding a small detail - The PI reported that the project flushed the filter in order to clear it. No scale was observed, and it looked like the liner of the well was disintegrating and collecting in the filter. Did the project analyze the filtrate for fine-grained mineralization by using XRD? This would give an indication of whether scaling was taking place.

PI Response:

Reviewer 29855

Comment: I suggest this project be renamed without the use of words such as "thermosiphon" and "natural convection."

This project must also establish that what was injected as CO_2 in well F3 is really what came out of the production well F1.

PI Response:

Reviewer 29852

Comment: This project has come to an end and funding seems to have been requested for modeling purposes. I believe that the modeling using this vast data set should not be a one-lab activity. A minimum of two major teams (e.g., a TOUGH and a STOMP team) should be involved in this follow-up project to achieve scientific integrity and to avoid any bias. This data set is too extensive and valuable to leave it to one group.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Push-pull well testing using CO2 with active source geophysical monitoring
Principal Investigator: Oldenburg, Curt
Organization: LBNL
Panel: Supercritical Carbon Dioxide/Working Fluids

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 25423

Score: 10.0

Comment: This is a new project, it started in October 2014. Several important tasks have already been completed. These are: identified end-member fracture types; performed simulations of CO2 injection and production into vertical fractures, and modeled seismically relevant parameters. The PI and coPI are being productive.

Preliminary results suggest that CO2 saturation in fractures reduces C11 (the stiffness normal to the fracture plane). This is an important accomplishment.

The expected final outcome of the project is the proof of principle of an integrated well-testing and geophysical monitoring technology. If successful, this will be an important contribution to developing geothermal resources. The PI has made steady progress toward this outcome.

PI Response:

Thank you for reviewing our project and providing affirmative comments.

Reviewer 29855

Score: 8.0

Comment: Push-pull well testing with CO2 or even N2 likely to provide a better characterization of the reservoir fractures, than currently available methods. The team brings expertise from prior work for DOE under the fossil energy program. Modeling indicates that vertical fractures can be identified and quantified.

Accomplishments have been satisfactory, considering that this the first year for this effort. Both CO2 saturation and the p-wave speeds provide indications of the extent of fracture, spacing, aperture, connectivity and porosity.
Results are once again satisfactory. Mostly models are provides. No field experiments have been done. It is essential that testing be conducted to verify the process. Perhaps simulated experiments in a laboratory would be worthwhile to prove the proposed concepts prior to field tests. Progress is adequate for the duration.

PI Response:

We agree that, provided our model results continue to show the approach will work, field testing will be critical to validate the modeling. We include in the project a task at the end to plan and design a field experiment to test the approach in the field.

Reviewer 29852

Score: 7.0

Comment: Project has just started resulting in minimal progress, according to expectation. In the first year, forward modeling of CO_2 push-pull tests will be accomplished. The results shown in the presentation were for very simple fracture properties. The hope is that the authors can improve on that during the first year and move on to more complex conditions. The worry is that so far there seems to be a focus on the C11 component although it seems to be insensitive over a large range of CO_2 saturation. A major concern is that the total volume of CO_2 injected in the fractures may not be sufficient to affect both Vp and resistivity. The results of the numerical exercises need to be reviewed critically before allowing to move on beyond the first year.

PI Response:

We have expected from the start that C11 would be sensitive to CO_2 saturation mostly in the low-saturation range. This is one reason that we have included other monitoring approaches, specifically electrical methods via well logging, because we expect electrical conductivity to be sensitive to CO_2 saturation over a much wider range of CO_2 saturations. The combination of seismic and electrical methods will allow sensitivity to saturation starting from near-zero saturation and extending up to nearly full saturation. We are focusing this first year on the early proof of principle in order to pass the first-year go/no-go evaluation.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 25423

Score: 10.0

Comment: The project is using state-of-the-art reactive transport models to simulate CO_2 in fractures. The results are to be integrated with seismic property models and well-logging models. The geophysical codes to be used were not specified. A field validation plan is going to be generated for the last task. This plan is an important part of the technical approach.

PI Response:

Thank you for reviewing the project. Our numerical implementation of seismic wave propagation was described in Zhang, et al., 2015. It is realized on a discrete grid using an explicit finite-difference technique, which was introduced by Madariaga (1976), Virieux and Madariaga (1982), Virieux (1986a). The inclusion of fractures follows the method of Coates and Schoenberg (1995). A perfect match layer (PML) boundary condition is used to reduce undesirable edge effects (Roden and Gedney, 2000, Komatitsch and Martin, 2007, Martin et al., 2008a,b, Martin and Komatitsch, 2009). For 3D calculations, an MPI (Snir et al., 1998) implementation is used to improve computational efficiency.
Reference:

Reviewer 29855

Score: 7.0

Comment: The approach is well defined and appropriate. It evolves logically from simulations and relies on data from oil field experiments. Simulations are however idealized. Resistivity changes with CO_2 saturation is one indication of the sensitivity to CO_2 push-pull testing. However, any type of metallic veins in the fracture can reduce the resistivity and mask this sensitivity to CO_2 saturation, and this method will fail. Provisions to address this would add value to this work.

PI Response:

This is an interesting point, i.e., the potential occurrence of highly (electrically) conductive minerals in/near fractures that would compensate for and mask the lower-conductivity caused by the CO_2 in the fracture. Our approach covers this possibility by making use of time-lapse (4D) approaches for both active seismic and well-logging monitoring. In short, our approach will look at differences between non-CO_2-filled (pre-push) and CO_2-filled (push) cases during the push-pull process.

Reviewer 29852

Score: 7.0

Comment: The approach so far appears to be good. The presenter explained very well how he thinks the project may develop over time and was open and honest about potential strengths and weaknesses. I could not really judge the quality of the simulations as not enough time was provided to explain boundary and initial conditions, retention parameters, etc. I was also not clear what information of the "push" and "pull" would be used in the analysis. Given the output will consist of pressure, saturation, Vp, and resistivity data, the projects needs to work towards presenting a data analysis plan. In addition, the PIs need to work towards the ability to provide criteria on when the method might be applicable and how a push-pull needs to be conducted under various conditions.

PI Response:

We will be numerically inverting data from our forward models, making data analysis the heart of the project. The injection and production pressure and flow-rate data during the push-pull process are important for determining hydraulic properties of the fracture. Following the first-year proof of principle, we intend to investigate ranges of conditions to determine optimal and non-optimal situations for the approach.

STRENGTHS

Reviewer 25423

Score: Not scored

Comment: This is an interdisciplinary project combining hydrogeology and geophysics. The project also integrates reactive transport and geophysical models. Two outside collaborators are listed (University Louisiana Lafayette and Schlumberger); having collaborators external to LBNL is a strength.

PI Response:

We agree that the participation of SLB brings enormous well-logging expertise to this geothermal application.

Reviewer 29855

Score: Not scored

Comment: The research team beings expertise from prior work for the fossil program.

Results indicated (on slide 4) shows fractures at a depth of 1800 m. This is impressive data on characterizing the fracture at great depths.

PI Response:

Thank you for the comment.

Reviewer 29852

Score: Not scored

Comment: Highly qualified PIs. Access to excellent simulators. A novel idea for this application will be tested. If successful, the potential cost savings can be substantial.

PI Response:

Thank you for the comment.

WEAKNESSES

Reviewer 25423

Score: Not scored

Comment: I am not a geophysicist, it is difficult for me to comment on this part of the project. On the modeling side, I see no obvious weaknesses.

PI Response:

Thank you for the comment.

Reviewer 29855

Score: Not scored

Comment: Sensitivity to CO_2 saturation on resistivity is good.

But sensitivity to wave propagation speed is limited to low levels of CO_2 saturation. This can limit data interpretations.

Presence of metallic veins in the field can mask all sensitivities to resistivity measurements.

PI Response:

We agree that reliance on the well-logging aspect will likely be necessary at higher CO_2 saturations. Nevertheless, having active seismic sensitive to the low-CO_2 saturation range is very important and powerful for the approach because even small amounts of CO_2 in the distal regions of the extent of the CO_2 injection will light up the seismic response. Time-lapse interpretations should handle the concern about high-conductivity of metallic minerals because such materials are highly conductive at all times, i.e., before and during push-pull. This project will be looking at the differences between pre-push-pull, during push-pull, and post push-pull.

Reviewer 29852

Score: Not scored

Comment: It seems hard to envision that the CO_2 volume in a few fractures will have the ability to affect field scale Vp or resistivity data. Good pressure data might be obtained but that is not sufficient to test the application in such a setting. The first year simulation results should be used for a go-no go decision on proceeding. Is this something that is just of academic interest or can something actually be done in the field?

PI Response:

We became interested in applying this approach and proving it for geothermal systems from our work in geologic carbon sequestration where fracture zones have been positively identified through time-lapse seismic as they became filled with CO_2. The key aspects of this approach are that it is based on time-lapse differences, and that we use both active seismic and electrical properties to cover both low and intermediate-high ranges of saturation. The first-year effort will more fully demonstrate applicability of the approach. Near the end of the project, we will scope out what it would take to demonstrate the approach in the field.

IMPROVEMENTS

Reviewer 25423

Comment: A small point - it was not clear during the presentation if the matrix mineralogy is a variable that will be explored (e.g., granite vs granodiorite). We had no time during the Q&A session to discuss this, and I did not have the opportunity to ask the PI afterwards. But it's worth being clear on the subject. It may not matter and it may not be a variable in the study, but this is an assumption worth stating.

Another small point-will the PI examine dynamic changes to the fractures? In other words, in the simulations, does permeability change as a function of reaction fracture wall with fluid? Same questions apply to fracture volume (porosity) and aperture, two fracture properties explicitly identified in the project documents. I think the process will matter, but I don't know if this is part of the work scope. Either way, it's an assumption that is worth making clear.

Please identify the roles of the two external collaborators.

Please specify the geophysical models to be used, or maybe state they are standard industry codes. The PI expressly identified the reactive transport codes being used, he should do the same with the geophysical models.

PI Response:

Effects of matrix properties may be important and we may look at that later in the project. But it is important to keep in mind that the time-lapse aspect of the approach to a large degree diminishes significance of these differences.
As for reactions of the CO_2-water mixture with the fracture wall, we do not anticipate these being important over the time-scale of the push-pull monitoring period. We are considering interactions of CO_2 in the fracture with matrix from a hydraulic point of view, e.g., imbibition into the matrix and tendency for CO_2 as the non-wetting fluid to be restricted to the fracture.

Rui Zhang from Univ. Louisiana Lafayette is working on the active seismic modeling. T.S. Ramakrishnan is leading the SLB team in the well-logging piece.
The geophysical models being used are numerical implementations of seismic wave propagation realized on a discrete grid using an explicit finite-difference technique, which was introduced by Madariaga (1976), Virieux and Madariaga (1982), Virieux (1986a). The inclusion of fractures follows the method of Coates and Schoenberg (1995). A perfect match layer (PML) boundary condition is used to reduce undesirable edge effects (Roden and Gedney, 2000, Komatitsch and Martin, 2007, Martin et al., 2008a,b, Martin and Komatitsch, 2009). For 3D calculations, an MPI (Snir et al., 1998) implementation is used to improve computational efficiency.

Reviewer 29855

Comment: Suggest addition of lab-scale experiments and data using a high pressure chamber filled with appropriate filler and implanted fractures to test influence CO2 and push-pull testing and inversion assessment. Lab experiments can improve the methodology and provide insights into potential problems likely in the field evaluations.

PI Response:

This is an excellent idea that will be considered during the project in light of modeling progress and budget.

Reviewer 29852

Comment: Project is too fresh for such recommendations.

PI Response:

Okay.

Tracers / Zonal Isolation / Geochemistry Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0005508
Project: SPI Conformance Gel Applications in Geothermal Zonal Isolation
Principal Investigator: Burns, Lyle
Organization: Clean Tech Innovations, LLC
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 9.0

Comment: Reversible conformance, diverters, loss circulation and zonal isolation products are necessary for the success of all types of geothermal systems.

This research will have a large impact with a successful field demonstration.

This project has succeeded its accomplishments and appears progress is near the end of this project.

PI Response:

Reviewer 23430

Score: 6.0

Comment: Zonal isolation is a critical aspect of geothermal technology. The project is aimed at developing a gel for geothermal zonal isolation during drilling, such that the gel can withstand temperatures ranging from 150 to 300 C and can be dissolved away by NaOH before the well starts to operate. The gel involves silicate nanoparticles and polymer molecules. Its viscosity remains low until an initiator is used to trigger gelation, which causing stiffening. Due to the proprietary nature of the gel, the claimed attractiveness of the gel is inadequately supported in the written report or oral presentation by data or scientific concept. Therefore, review of this project is difficult. The testing mainly involves sand pack permeability testing.

PI Response:

Reviewer 29850

Score: 5.0

Comment: Impact - Project is in-line with GTO's mission of being able to seal well/fractures in high temperature geothermal systems.

Quality

- Delayed gel set for hours with new initiator system
- Hydraulic conductivity is > 10e-8 cm/sec (equivalent to a fine silt/clay) with gel in a sand pack flow test.
- Batch test suggest that it is reversible

Productivity

- According to speaker, the process is reversible and costs only a fraction (cents/lb) to other gels (dollars/lb) production.
- No project costs were reported.
- Planned goals and milestones changed (not sure these were negotiated with DOE)

PI Response:

Reviewer 23404

Score: 7.0

Comment: This project focused on development and testing of a high temperature gel for geothermal zonal isolation. If successful this product would prove to be a benefit to geothermal applications by providing another means of zonal isolation. Right now the technological development is in the laboratory stage and the developer is seeking opportunities for field deployment.

1. Quality-the work appears to be reasonably high quality in terms of being able to develop the new initiator system for the gel to cause it to "form". It is a lab study at this point and needs to make some leaps in order to grow to field application.

2. Productivity--it appears that the research team has made continuous progress towards meeting stated goals. Key for this work is better consideration of field deployment--the presence of an industry partner would additionally provide additional credibility.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 9.0

Comment: This project has a results driven scientific/technical approach

PI Response:

Reviewer 23430

Score: 6.0

Comment: The approach mainly involves gel development and sand pack permeability testing. This approach is reasonable. However, the inadequate technical information in the report makes it impossible to evaluate the approach. It is thus unclear if the approach has been executed with adequate rigor. It is also unclear if the work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources.

PI Response:

Reviewer 29850

Score: 4.0

Comment: A gel that will work in a high temperature systems has been produced. The gel is a silicate nano-particle polymer gel. The gel has been tested up to 250C (less than the desired range of 300C). The gel is reversible using a 20% caustic solution. The gel was tested in a sand pack flow through cell.

Company has issues with high temperature testing equipment (mostly the seals).

Not enough information was given on the rigor and appropriateness of technical approach.

They state that the technology is ready for field application. Hard to believe that they are ready to transfer this technology to the field without some sort of intermediate scale testing. The bench scale results have examined shearing on gel set and have suggested that shearing will not have an impact. Testing of gel has been accomplished in sand packs and not a fracture system with considerably larger apertures. Results have not be evaluated against field fracturing pressures and conditions.

PI Response:

Reviewer 23404

Score: 6.0

Comment: This work is high in engineering/science, in that it appears to have produced a material that will set in a gravel and resist pressure at high temperature. As pointed out in the review questioning, and not fully answered, geothermal loss circulation zones, for example, can be cavernous. It is unclear how well the material would fill and gel in such an environment--and if it would work at all. I believe the question was asked about fractures that may be large--and the answer was unclear. So perhaps some more thought should go into the deployment in large holes? Does the material cure from the outside in --or uniformly once it is switched into the set mode? For example, will a bucket of it set up, or does it need to be in thin stringers? This additional information should be evaluated and presented.

Also, durability of a plugging material such as this should be evaluated (perhaps this has been done) over a range and cycle of conditions. For example, the well can be prepped for placement, but well conditions once placed change with time (temp, pressure, chemistry)--such an evaluation may be warranted.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: This project identifies specific needs for the geothermal industry.
This project has shown results with other applications of waterfloods and CO2 EOR

PI Response:

Reviewer 23430

Score: Not scored

Comment: A gel having high temperature capability, low viscosity prior to gelation, stiffness after gelation and solubility in a solvent (for removal) is of great value to zonal isolation. This project report claims to have achieved these characteristics. However, there are inadequate data or scientific concept to support the claims, presumably due to the proprietary nature of the information.

PI Response:

Reviewer 29850

Score: Not scored

Comment: The project produced a gel that appears to be stable to temperature up to 250C for 1000 hrs with a hydraulic conductivity of ~10e-8 cm/s. The gel has a number of hours of working time before setup and appears to be lengthened by shearing. The gel is reversible with the addition of caustic solutions. The gel appear too cheap to make (cents/lb).

PI Response:

Reviewer 23404

Score: Not scored

Comment: the researcher has developed a material which appears to function in the desired manner in the lab. It meets criteria conceptually valid for a temporary plug in a geothermal environment.

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: The SPI gels are mostly water base and are delivered to operating sites as premixed product. It would be nice to if they could mix on the fly at the operation.

PI Response:

Reviewer 23430

Score: Not scored

Comment: Although the sand pack permeability testing is relevant, it does not address the effectiveness of sealing cracks that can be much larger than the gap between the sand particles in the sand pack. The objective is to develop the technology so that it is ready for pilot scale testing.

PI Response:

Reviewer 29850

Score: Not scored

Comment: It would be nice to have more information on expected performance in the field. At present, the testing has been conducted at the bench scale in mostly batch type reactor systems with limited testing in sand packed flow through cells. The project could benefit from a more rigorous testing procedure under relevant field conditions. Not enough information was given to assess the gel formations and performance other than a few statements "unique and new", "interesting results", Investigator lack of dynamic experimental testing as evident with the issues with the seals. The gel formation and breakdown was only conducted in batch tests. It is not clear how the gel breaker will be applied to a gel that was in a formation to allow complete breakdown. The project is expected to run out of money this summer with no commercial path forward.

PI Response:

Reviewer 23404

Score: Not scored

Comment:
1-it is unclear if the material could be placed in a large fracture or void, typical of geothermal environments--this needs to be evaluated and represents a gotcha.

2-it is unclear if the material was evaluated over the range of conditions --heat, stress, chemistries it may encounter during its short expected functional life

3-the answer to the question of removal was to apply a caustic--it is unclear of how that would work, for example, if the plug was in a fracture--presumable the caustic would have access to a small surface area--

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: No apparent improvements that I can recognize.

PI Response:

Reviewer 23430

Comment: The providing of a little bit of scientific concept behind the gel structure and some data on the characteristics and performance of the gel will make the review of this project more feasible.

More effort should be given to results dissemination using written and oral means, with the targeted audience including professionals and the general public.

PI Response:

Reviewer 29850

Comment: The gel product needs to be testing in a more standard dynamic testing apparatus by an independent

A better path forward towards commercialization is necessary

PI Response:

Reviewer 23404

Comment: please see weaknesses--if an industry partner was to become involved in this study it would grow meaningful legs.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Radioisotope Tracers and Fracture Attributes for Enhanced Geothermal Systems
Principal Investigator: Christensen, John
Organization: LBNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 7.0

Comment: The only reason I scored this lower is that it is a new project and it is difficult for the investigators to show results at this review. What they preliminary investigations demonstrated is that it is a method to determine fracture surface area with natural occurring isotopes and tracer.

PI Response:

Reviewer 23414

Score: 5.0

Comment: These folks are just getting started. Otherwise I'd vote higher. They obviously have thought long and hard about the work and appear poised to go forward.

PI Response:

Reviewer 29850

Score: 6.0

Comment: Objective is to quantify the distribution and mobility of radon and the associated uranium-series isotopes through careful characterization of rocks and minerals before, during and after a hydrothermal reactive transport experiment. The experimental results will then be incorporated into a 3 dimensional reactive transport model that will improve our ability to characterize fracture aperture.

If successful, project could measure fracture surface area for the assessment of an EGS system performance. For this to be successful, the EGS fluid residence time would have to be in a window that is appropriate for the ½ life of radon (~15 days according to Hoehn et al, 92). The success would likely require a homogeneous distribution of radon production along the flow pathway.

1. Quality – Project is collaborating with UCB and Univ. of Delaware (although only at 10% of the total funding contribution).

2. Productivity – Project appears to be on track according to milestones. It is unclear what capital equipment is being purchased for this project (~150K in the first year).

PI Response:

Reviewer 23450

Score: 8.0

Comment: This reviewer likes the concept of using different natural occurring tracers with fairly short half-lives to quantify rock surface characteristics. Instead of injecting tracer as a point source in reservoir, this approach conceptually allows characterization of a larger fracture network, independent of well placement and completion. This larger view of the reservoir can provide a much different interpretation than a single injection well tracer test.

The experimental work and procedures are well designed to measure natural occurring radio-isotopes from the rock matrix at elevated temperatures with precise control of P,T, and fluid velocity. The reactor test apparatus is collecting useful information that is verified and validated by numerical modeling. The experimental procedure appears sound and well thought out with the ability to use non-H2O fluid such as carbon dioxide, another proposed EGS working fluid.

The project funding of $491K was spent on capital equipment (test apparatus) and ~1.5 FTE which seems appropriate to the task and national lab cost structures. Work performed to date is in preparation for the next set of measurements.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 8.0

Comment: The technical and scientific approach is sufficient. Using Radon 222 might raise some questions from regulators but I trust LBL for knowing what they are doing.

PI Response:

Reviewer 23414

Score: 10.0

Comment: Nice combination of theoretical and lab work.

PI Response:

Reviewer 29850

Score: 6.0

Comment:
Work has focused on designing the experimental apparatus.

I would also like to see a laboratory task that more closely resembles a fracture geothermal system rather than a porous media system. I am a slightly concern on the effects of velocity distribution in multiple fractures and how this will the uncertainty of the fracture aperture/surface area determinations.

PI Response:

Reviewer 23450

Score: 8.0

Comment: The research and experimental work appears very solid and well designed for the problem. The technical and scientific characterization of short-lived isotopes as a naturally occurring tracer is innovative. However, are concentrations too low and half-life too short for routine use? Are there other gaseous or solid isotopes that can be used in conjunction with 222Rn to interrogate deeper into the fracture system using this approach?

Experimental work is proceeding, research should examine sensitivity to water chemistry, pH, oxidative reductive potential (ORP), temperature, non-condensable gases. Water chemistry and rock/water interactions can be complex.

The use of rocks from known geothermal areas such as Desert Peak (an EGS site) and the Bishop tuff allows testing of this concept at actual sites. I believe there is value in combined experimental, numerical, and field testing to demonstrate and transfer a technology.

The impact of rock heterogeneity and distribution of 222Rn and other isotopes in the geologic media will be better understood with this research.

PI Response:

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: The use of natural occurring desorbing isotopes is unique.

PI Response:

Reviewer 23414

Score: Not scored

Comment: Combining multiple isotopes to interrogate different length/time scales.
Experimental testing to test hypotheses.

PI Response:

Reviewer 29850

Score: Not scored

Comment: Natural tracers such as radon have been used for years as an environmental tracer for groundwater systems.

PI Response:

Reviewer 23450

Score: Not scored

Comment: The conceptual idea of using naturally occurring, short half-life isotopes is very appealing by interrogating a larger fracture network than a single well tracer entered as a point source in a reservoir. Using isotopes with differing half-lives can provide overlap and complimentary data sets for detailed analysis.
Taking the basic experimental measurement is necessary to examine in detail the complex rock and water interactions.
The project team is very well qualified to conduct these experimental measurements and develop methods to interpret field data.

PI Response:

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: The project is a new project and it is difficult to determine if it has any weaknesses.

PI Response:

Reviewer 23414

Score: Not scored

Comment: I worry that the experimental results might end up "core-specific" and that might by necessity narrow the implications of the broader theoretical work. 'Just a thought.

PI Response:

Reviewer 29850

Score: Not scored

Comment: The biggest weakness is the fairly short half-life of the Rn limits this to a number of systems with the correct combination of residence time and production rates. I would like to see a quick look at existing tracer tests in fractured geothermal systems to see which sites would be amenable to this type of analysis. I would also be good to see a plot of the parameter of an EGS system where it would work.

PI Response:

Reviewer 23450

Score: Not scored

Comment: There was a comment that prior work using 222Rn not work, it would have been helpful to follow up on this comment and how the project is designed to address these prior issues.

It would seem that for a larger fracture system with distances of 1000’s m and flow times from the deep reservoir to the production well on the order of hundreds of days, the shorter lived half-life isotopes will have decayed to a low lever by the time of reaching a production well. How does one differentiate the timing and distance of an isotopic particle?

PI Response:

IMPROVEMENTS

Reviewer 23412

Comment: There are no apparent improvements needed at this phase of the project

PI Response:

Reviewer 23414

Comment: Be prepared to say why your core-based results are applicable (or not) to a wider range of rock. But that's down the road.

PI Response:

Reviewer 29850

Comment: See comments in previous sections.

I haven't completely thought this out but you may want to check your preliminary modeling results with the conclusion; one day residence time with conc of 500 and 2 day res time with conc 1050. Would not the decay result is a 2 day res time less than 1000 at steady state?

PI Response:

Reviewer 23450

Comment: Project is in its early stages.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Tagged Nanoparticles for Fluid Flow Monitoring
Principal Investigator: Kemp, Richard
Organization: SNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: This project is tagging fracture stimulation ceramic proppant. The research and testing has shown some setbacks but the researchers are addressing the issues.

PI Response:

The team appreciates the reviewer's note that we are addressing the "trouble issues" on this project. Research and development pathways to implementation essentially never are a straight line, but a series of steps forward and backwards.

Reviewer 23414

Score: 8.0

Comment: Have done a lot of work already in a bunch of areas - nanoparticle synthesis, coating design, etc.
The choice of REE tracers is smart.

Strong industrial linkage.

PI Response:

The team agrees that the link with CARBO is a key feature leading to enhanced chances for success.

Reviewer 29850

Score: 6.0

Comment: Objective was to develop a lanthanide tagged ceramic nanoparticle system that can be loaded into a proppant and used as a tracer to track fluid flow. Researches have prepared 3 of the 4 nanoparticle based systems. Work has focused on constructing the nanoparticle systems. Only a one year project.

If successful, project could measure relative flow rates in individual fractures to allow for assessment of an EGS system performance. Some uncertainty would exist on the distribution of the particles and their relationship to the flow pathways.

1. Quality – Project is working with one of the leaders in ceramic proppants. Project has produced results in loading porous proppants. REE are seen inside the ceramic pore structure.

2. Productivity – Project appears to be on track according to milestones (mostly in proppant loading). Future work includes REE release.

PI Response:

Agree with the comments. RE release and understanding that critical issue more completely as we move forward is an important task for our team.

Reviewer 23450

Score: 9.0

Comment: This project has the distinct advantage of working with a commercial company to tag ceramic proppant with different tracers in a time-release control manner. This research is well suited to created fracture diagnostics using tagged proppant for diagnosis of individual acting and non-acting created hydraulic fractures.
The research has been able to create tagged proppants with a variety of nano-particles, understand the release rate of the nano-particle, and delivery the lab scale samples to Carbo, the commercial partner. Carbo is a leading manufacturer for ceramic proppants. These nano-particles can work in both hydrothermal and hydrocarbon environments, broadening their applicability and market potential, which should reduce commercial costs.
Combined lab and field measurements complement each other very well, with a number of technical hurdles identified and solved. The project budget

PI Response:

We agree that CARBO is an excellent partner for our national laboratory team. While the one-year nature of the project certainly lends a sense of urgency to our work, it may be somewhat too brief to meet all our milestones by the end of the first year. We have already alerted the DOE office that we would like to continue this project forward into the next fiscal year, and will likely ask for some additional funding to help accomplish our goals.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 9.0

Comment: The approach SNL and Carboprop are using is reasonable

PI Response:

The team appreciates the comment.

Reviewer 23414

Score: 6.0

Comment: 'Need to be more explicit about the back-end of what they're actually tracing. I suspect they know it (Their partner certainly knows it) but, beefing up the answer to the "So if it all works out, what do we learn that's new" question.

PI Response:

We are unsure exactly what this statement means - "what they're actually tracing". We plan to follow the RE-tagged nanoparticles to the surface and measure their concentrations at that point by ICP. We plan as well to focus on hydrocarbon-related systems initially due to the short timeline; however, concepts that are studied and (hopefully) understood using hydrocarbons can be applied as well to water-based systems. As indicated by the reviewer, we do understand the larger context and our partner certainly understands anything we do not. We did not focus on communicating this aspect of the project (essentially the motivation behind the effort), as we considered it to be a given to this audience and to the DOE as it directly responds to their stated needs.

Reviewer 29850

Score: 5.0

Comment: Work has focused on loading REE into porous proppants. I would consider this to be the easy part of the problem.

Coating assessment, diffusion of REE from proppant and demonstration of system yet to come. No mention of scale-up issues but assume Carbo has been assessing this issue. No prediction of proppant performance in a field relevant situation. Does the tagged proppant reside in the fast flow pathways? Will enough REE tracer be released to be easily detected at the production well? Will the REE concentration be above background? Will the concentrations be high enough to allow for a quick analysis of the tracers to adjust field operations? Is the porous ceramic strong enough to withstand crushing? Cost?

PI Response:

The reviewer brings up germane points that are being/will be addressed as the project matures. The oral presentation basically covered about 4 months of work. The points that the reviewer brought up are certainly the ones that we are focused on now. Several points on the porous proppant - CARBO has designed these materials and combinations of these materials with dense proppants to handle any crushing issues. This is their principal line of work and they are experts in doing so. Furthermore, similar CARBO materials have been used in the field for controlled release of anti-scalants for example. This effort builds upon that solid technology foundation.

Reviewer 23450

Score: 9.0

Comment: Rare earth doping of ceramic proppant has many useful commercial spin-off outside geothermal industry with the petroleum industry at the forefront of fracture research. Developing a tagged nano-particle proppant is cross-cutting for two industries and can play a role in technology transfer. The SEM of a proppant coated with a nano-particle is very interesting.

I especially like the aggressive time line to technology deployment and commercialization

PI Response:

Again, we appreciate the positive comments. Teaming a national laboratory group with fast-focused industrial company that requires rapid response and action has been educational for the scientists involved!

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: Measuring proppant degradation to determine flow properties is a good idea.

PI Response:

We believe this to be true as well.

Reviewer 23414

Score: Not scored

Comment: synthesis work, industrial partnership

PI Response:

CARBO is an excellent partner with which to work. They have a good mix of complementary skills to the Sandia team, and far more practical experience in the immediate area.

Reviewer 29850

Score: Not scored

Comment: Characterizing flow in fractures has been a challenge. This project begins to address this challenge.

PI Response:

We agree that this is a quite difficult project, and will not be totally solved in a one-year funded project, even with the right team and the right industrial partner - the problem is too big. However, we are encouraged with the initial success of our approach; however, as a review pointed out above, many issues still remain.

Reviewer 23450

Score: Not scored

Comment: Established commercial partner with multiple applications including hydrocarbons with opportunity for technology transfer and rapid commercialization of DOE funded research.

Like short time frame to project completions, shows focus. Several alternative rare earth doping schemes available, shows creative problem solving. Patent filed shows commercial potential and opportunity for technology transfer.

PI Response:

See our responses above to similar review comments. However, we do note that the joint patent was filed by the CARBO patent team, thus validating the reviewer's comments that if we are successful technically there is a real opportunity for technology transfer (certainly, CARBO believes this to be true).

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: This application is more suitable for oil and gas production.

PI Response:

Certainly our initial approaches in a one-year project have to be narrowed down. Our submitted research proposal was initially a three-year project which was downsized to a one-year project. Due to the reduction in timeframe, the focus was narrowed by both DOE-EERE management and the team in order to increase chances for success.

Reviewer 23414

Score: Not scored

Comment: what's the final output?

PI Response:

While the "dream output" would be a commercial product package of proppant/tracer that would function tracking underground fluid flows for a year or more, in this more limited project timeframe our anticipated/probable output would be the production of knowledge and understanding that will prove that our concept of using RE-tagged nanoparticles is valid. This basic information will be used by CARBO and any other interested industrial company for further implementation.

Reviewer 29850

Score: Not scored

Comment: Would like to see more work on the predicted performance of the tagged proppants. Modeling efforts could help identify the key challenges of using such proppants in the field and the key issues in designing such as system.

PI Response:

This is a key feature of the second half of the project year. We agree as well that this is an important and key understanding that is more broadly applicable than to just our system. This may play a strong role if our team asks for additional funding in the next fiscal year, and we appreciate the insight of the reviewer in noting this.

Reviewer 23450

Score: Not scored

Comment: Good project

PI Response:

We agree!

IMPROVEMENTS

Reviewer 23412

Comment: No suggested improvements

PI Response:

Our team appreciates the vote of confidence.

Reviewer 23414

Comment: start thinking about the back end

PI Response:

As noted above, the oral presentation covered only the initial parts of the project - we needed to know whether or not we could make these compounds and put them into proppants. The project focus has moved more towards the back end according to our projected timeline.

Reviewer 29850

Comment: See questions in scientific approach.

PI Response:

Addressed above.

Reviewer 23450

Comment: Good project, nearing completion.

PI Response:

We are less sure of the phrase "nearing completion" as we have many critical technical challenges ahead. As reviewers have noted above, much of the difficult and more ground-breaking work is still to be done, as is the ultimate testing of the completed package in either lab- or test well facilities. This is an extremely difficult project to accomplish everything we would like in one year, and the team anticipates extending into the next fiscal year and hopefully, based on these promising results, obtain some more funding to help us achieve our goals.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Fluid Chemistry and Fracture Growth: What's the Connection?
Principal Investigator: Knauss, Kevin
Organization: LBNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23554

Score: 6.0

Comment: The project proposal points out that this research links the fields of geochemistry and rock mechanics. The results provide unique data to confirmation or at least substantiate Dove's model relating stress and fluid chemistry. The reported results are regrettably behind schedule and the experiments have been limited to one material (glass) and needs to be extended to other media and a wider range of temperatures for eventual application in real-world problems. What has been accomplished is noteworthy but falls short of the intended goals.

PI Response:

Reviewer 29853

Score: 8.0

Comment: Understanding the impact that fluid chemistry has on fracture propagation in subsurface environments is a critical need that will facilitate future development of EGS and hydrocarbon extraction. This particular project represents a straight forward approach to begin to understanding the interplay between fluid chemistry and fracture inception and growth. It appears from the presenters provided information and discussion that they Team has been able to quantitatively establish that (at least in homogenous systems represented by a glass plate) that low TDS water (deionized water) is more effective at initiating fractures. This is likely due to the strong chemical gradient driven by mineral dissolution at the fracture surface. The Team seems to be making reasonable progress on their deliverables although it was not evident how they are doing with respect to budget.

PI Response:

Reviewer 23419

Score: 6.0

Comment: This is a very well defined and focused project to provide experimental data to constrain fracture growth mechanisms under controlled conditions. The materials are appropriate to validate previous theory. The use of hydrothermal atomic force microscopy (HAFM) and vertical scanning interferometry (VSI) to image crack initiation and change is novel. Progress and productivity have been hampered by the loss of staff (the postdoc) intended to perform the work. Additional hurdles include the lack of a jig that fits the HAFM and the small field of view that can be imaged. The investigators have managed to validate the performance of the experimental apparatus to make images and movies of crack propagation. Due to staffing transitions they have not yet tested varying temperature or pH conditions. The project is relevant to GTO goals of understanding fracture in EGS stimulation experiments, but is not likely to be directly applicable to field experiments or EGS injectivity data.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23554

Score: 7.0

Comment: A creative and rigorous approach to providing experimental data to confirm modeled predictions. The project is behind schedule because of staffing shifts and it deserves funding to complete planned phases.

PI Response:

Reviewer 29853

Score: 8.0

Comment: The approach to this research uses the simplest of systems which may or may not have any relevance to the natural system. However, this reviewer recognizes the need to start with a simple system which introduced a minimum number of uncontrollable variables. The approach is generally novel and represents a reasonable approach to quantifying the necessary parameters and forcing functions that control fracture propagation and growth. The presenter spent a good deal of time discussing mining behavior in the experiment, however, it is not clear what the impact of this is or how it can mitigated. Clearly this project will benefit from conducting experiments and model verification on more complex systems where issues such as crystal orientation, preferred bedding planes, and differential hardness can be addressed.

PI Response:

Reviewer 23419

Score: 8.0

Comment: The experimental study is well designed to acquire the data to validate the Dove model. The project leverages existing HAFM equipment. However, the small field of view of HAFM hinders the ability to achieve the objectives as stated. The PI has initiated new collaborations to use VSI in France which will improve the likelihood of success. They have trained new staff to continue the project after the loss of the previous post-doc. The PI clearly understands materials required for future studies of varying pH.

PI Response:

STRENGTHS

Reviewer 23554

Score: Not scored

Comment: A rigorous and creative approach to a tricky experimental problem

PI Response:

Reviewer 29853

Score: Not scored

Comment: This was one of the better projects presented in the session. This is an area that is in critical need of significant advancements in our understanding of how fractures propagate under induced stress regimes not only in the geothermal field, but in the overall field of subsurface science. The presentation had very nice images that did an outstanding job of illustrating the main points of the research. The experimental approach is reasonable and sound. By choosing to conduct experiments in such a way that there are minimal uncontrolled variables, the project stands a reasonable chance of accomplishing their objectives. Another strength that was presented was the phased approach, whereby they will qualify more homogeneous systems first and moving onto more complex systems in later phases. The team does a good job of using advanced imaging to monitor their experiments. A particular strength of this project is the use of the Hydrothermal Atomic Force Microscope and the Vertical Scanning Interferometer. The resulting images elucidated well the interplay of stress, temperature and to a lesser degree the chemistry on how a crack propagates in a homogeneous media. The team encountered some difficulties during the study, but they showed good adaptability in dealing with this unplanned issues and were able to move the project forward. The team has made good progress and seems imminently capable of meeting all of their objectives.

PI Response:

Reviewer 23419

Score: Not scored

Comment: The project has well defined goals and objectives. The experimental methodology is appropriate and new equipment has been completed to allow imaging of crack propagation. The PI has a thorough understanding of the theoretical background and approaches to quantitatively measure crack propagation, and the influence of temperature and chemistry on growth.

PI Response:

Reviewer

Score: Not scored

Comment: test

PI Response:

WEAKNESSES

Reviewer 23554

Score: Not scored

Comment: Limited to one material medium and behind on additional confirmation experiments.

PI Response:

Reviewer 29853

Score: Not scored

Comment: Although the Team has made progress in conducting their study, based on the presentation it appears that some ground needs to be made up. The presenter did a reasonable job of explaining they projects reliance on a simple glass model for conducting their experiments. It was not until the review panel pressed him that he discusses moving the experiments into more complex heterogeneous media where things like grain boundaries and mineralogical heterogeneities will impact fracture growth and stress accommodation. One of the major weaknesses of this particular project is the lack of diversity in the Team members. Consistently the best projects presented at the review were those that had multiple institutions involved.

PI Response:

Reviewer 23419

Score: Not scored

Comment: The experimental results may have only limited application to fracture propagation in real systems with oriented crystals in minerals rather than amorphous glass.

PI Response:

IMPROVEMENTS

Reviewer 23554

Comment: Follow plans to test additional materials and possibly real rocks.

Continue efforts to extend experimental temperature range.

PI Response:

Reviewer 29853

Comment: The project model relies on measuring the growth and rate of growth of fractures under controlled systems, yet the team seems to struggle with actually measuring the speed of the fracture growth. The ability to measure the speed at which a fracture grows would be of great benefit to the experiments and would significantly aid in the DOVE model the results. Generally the project could be improved by making more overall progress. This particular issue seems to be self-fixing in that the new Postdoc is on board and is trained to conduct the experiments. While this review recognizes the need to work on simple systems first to understand how to conduct the experiments and model them. The project has limited application at this phase, moving into a more heterogeneous system would be a huge aid in making the project more applicable to the general needs of the community.

PI Response:

Reviewer 23419

Comment: The PI has a good handle on ways forward to make progress. They have identified a new staffing plan and have trained a new post doc to work on the project. They have identified potential future collaborations and additional imaging systems in France. No additional recommendations.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Temporary Sealer Materials
Principal Investigator: Sugama, Toshi
Organization: BNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: The use of reversible specialized cement for zonal isolation, loss circulation during drilling and operating a geothermal operation is a necessity. BNL has shown very good results and accomplishments.

PI Response:

Your comment and project support is appreciated.

Reviewer 23430

Score: 8.0

Comment: This project is aimed at using a developed temporary cementitious lost-circulation control sealing material to improve the sealer self-degradation, to design a set-controllable formula for operation at 85 C, to evaluate the solubility of the degraded cement in less- or non-corrosive acids at 90 C and more than 70 wt.% dissolution, to evaluate the mechanical properties of the sealer before the self-degradation, to develop plugging technology with the use of self-degradable fibers, and to transfer the technology to the geothermal industry. If successful, the project will reduce the total costs of sealing and drilling operations. Due to the slag and fly ash used in the mix design, the use of this cementitous material in place of Portland cement will mitigate the environmental impact of Portland cement. The report is detailed about the formulation, science and performance data, thereby providing adequate support for the claimed abilities of the developed cementitious material. The progress is excellent.

PI Response:

Thank you for your comments and support for expediting our project's progress.

Reviewer 29850

Score: 7.0

Comment: Objective was to improve sealer self-degration down to 0.5 to 5 mm fragments, 85C, solubility with acid, test mechanical properties, and transfer technology to industry. The project is ~ ¾ finished for a 2 yr project.

If successful, project could help reduce drilling cost due to lost circulation with the ability to degrade the cement with acid at a later time.

1. Quality – The project is focusing on develop a cementatious material that is pumpable, and withstand high temperatures, and is mostly reversible. These are all qualities of cement needed for GTO. Project work appears to be on track. Researcher appears to be well qualified.

2. Productivity – The project has produced a product that appears to ready for continue testing.

PI Response:

Thank you for expressing strong support for this project.

Reviewer 23404

Score: 8.0

Comment: the work described in the write up and presentation are a combination of a being high quality and high productivity effort. These researchers have completed a great deal of laboratory work. The work appeared to be systematic and focused on the needs of downhole deployment and functions of a cementitious material that was reversible (it could be removed be thermal degradation). if successful in all of the goals developed, this could prove to be valuable technology--as discussed later, deployment in a well at geothermal conditions needs to be demonstrated--if it was necessary to pull out of the hole that would add--perhaps significant cost.

PI Response:

As described by reviewer, there is no doubt that a field demonstration and validation test will be required to ensure that developed cement adequately plugs and self-degrades in real wellbore fractures. However, prior to field testing, we have a plan to conduct scale-up in-house demonstration work using an upgraded high-pressure and -temperature slot apparatus, which allows us to carry out an entire engineering operation process throughout from initial plugging and self - degradation to dissolution in this apparatus.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23412

Score: 9.0

Comment: The scientific and technical approach is adequate

PI Response:

Thank you for your comments.

Reviewer 23430

Score: 8.0

Comment: The approach involves cement mix design for achieving the combination of abilities described in the objective. The concepts behind the mix design are sound. The approach has been executed with adequate rigor. The work elements, procedures and methods, instrumentation, equipment and staffing are all adequate for achieving the project's objectives with the available resources. The results dissemination is adequate.

PI Response:

Thank you for your comments.

Reviewer 29850

Score: 6.0

Comment: Work has focused on laboratory testing of the cement product. The researcher has developed a fracture aperture testing apparatus to test the plugging. Degradation work suggests that cement will dissolve into 5 mm particle. Slight concern on the fate and transport of these particles in the subsurface.

PI Response:

Some cement particles of 5 mm size were present at volumetric fraction of ~10 % in a whole self-degraded sealer before their acid dissolution. After acid treatment, 88 wt% of degraded cement was dissolved, and also these coarse particles were converted into 2.5 mm size at a less than 5 % in non-dissolved remnants.

Reviewer 23404

Score: 8.0

Comment: The approach is systematic, many parameters are included--chemical-thermal-fluid are operative and complex in the way they interact over time. The researchers appear to have a solid grasp on many if not all of these factors. In terms of communication of the material a deformation map would have been useful indicating how the different parameters were linked together.

PI Response:

Thank you for suggesting that we address physicochemical factors promoting the self-degradation of cement to better understand its deformation mechanisms. Certainly, we will try to find as many parameters from our limited data collected over the past three years, leading to the modeling study of self-degradation cement systems.

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: Cement materials are readily available.
Product is delivered to operation location and mixed and pumped.

PI Response:

To do so, our effort to transfer this technology to geothermal industries is ongoing.

Reviewer 23430

Score: Not scored

Comment: The project objectives have largely been met. The work is rigorous and detailed, involving material development and testing that is substantial in scope.

PI Response:

Your comments are appreciated.

Reviewer 29850

Score: Not scored

Comment: Researcher appears well qualified for cement research.

PI Response:

Thank you.

Reviewer 23404

Score: Not scored

Comment: the strengths of this project include:
1-the product is a cement and cements are common items in the well construction industry.---this is a big plus--the same type of deployment equipment as that used within the industry perhaps could be deployed.
2-the researchers have attempted to include many of the environmental parameters they consider important into the set of experimentals they developed.

PI Response:

Thank you for your comments. Clearly, one inevitable factor for developing wellbore cements is to be environmentally green and friendly materials.

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: There are no apparent weaknesses

PI Response:

Thanks.

Reviewer 23430

Score: Not scored

Comment: Data to support the long-term absence of degradation at 85 C are needed. The difference between the previously developed temporary cementitious lost-circulation control sealing material and the cementitious material developed in this project is not clear enough. The goal of transferring the technology to the industry has not been met.

PI Response:

The reviewer comment is right. We have never investigated the long-term integrity and liability of this temporary cement at 85C, nor described the differences between our previously developed temporary cement and this newly developed cement in this presentation. Work to respond to these comments will be conducted in the future project.

Reviewer 29850

Score: Not scored

Comment: The project is upgrading the fracture aperture testing apparatus to higher temperatures. Could benefit from a larger scale testing system that the bench scale system being currently used.

Industrial partner was not identified. I expect this project will have issues moving to the field without one.

PI Response:

The bench scale slot apparatus being currently used is needed to be upgraded for performing scale-up in-house demonstration to ensure that developed temporary cement can duplicate the same results in upgraded slot apparatus, which is capable of conducting a whole engineering processes from plugging and self-degrading to dissolving. If this demonstration is succeeded, the reliability of this technology will be proved by industrial partners for potential field testing.

Reviewer 23404

Score: Not scored

Comment: 1-this work was extremely complicated in the number of parameters studied--many of which were interdependent. It would be extremely helpful if the researchers could develop a matrix or a set of matrices to show what they were doing-- at time it was unclear.
2-technically placing cement in large fractures or voids may not? Have been demonstrated?--it should be done to prove that this technology would work--this condition represents the big problem in some geothermal wells.
3-it would be good if the researchers could trace the potential life cycle (temperature, pressure, fluid chemistry) of a void/fracture they seek to temporarily plug to verify that they the material would perform to their specifications when it was supposed to at each step in the life.
4-unsure if these folks have an industry partner

PI Response:

Regarding comment 1, we plan to upgrade the current slot apparatus. The upgraded apparatus will be designed to have capability for an entire operation process, plugging →self-degrading →dissolution, at different temperatures, pressures, and slot sizes.

Regarding comment 2, using self-degradable PVA fiber of 0.76 in. length, our technology can plug the slots up to 0.5 square inches. Work to develop the plugging technology for more than one square inches is currently being undertaken.

Regarding comment 3 and relating to comment 1, if we can design such apparatus, it is possible to conduct life-cycle study of temporary cement under different temperature, pressure, and slot size conditions.

Regarding comment 4, such a singular material system is currently not commercially available, nor are there scientific and engineering literatures relating to this unique system. Thus, a success scale-up in-house demonstration by using upgraded slot apparatus described above will aid in facilitating our collaboration with industrial partners.

IMPROVEMENTS

Reviewer 23412

Comment: Improvements would be to consider involving cement pumping service companies.

PI Response:

We agree with reviewer's comment. If ≥one inch long fiber as temporary bridging additive is adapted to seal large-size fractures, the blending and pumping devices for fiber-rich cement slurries would play an important role in placing cement in the fractures without any downhole transporting problems.

Reviewer 23430

Comment: Optimization of the mix design and complete determination of the basic mechanical, durability and other properties of the resulting cementitious material are needed prior to technology transfer. Communication of some of the research results to the general public is recommended.

PI Response:

In an effort to expediting any technology transfer to industrial partners, we will optimize the formula and complete the physicochemical characterizations of the optimized formula. All information obtained will be forwarded to National Geothermal Data System (NGDS), and published in DOE Office of Scientific and Technical Information (OSTI) and journal articles.

Reviewer 29850

Comment: See weaknesses. The researcher has developed a fracture aperture testing apparatus to test the plugging. I would like to see this apparatus also used in other sealer projects to provide consistency of product results to the GTO.

PI Response:

Certainly, this apparatus was designed based upon API standard on lost-circulation controlling slot testing, so that it can be applied to the other sealer projects.

Reviewer 23404

Comment: the work would greatly be enhanced by developing a "matrix of understanding" of all of the relevant parameters so that a reviewer could better and more easily understand what was done, how it was done, etc.

Also--it is not clear if an industry partner is on board.

Also, it is not clear if this material could be deployed though the drill string??? If not--having to trip in and out could be a deterrent to use

PI Response:

We will develop such matrix providing a better understanding of mutual relations between all relevant parameters. Prior to transfer this new temporary cement-based lost-circulation controlling technology to private sectors, the scale-up in-house demonstration at BNL will be required using an upgraded high-pressure and –temperature slot apparatus to ensure that this technology can duplicate all results of bench-top R&D works being conducted thus far. This material will be applied to the pre-existing fractures in wellbore formation in order to solve lost-circulation problems of drilling-mud during the drilling operation.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006764
Project: A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation
Principal Investigator: Tester, Jefferson
Organization: Cornell University
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23412

Score: 8.0

Comment: This project uses a very well characterized field/demonstration site to test reactive tracers.
The measured and simulated data agree when determining fracture aperture.
The use of reactive tracers to determine the aperture is the next experiment.

PI Response:

We appreciate the positive comments and are looking forward to this summer's field work

Reviewer 23414

Score: 9.0

Comment: these folks are doing an outstanding job - field testing, nanoparticle synthesis, reactive-transport analysis, reactive vs. non-reactive tracers, and so on. It’s easy to have confidence that these folks are going to provide GTO with a very useful product.

PI Response:

We appreciate the positive comments.

Reviewer 29850

Score: 7.0

Comment: Objectives of the project are to develop an inversion algorithm, a methodology to select tracers, field validation at a pilot scale, full field validation. Project is using a combination of conservative, sorbing, and reactive tracers. The tracers could be used to assess the performance of hydrogeothermal systems and EGS operations.

1. Quality – The project is a combination of pilot field scale experiments on the order of 10m x 10m and numerical studies. The field site has been characterized under previous work (mostly drilling and GPR) and has a series of shallow wells in a general 5 spot pattern. The field site also has a number of DTS sensor rods mostly located in the SW corner. Quality of the GPR and wells was not provided in the limited information provided for the review. The model will use

PCA techniques and generic algorithms. The project is less than 6 months old and not enough data (or progress) was provided to assess this technique. Preliminary data could suggest progress but more work needs to be done.

2. Productivity – Project is basically on track. It may be slightly behind but I expect it to gain momentum and perform well.

PI Response:

We appreciatate the reviewer's thoughtful comments. We concur that we are at an early stage of the project. We have documented the reproducibility of the GPR measurements. While we are convinced that the GPR measurements are sufficiently precise, the interpretation of the data and its translation into an aperture distribution does have inherent uncertainty that we intend to quantify in the upcoming field work.

Reviewer 23450

Score: 2.0

Comment: The proposed field work is stated to "provide much needed evidence supporting inferences made from computational modeling of thermally reactive tracers." (Peer Review Summary).
Altona has been the site of a decade of research and characterization; several questions arise about the integrity of the site and associated analysis:

- How much disturbance has then been to the in-situ fracture properties with the repeated testing with different temperature water, pressure cycling, reactive and non-reactive and well vandalism?
- Is the fracture aperture measured using ground penetrating radar repeatable?
- Answers indicated that it is unknown if the in-situ measured properties are unchanged, though repeated tracer testing does provide repeatability. The fracture aperture has not been re-measured using ground penetrating radar; this may be worthwhile to confirm the aperture distribution and repeatability of the GPR method.
- How scalable or transferable are the results at 2 meter well spacing at Altona to well spacing on the order of hundreds of meters in commercial settings?

The main focus is series of modeling exercises to use conservative and reactive tracers to characterize the presented matches of the observed data were fair to good. The concern is the lack of uniqueness on such a small spatial scale (2 m) and the acknowledged, high parametric sensitivity to non-unique matches. In other words, can the measured tracer data in a field setting with well spacing on the 2 to 3 orders of magnitude greater than the study site, can tracer date in a field or EGS context contain sufficient temporal and spatial resolution to reduce the degrees of uncertainty in the analysis?

Given the stated goal, it is unclear if this has been achieved. The total project funding of $528k has supported some field testing and a lot of modeling

PI Response:

1. Reservoir Disturbance -- To address the concern raised by the reviewer of reservoir disturbance by vandalism to the fiber optic network at the site, all damages were repaired. No further vandalism of the site has occurred since this incident three years ago. Any residual tracer left within the formation is rapidly flushed from the system within a day due to a presense of a background hydraulic gradient. The pressure cycling experiments will be repeated in August of 2015. Any significant changes in the reservoir are expected to result in deviations in the observed pressure cycling results.
2. Repeatabilty of the GPR measurements -- GPR measurements were repeated multiple times during the original experiments in 2011 and the observed reproducibility of the signals was good. Repeating the GPR measurements at this

time is complicated because a fiber-optic (FO) network now exists throughout the site. Since the FO network contains large amounts of stainless steel, radar measurments may be significantly influenced.
3 Scalability of results -- The well separations we are investigating at Altona are 14 meters, not 2 meters as the reviewer indicates. The issue of scalability is being addressed throughout the experimental and modeling program. As we will be conducting additional experiments at two more field sites - one in the Hubbard Brook Experimental Forest in New Hampshire where the well separations are ~35 meters and another whose location is to be determined. The location of the third site will be determined with help from AltaRock, our collaborating partner, who has agreed to assist us in identifying a high temperature geothermal reservoir suitable for full-scale testing. In addtion, given the range of fracture openings from full closure to less than a mm up to about 5 mm, we expect that 14 m of well separation having a length scale to aperture ratio of over 1000 to 1 will more than adequately sample aperture distributions that would be encountered in discretely fractured, EGS reservoirs with much larger injection to production well separations of 100 to 1000 m.
4. Funding and current achievements -- We are at the very beginning of this 3 year project. Before beginning the project, we have funded our modeling and experimental work using other funds. In the current project, funds have only been used to provide 1 semester of Graduate Research Assistant support to develop the modeling capabilities specifically for the Altona experiments. Little funding has been spent on field work so far, because the bulk of the field work has not yet occurred. The next phase of field studies is being carried out during the summer of 2015.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23412</u>

Score: 8.0

Comment: The scientific approach is adequate using the test site

PI Response:

We acknowledge the reviewer's comment.

<u>Reviewer 23414</u>

Score: 10.0

Comment: all good

PI Response:

We gratefully acknowledge the reviewer's postive reaction to our work.

<u>Reviewer 29850</u>

Score: 6.0

Comment: Work has focused on initial model development and assessment of previously collected data at the pilot scale field site. Preliminary model results show progress. The field site appears promising for the previous data interpretation with a single horizontal crack at approximately 8 m depth. It appears the project will rely on GPR inferred fracture aperture where one would expect a preferential flow pathway from the center to the SW or SE. Despite the existing boreholes and DTS well, there is limited monitoring at the site that could prove to be an issue for validating the modeling/tracer results. Mass balance at the field site could also prove to be an issue.

PI Response:

It is not clear that the reviewer understands that we are at a very early stage of this DOE-funded project. It is also unclear to us why he/she apparently does not consider our monitoring of hydraulic head and water temperature changes in five wells in addition to recording temperature in over 1,000 locations throughout the well field as sufficently robust to reach conclusions and validate scientific observations. If the reviewer's concern regarding mass balance refers to our ability to capture sufficient tracer at the production well then this is not well founded. Mass balance closure of recovered tracer has not been an issue for the vast majority of field experiments that we have conducted at Altona.

Reviewer 23450

Score: 2.0

Comment: Lots of rehash of prior efforts in thermally reactive tracers, what is new or novel in this effort? Literature review was rather weak on this. There seems to be a great deal of modeling and adjustment of parameters to achieve a non-unique match of tracer responses. It is not clear from the presented materials how this will be translated into a robust process to characterize fracture aperture distributions at well spacing 2 to 3 orders of magnitude greater spacing than Altona.
The field testing and modeling activities have been to characterize a site that over the last 10 years has been extensively characterized by GPR, caliper logs, gamma logs, formation electrical conductivity logs, slug tests, pump tests, tracer testing, and heat exchange experiments. The measured aperture field comparison with the genetic algorithm (p 7, presentation) and the comparison of the measured and GA dimensionless drawdown vs. time shows the error increasing with time, at 200 days the error is ~2.1%. It would be helpful for to know what the key sensitivity are to which parameters and what can be done to improve model robustness.
Modeling has many uses; modeling for modeling’s sake seems a waste of limited taxpayer resources. The total project funding is estimated at about 2 FTE and support ($528K from presentation materials); it is recommended that the balance of the project funds be allocated to other fracture characterization projects showing greater results.

PI Response:

Since our group has over 30 years of experience in using and modeling tracers for geothermal reservoir characterization, we are not sure what literature review is being referred to here. Is it from the proposal, from previously presented and published papers or from our annual report? The novelty of our effort in this specific project is centered around our ability to evaluate the performance of thermally reactive tracers in a field environment with a well characterized fracture. Past efforts to characterize fracture aperture distributions by other research groups have been largely limited to small lab scale experiments (<~1 meter). Our experiments are conducted between wells spaced 14 meters apart. All of our modeling predictions are compared to observed field experiments. In addtion, a large portion of our modeling work involving PCA and genetic algorithms is completely new. As a result of our experimental work in this well-characterized setting, we feel that quantification of our modeling approaches can be achieved with both charactrerization and understanding of inherent uncertainties.

Our modeling techniques will first be evaluated at the Altona Field Laboratory and then further evaluated in wells spaced 35 meters apart and finally at a high-temperature field site. Therefore, issues of scalability will be directly addressed in the coming years.

We consider an error of 2.1% sufficiently adequate to predict thermal performance. The small deviation is a product of this example's focus on fitting early tracer breakthrough results. Increasing the focus of the inversion algorithm on later tracer breakthrough would effect late time thermal breakthrough prediction accuracy.

The reviewer implies that we are "modeling for modeling sake." We disagree with this statement, because the purpose of our project is to prove the ability of our modeling approaches in highly constrained field experiments. The point is that we can show whether or not our innovative modeling approaches and predictions adequately capture the results of real field experiments and these are complemented by geophyscial techniques.

STRENGTHS

Reviewer 23412

Score: Not scored

Comment: The test site is very well characterized

PI Response:

no comment

Reviewer 23414

Score: Not scored

Comment: All of it.

PI Response:

no comment

Reviewer 29850

Score: Not scored

Comment: Despite some of the limitation of the field testing site, the monitoring data is better controlled than at a commercial field site. The PCA/GA modeling approach is interesting and I am looking forward to more results.

PI Response:

We appreciate that the reviewer recognizes this important aspect of our field work.

Reviewer 23450

Score: Not scored

Comment: The experimental and modeling methodology is sound.

PI Response:

no comment

WEAKNESSES

Reviewer 23412

Score: Not scored

Comment: No apparent weaknesses

PI Response:

no comment

Reviewer 23414

Score: Not scored

Comment: I was a little confused about the choice of functional groups on the nanoparticles, but that's probably just me.

PI Response:

We would be happy to provide detailed information on the design, selection and synthesis of the nanoparticle we are using.

Reviewer 29850

Score: Not scored

Comment: Would like to see some additional monitoring at the field site. Perhaps some additional slim hole sampling wells could help constrain the tracer field data. These well could also be used to assess the GPR inferred fracture apertures.

Unclear if the analysis method will be able to assess the number of fractures, the spacing of fractures and the orientation of fractures. The tracer results will only provide residence time, surface area and detection.

PI Response:

We already have 5 groundwater wells and 10 temperature monitoring wells within a 10 x 10 meter area. Considering the cost of drilling wells in this very hard rock and remote location would be considerably expensive, drilling additional wells is not practically feasible in this project. The cost to benefit ratio is too low in our view given the limited additional information they would provide. However, we have considered coring into the formation enable to obtain a detailed lithologic section as well as competent samples from the fracture surface.

Reviewer 23450

Score: Not scored

Comment: The project has not achieved the stated goal of provide much needed evidence supporting inferences made from computational modeling of thermally reactive tracers. This goal is rather nebulous and the results are consistent to this end.

The project has spent a great deal of effort to model fracture aperture distribution at 2 m well spacing, with acknowledged difficulties with parameter sensitivity and non-uniqueness. No action plan is presented to address this major short coming.

Then there is the potential issue of disturbance of the previously measured fracture aperture distribution at Altona and the lack of demonstrated repeatability of the initial results.

PI Response:

Our stated goal has not been achieved yet, because we have not completed our fieldwork and analysis yet as we are at the beginning of this 3-year project. The well spacing is not 2 meters - it is generally 14 meters and the minimum is 7 meters.

Our action plan to address the inherent concern of non-uniqueness is to establish probability distributions for our fracture aperture profile predictions. This essentially means that we obtain a "family" of reservoir models that all fit the data sufficiently well to predict thermal performance. The statistical distribution of our thermal breakthrough predictions quantitatively addresses the issue of non-uniqueness.

As previously discussed, the potential issue of disturbance is frequently addressed as repeat tracer experiments and periodidc pressure tests are conducted. Repeating GPR measurements at this time cannot be readily conducted as the presence of the fiber-optic network will introduce disturbances to the radar signal due to the presence of the fiber's metal casing. In addition, the existence of a dammed reservoir located about 50 meters to the west of the site and a groundwater seep about 50 meters east produces a fairly constant hydraulic gradient throughout the site. This consistent hydraulic background gradient has yielded adequately repeateable tracer results year after year.

IMPROVEMENTS

Reviewer 23412

Comment: There are no apparent improvements needed

PI Response:

no comment

Reviewer 23414

Comment: None

PI Response:

no comment

Reviewer 29850

Comment: One improvement would be to complement this pilot scale field test to a large scale laboratory experiment that is better characterized and controlled. Not convinced that the Cdots can be used in most field situations where dilution of the tracer will be an issue. Also would like to know more on the protocol on selecting tracers, not clear how tracers can be chosen without some prior results of reservoir temperature, flow pathways and residence time.

PI Response:

Given the positive results we have achieved so far at this field laboratory we do not feel that a bench-scale experiment which would reduce the spatial scale by more than an order of magnitude would provide any additional useful information. If the results of our field experiments were not encouraging, then we could consider scaling down to laboratory experiments.

C-dots have a detection limit of 10 parts per billion which should be sufficient for most practical EGS reservoirs. For example, tracer experiments conducted at the Soultz-sous-Forets EGS site in France produced tracer returns at concentrations of 100 parts per billion after 150 days when injecting 150 kg of fluorescein.

Reviewer 23450

Comment: Transfer unallocated funds to other projects.

PI Response:

This comment is completely unjustified.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Geothermometry Mapping of Deep Hydrothermal Reservoirs in Southeastern Idaho
Principal Investigator: Conrad, Mark, Mattson, Earl
Organization: LBNL/INL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 24896

Score: 8.0

Comment: This project clearly addresses relevant goals for hydrothermal resource evaluation and confirmation. Timely identification and vetting of hydrothermal resources with significant economic potential is critical for attaining DOE goals of increased utilization of geothermal production capacity. Given that identified but undeveloped reserves (or perhaps even those in underdeveloped systems) are not likely to be sufficient to meet program goals, exploration methodologies that permit screening of potential plays such as this are important. This is especially true of this study as it incorporates and evaluates the usefulness of legacy data for such screening. Interpretation of legacy chemical analyses incurs significantly less cost than field programs and new chemical analyses.

It appears that the PI's have made excellent progress in the stages of this project to date. The preliminary results of both the equilibrium geothermometry and the isotope components of this study suggest that the chemical analyses and their interpretations are of high quality. Based on comparison of project milestones and results to date, it appears that the project is on track to meet its goals. The goal of a thermal map of the Snake River Plain by Fall, 2015 may be a bit ambitious if it is to incorporate results from work this summer.

PI Response:

We are collecting the last samples now to fill out some sparse areas of the map in the northern area of the SRP. Due to the late funding in FY15 we may ask for a no-cost extension to complete the report.

Reviewer 23419

Score: 7.0

Comment: The project focusses on geothermometry using new techniques and identifies several key issues to be addressed. 70 new samples have been collected and temperatures derived from the RTEst model have been compared between new and old samples. There is general agreement between the RTEst model and that using SO4 as a geothermometer. Isotopes of oxygen and methane appear correlated with high temperature systems. The results will be integrated with the Snake River Plain Play Fairway activity. One goal is to more rapidly analyze well and spring samples using isotopes - but it was never stated what level of improvement in analysis time was achieved.

PI Response:

The gains in isotope sampling versus earlier work is that we now have techniques that are both more sensitive (allowing analyses of samples with lower concentrations) and more automated (improved prep systems have significantly reduced the time necessary for many of the analyses we are doing). This means we can and have analyzed a significant number of samples at concentrations lower than previously possible without collecting and processing very large samples.

Reviewer 23549

Score: 9.0

Comment: The potential impact is very high; geochemical prospecting can be a relatively inexpensive way to explore for resources and this project explicitly will use the geochemical data to calculate reservoir temperatures. Furthermore, this project is one component of a more comprehensive, integrated investigation of geothermal potential in the Snake River Plain. The project has compiled a wide array of data and done critical comparisons to evaluate utility of various data sources and types.

PI Response:

Reviewer 25423

Score: 10.0

Comment: The potential for positive impact is very high with respect to reducing the risk and cost of geothermal exploration. The PI's have been productive; they have completed some high quality technical work and produced important results, the highlights of which include: 1) collected and analyzed a large number of water samples (>70); 2) calculated reservoir temperatures using different methods, and compared the quality and agreement of these calculations; and, perhaps most importantly, 3) determined that it is likely that historical chemical analysis are fairly useful for initial assessment of geothermal reservoir temperatures. I assigned a high score to the project because of the productivity and potential impact.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 24896

Score: 8.0

Comment: The multi-tool approach proposed by the PI's is to be lauded and has the potential to provide significant improvement in reliability of chemical thermometry. The multicomponent equilibrium geothermometry proposed here is a modification of established geochemical methodologies that have proved effective for understanding the origin of water compositions that have not undergone extensive mixing, dilution, or degassing. Water compositions that have experienced significant modification through these processes can generate erroneous results, although the PI's are being very conservative in interpreting these results by assuming generous error bars. Perhaps the combination of hydrogen and oxygen isotopic studies can mitigate the uncertainties associated with this problem. The methodology for implementing multicomponent equilibrium modeling in this study is a bit unconventional (see my comments under improvements) and could be modified to improve reliability of the results and perhaps even gain additional information from the calculations. The oxygen and hydrogen isotopic results presented by the PI's suggest that most of their waters are meteoric waters that have experienced relatively little water-rock interaction. This is to be expected in the Snake River Plain, where the shallow aquifer is certainly a major source of fluid. The isotopic analyses have yielded a number of intriguing results, especially the hydrogen and oxygen results considered in temperature space and the methane results.

PI Response:

Reviewer 23419

Score: 5.0

Comment: The project seeks to test ability to derive geothermometry using new samples and new isotopic techniques and validate these approaches against established geothermometers. The approach includes validation of these new techniques but the project summary and presentation provide little information on how these new techniques work, making it difficult to assess the soundness of the methodology. It is not apparent that the new methods achieve significant time savings in geothermometer determinations, or that the methods will be widely adopted. When questioned during peer review the PI and team could not clearly articulate how the model worked, other than to say we should have visited the poster presentation the previous evening. Historically, geothermometers contribute a range of temperatures, many of which are not good predictors of actual reservoir temperature. During Q&A it was stated they have validated the RTEst model against known temperatures but this was not evident from the review materials provided and it would have been helpful to show that model validation step.

PI Response:

The approach(es) of multicomponent geothermometric technique (RTEst) was developed and validated by a series of works previously (carried out as a separate project). The current project was related to application of this tool. Furthermore, space to present in depth background on how these complex analyses work was not available under the prescribed format for the review presentations. Reviewers are directed to:

Improved Geothermometry through Multivariate Reaction-path Modeling and Evaluation of Geomicrobiological Influences on Geochemical Temperature Indicators: Final Report, INL/EXT-14-33959.

Neupane, G., E.D. Mattson, T.L. McLing, C.D. Palmer, R.W. Smith, T.R. Wood, and R.K. Podgorney, "Geothermal Reservoir Temperatures in Southeastern Idaho using Multicomponent Geothermometry", World Geothermal Congress 2015, Melbourne, Australia, 19-25, April 2015.

Palmer, C.D., Ohly, S.R., Smith, R.W., Neupane, G., McLing, T., Mattson, E., 2014. "Mineral Selection for Multicomponent Equilibrium Geothermometry", 2014 Geothermal Resources Council Transactions, Vol. 38, p 453-459, 2014.

Neupane, G., J.S. Baum, E.D. Mattson, G.L. Mines, C.D. Palmer, R.W. Smith, "Validation of Multicomponent Equilibrium Geothermometry at Four Geothermal Power Plants", proceedings of the Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 26-28, 2015.

Reviewer 23549

Score: 10.0

Comment: The approach being employed is very strong. They have compiled existing data from both wells and springs and assessed these data asking all the right questions: how many samples are needed? Where are the data gaps? Are well data and spring data equally useful? Are legacy data good enough to use? In addition they have compiled a very wide range of data types to assess which are most useful. The use of RTEst to calculate reservoir temperatures seems appropriate although not really documented in the presentation.

PI Response:

We agree on the documentation of RTEst (because it was dealt previously with a separate project), see references listed above

Reviewer 25423

Score: 5.0

Comment: The technical approach is rigorous and of good quality, and employs modern quantitative geochemical methods. Execution of the plan and timely completion of the tasks has been exemplary. However, several weaknesses need to be addressed as discussed in the following sections. These issues are what motivated me to assign a modest score for this category.

PI Response:

STRENGTHS

Reviewer 24896

Score: Not scored

Comment: The strength of this project lies in the application and combination of two appropriate, well-tested approaches to address the problem of early geothermal resource identification. Isotopic analyses of select systems can provide both an independent means of estimating reservoir temperature and aid in the interpretation of subsurface processes influencing water composition. For fluids that have not experienced significant compositional modification due to dilution, mixing, or devolatilization, inverse thermodynamic modeling of the vein used in this study can provide reasonably accurate estimates of reservoir temperatures.

The incorporation and evaluation of legacy data is an important component of this study. While there is not a lot of legacy isotopic data available for most areas, systematic geochemical surveying of water resources in many areas affords an excellent starting point for applying the results and methodologies of this study to other areas. This could lead to application of these methods even in the absence of funding for extensive geochemical sampling and analysis.

Another considerable strength of this project is the collaborations that the PI's have developed with geographically related projects. The combination of this study and the He isotope study by Dobson and colleagues is producing some interesting synergistic results.

PI Response:

Reviewer 23419

Score: Not scored

Comment: Results will be integrated into Utah States SRP Play Fairway project. Results are generally consistent across SRP (within +_30C)

PI Response:

Reviewer 23549

Score: Not scored

Comment: See above under approach. Another strength is the strong collaborative effort and sharing of samples, which will result in wide analytical yield for those samples that are collected. These results will be integrated with other geochemical tracer studies and a broader Play Fairway analysis of the SRP. Although the emphasis is on calculated temperatures from their in-house, multi-component geothermometer, they are attempting comparisons with others, such as the sulfate thermometer. The comparisons between spring data and well data, on the one hand, and RTEst calculations using newly acquired and older data are convincing. These are important results.

PI Response:

Reviewer 25423

Score: Not scored

Comment: This project possesses many strengths. The collaboration among Berkeley National Lab, Idaho National Lab, and the University of Idaho is an important strength of this project. An important scientific strength is the use of stable isotopes of water and dissolved methane to evaluate processes and environments of formation. Collaboration with another AOP project (WBS# 3.1.2.5 - Use of He Isotopes for Geothermal Resource Identification in the Cascades and Snake River Plain) provides important synergies.

PI Response:

WEAKNESSES

Reviewer 24896

Score: Not scored

Comment: The principle weaknesses of this project lie in uncertainties surrounding the mineral assemblages involved in the multicomponent equilibrium geothermometry calculations. As expected, when mineralogic information is available to guide the calculations, the Rtest routine produces sensible results. As I detail under "Improvements", the method of implementing mineralogical assumptions into the calculations is a bit odd and probably prevents additional insights from being gleaned from these calculations. .

PI Response:

Reviewer 23419

Score: Not scored

Comment: There is no discussion of how the new methods might be more widely used in the geothermal community, lessening perceived impact outside of Idaho and SRP.

PI Response:

The results of this work will be disseminated in the form of publications and presentations that will go into greater depth on the general applicability of the techniques that have been employed for this project.

Reviewer 23549

Score: Not scored

Comment: One weakness is the emphasis on RTEst geothermometry results and the difficulty in assessing uncertainties of the calculated values. There really are two sources of uncertainty which weren't adequately addressed. One is the calculation uncertainty for a given set of assumptions, which they claim to be on the order of 10-20C. The more difficult appraisal is for uncertainties arising from different assumptions about source mineralogy and pathways between reservoirs and surface. These might be very large but don't seem to have been given much attention. Although a comparison of RTEst values with those from a sulfate geothermometer were said to be "pretty good" this is not consistently the case; close to 20% of the values are outside their claimed resolution of ± 30. At least one value disagrees by >100C. There are other multicomponent geothermometers, such as GeoT and no comparison was made with alternate results. Nevertheless the best approach, one that they are using, is to try to use independent thermometers for comparison.

PI Response:

There are many uncertainties with any geothermometer including differences in geology, mixing with shallow water with much different chemistry and the potential for re-equilibration of fluids with lower temperature along the pathway to the sampling point. That is why we are using as many different techniques as possible to get the best ideas about these uncertainties. The comparison of RTEst values with those from a sulfate geothermometer was based on a subset of data that was available (analyzed by the review time). The comparison of values (e.g., estimated T) from different geothermometers and their similarities or differences will be dealt in detail as we finish sampling and get the full spectrum of data for the ESRP. However, as the reviewer(s) stated, different geothermometers have varying degrees of success on dealing with waters impacted by diverse geochemical and physical processes and our ability to quantitatively decipher and incorporate those processes while developing temperature estimates.

A project has been proposed to compare GeoT and RTEst

<u>Reviewer 25423</u>

Score: Not scored

Comment: The PI's did not present their dataset within the context of the bigger picture, making it more difficult for reviewers to understand the project. The multitude of questions from the review panel are a sign of this.

Conflicting information exists regarding the project team. On the one hand, the PI spoke of the project as being a collaboration with "local" universities. And according to the project summary document the collaboration includes, "…three Idaho universities through Idaho's Center for Advanced Energy Studies (CAES). Later in the document it states " CAES is assisting with field water sampling and water chemistry analyses." Given what I learned during the review, at most this assistance amounts to student labor in the field. It is true that the experience is good for the students. However, is the project benefiting from outside perspectives of collaboration with non-LBL and non-INL scientists?

According to the other project documents, the collaboration is with one university (the University of Idaho). The PI from the University of Idaho was formally a scientist at Idaho National Lab. While it is true that the students from the University of Idaho provide fresh energy, they are under the guidance of a former INL scientist. Is the collaboration with the University of Idaho providing an outside perspective? Does the program value such a perspective? I am not criticizing the PI, but I am asking the Project Officers to consider this issue. These comments about collaboration are not reflected in the scores I assigned in the Scientific/Technical Approach category.

When asked a question about the multicomponent geothermometry tool RTEst, the response was something along the lines of, "You needed to come to the poster where we addressed this." Please, do not respond in this way to a reviewer's question. Provide an answer. Or state that the subject is very detailed and would require too much time to address in the allotted schedule, but that the PI's would be happy to show the reviewer a poster that would address the question.

There were many questions about the multicomponent geothermometry tool RTEst, none of which was adequately addressed during the Q&A. Examples of these questions are 1) the code seemed to require circular logic to implement; 2) what thermodynamic database is being used? Does it address solid solutions? 3) the thermodynamic database for clay minerals is very poor, yet many of the secondary alteration minerals are clay minerals. How is this being handled with the RTEst code? The comments in this paragraph are a part of the reason why I assigned a low score in the Scientific/Technical Approach category.

Please note, my "Weaknesses" section is much longer than my "Strengths" section. This is not a reflection of the overall quality of the project, which I think is very good. This is more a reflection of the more extensive explanation needed to describe the weaknesses.

PI Response:

Weekly conference calls are conducted with LBNL/INL/UofI. Students participate in these calls. A MS thesis is being prepared in coordination with the project on a subset (Twin Falls/Banbury) of the SRP area. A laboratory mixing study is being conducted in the laboratory with the UofI student being advised by INL researchers. We are expecting results by the fall.

We agree that the poster answer was not the best response. Thank you for the suggested alternatives.

For the 3 questions:

1) We don't believe that there is circular logic, the code does require the user to select a set of mineral assemblage and analyzed water chemistry.

2) The presented RTEst values were determined with Thermo.dat [the default Geochemist's Workbench (GWB) database], which is based on the LLNL.dat database. LLNL.dat (and Thermo.dat) is the most comprehensive database available for geochemical modeling. However, a user can select any other internally consistent database (provided that it is formatted to be suitable for GWB) for the RTEst geothermometric modeling. With the exceptions of experimentally determined thermodynamic values, majority of the thermodynamic values included in various databases have been derived with SUPCRT92 (as with the LLNL.dat). Furthermore, we are in communication with Nic on the use of other data bases.

3) We agree that the thermodynamic database for clay is generally weaker than for other minerals. To formulate a mechanism to select the right member of clay mineral from a group of solid-solution clay minerals is very challenging if not impossible (even for a well-studied system, it is challenging to address this issue). One good aspect of the code is that it is not extremely sensitive to one particular mineral because the objective function of the code relies equally on all minerals included in the assemblage. Finally, creating new databases is outside the scope of work for this project. However, we will keep testing approaches to determine the best way to incorporate clay minerals (with available thermodynamic values) in the mineral assemblage for the development of temperature estimates.

IMPROVEMENTS

<u>Reviewer 24896</u>

Comment: The principle areas for improvement that I see in this study lie in the mechanics of applying inverse thermodynamic modeling to geothermometry of these fluids. Based on discussions with the PI's at their poster as well as our discussion after the review, there are several procedural modifications that they may want to consider as they continue to develop this method:

1) In the absence of independent information about the mineral assemblages associated with the waters, the PI's have developed a database of model mineral assemblages that occur at various temperatures in geothermal systems hosted by various lithologies. These mineral assemblages are then used to force which minerals are considered in their calculations. I have never seen the technique applied in this way. Typically the code should be (and the guts of their code, Geochemist's Workbench is) able to sort out which minerals are likely in the assemblage. Certainly there are phases that show up that are unrealistic. However, the composition of waters can often be a clue to what mineral assemblages the waters have seen, which would be a nice addition to this study. This is especially true for the subset of samples that come from ambiguous lithologic situations (margins of the SRP, deeper wells that may be sited in rhyolites, etc). Given the

"optimization" the authors do to correct for dilution, devolatilization, etc., forcing the mineral assemblage considerably reduces confidence in the results.

2) Given the optimization variables in the calculations, it was unclear how the PI's are able to constrain pH at elevated T.

3) The thermodynamic database used in this study contains data of variable quality and for phases that likely exhibit considerable solid solution in the systems under investigation. This is especially true for the phyllosilicates (clays, chlorites, fine grained micas). It would probably be best to avoid using these phases in the calculation as they do not really provide a constraint on the calculation since there is no way of knowing the activity corrections required to consider them.

4) The use of microcline as an Al proxy is probably a bad choice for the basaltic lithologies as it is rarely encountered except in very low pressure, high temperature systems.

5) I noted on the poster that at least some of the mineral assemblages used were not realistic...for instance the coexistence of low temperature zeolites like chabazite with chlorite. The study might benefit from some review of the assemblages in the database.

PI Response:

1) GWB defines all possible minerals for an input water chemistry. In general, the code picks geochemical values (e.g., saturation indices) of minerals that are included in the input file as likely mineral assemblage from the GWB output file(s), and proceeds optimization routine. The current version of the RTEst does not allow auto-select mineral assemblage. This potential option was brought up to the discussion when we were developing RTEst, and determined this not to include. Allowing the model (RTEst) to auto-select the mineral assemblages for an input water chemistry would likely violate the phase rule, select minerals that generally do not coexist, or select unrealistic phases (as the reviewer's stated). We agree with the reviewer that the list of minerals (or phases) that GWB provides for input water chemistry could assist the user to think 'outside the box'. Regardless of whether auto-select option is included in the RTEst code or not, a user can always access the GWB output file(s) with a list of minerals (phases) and their geochemical calculations (e.g., saturation indices). Therefore, our suggestion to future RTEst users would be to look and consider GWB output file(s) while refining mineral assemblage for a blind water sample.

The review work of secondary mineral possible under a set of expected geothermal systems was presented at the last GRC meeting (Palmer, C.D., Ohly, S.R., Smith, R.W., Neupane, G., McLing, T., Mattson, E., 2014. "Mineral Selection for Multicomponent Equilibrium Geothermometry", 2014 Geothermal Resources Council Transactions, Vol. 38, p 453-459, 2014). The input file generator associated with RTEst offers a list of likely minerals that can be used to define a mineral assemblage for an input water chemistry based on its chemistry (acidic, neutral, or alkaline waters) expected reservoir temperature (low, intermediate, or high), and lithology (e.g., silicic, carbonate, calc-alkaline, thoeiilitic, etc.). Besides this, RTEst also allows the user to select other mineral assemblages than those suggested by the input file generator routine.

2) At every iteration, GWB recalculates pH for the new conditions (temperature, mass of water, and/or fugacity of CO2) and uses that pH to calculate the saturation indices of minerals.

3) Despite the variable quality of the thermodynamic database for clays, they must be included in the calculations as secondary minerals for multicomponent geothermometry to be complete. Modifying the clay thermodynamic data base is outside the scope of this project. The database can be updated with new information as it comes available.

4) We are still exploring this, our previous experience using other minerals suggest the microcline works the best despite its low occurrence.

5) We looked at the poster and chabazite is not used. "Cha" in the figures represents chalcedony, perhaps this is the confusion.

Reviewer 23419

Comment: A plan to disseminate results so that more groups might adopt the methods would be beneficial.

PI Response:

We do have plans to publish the results in peer-reviewed journal and are giving presentations at meetings (GRC, the Stanford Geothermal Workshop, the Goldschmidt Conference).

Reviewer 23549

Comment: Comparison to other multicomponent geothermometer results would be useful, not just for this project, but for the community as a whole. Each group seems to have their favorites; an outsider wonders if a consensus can't be found.

PI Response:

We have compared our results to standard geothermometers and GeoT, another multi-component geothermometry model. The comparison with the latter is generally very good.

Reviewer 25423

Comment: Recommended improvements are listed below. These points also factored into my assigning a lower score in the Scientific/Technical Approach category:

The PI's do a nice job of identifying project weaknesses, they did not do as well in explaining how they will address the weaknesses. Case in point, on a project document they state, "there may be some re-equilibration of thermal waters at lower temperature" and that additional efforts will be needed. They did not identify how they will tackle this problem. Other examples follow.

During their presentation the PI's discussed the need to address 1) redox and 2) other sources of sulphate that could impact their measurements and interpretations. Both subjects were also broached during the Q&A. However, the PI's did not provide any specific information. The PI's need to specifically address both subjects. The latter is of particular importance; it may be the most critical question in the entire project.

The PI's recognize the importance of addressing aluminum, as evidenced by their statement in the PowerPoint, "Does aluminum need to be measured and/or what are the appropriate proxy minerals to use". This subject also came up during the Q&A. However, the PI's did not provide any specific information. The PI's need to specifically address this subject.

Also address the points outlined in the "Weaknesses" section.

PI Response:

RTEst (or any other geothermometry technique) cannot predict the reservoir temperature with water chemistry that is re-equilibrated at a lower temperature. For this reason, all geothermometry techniques are conservative in their estimation of the reservoir temperature. However, we are currently conducting laboratory batch experiment to begin to understand the time that is required for the re-equilibration and this information will have to be examined with non-geothermometry tools to evaluate if the water could be re-equilibrated.

RTEst does not address redox at the moment. If the user knows how redox is affecting the chemistry of the water, the user can adjust the chemistry before using RTEst.

Regarding other sources of sulfate, in some cases this can be inferred from the sulfur isotopic compositions of the sulfate and a strong knowledge of the local geology. It can also be used to determine if there is evidence of subsurface reduction of the sulfate by microbial activity. However, the only way to directly address this question is with drilling.

We suggest that aluminum should be measured when collecting new water samples. For sites that are using historic data without aluminum, a limited number of new samples should be collected to determine an appropriate proxy mineral.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Use of He isotopes for geothermal resource identification in the Cascades and Snake River Plain
Principal Investigator: Dobson, Patrick
Organization: LBNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 24896

Score: 6.0

Comment: The principle impact of this project on GTO goals would be the facilitation of early identification of blind geothermal systems associated with mantle-derived heat sources. He isotopes have proved to be important tools for understanding mantle contributions to crustal rocks. Their application to geothermal exploration is in its infancy and has not been well established. Given the specialized nature of the equipment and resources necessary to conduct He isotope analyses, it is unlikely that they will evolve into a workhorse technique for geothermal exploration, at least on the industry side. Nevertheless, this project potentially provides an important test of their applicability. This stems in part from the background of previous studies by the PI's in the western US and more importantly from the collaboration between this project and other geochemical projects currently underway in the region.

It appears from the milestone data that significant progress has been made and that the project is on target for a timely conclusion. Collaborations with others working in the Snake River Plain appear to be on track for a useful synergy between the projects. Early results from the project suggest that there may be surprising results in some areas in Idaho, namely the lower Wood River Valley/Camas Prairie region and the Thousand Springs areas.

PI Response:

He isotopes have been used by some industry exploration teams (such as Ormat and Unocal), but I agree that it is more of a specialty tool at this point due to specialized nature of these analyses. Our collaboration with the INL-LBNL geothermometry team provides us with important geologic context with which these data can be interpreted. These data are also being incorporated into the Utah State-led play fairway project.

Reviewer 23419

Score: 8.0

Comment: The investigators have identified an area that may help uncover blind geothermal systems in areas where high rainfall and cool groundwater mask potential high temperature systems. The project has created an extensive compilation of data for the Cascades and leveraged collaborative projects for new sampling in Idaho. High He isotopes (indicative of mantle or magmatic contributions to the heat source) are generally associated with high predicted temperatures from geothemometry. Results from the first year were presented at the Stanford workshop. Due to funding and time restrictions, project focus was shifted exclusively to the Snake River Plain. The project team has created a strong collaboration with which to perform field work and integrate He isotope information with geothermometry from other projects. The Cascade compilation is being included in the Cascade Play Fairway project of Wannamaker.

PI Response:

Elevated 3He/4He isotope values are not necessarily linked with elevated temperatures, but do tend to indicate association with magmatism or enhanced permeability in the lower crust that facilitates input of mantle-derived He into geothermal fluids. In the case of a young intrusion serving as the heat source for a hidden signal, an elevated He isotopic ratio may be a useful signature to prompt additional exploration.

Reviewer 23549

Score: 6.0

Comment: The compilation is useful as an exploration tool and the new data will also be useful. Although moderately high values of 3He/4He have been found their interpretation is complicated. The ultimate value of this project will be its integration with other geochemical tracer studies and other geological/geophysical studies of the SRP.

PI Response:

The interpretation of the He isotope data is being conducted through integration of data compiled for the Snake River Plain Play Fairway analysis and geothermometry data from the INL-LBNL project.

Reviewer 25423

Score: 10.0

Comment: The project has produced some quality accomplishments for the stage it is in. Foremost among the accomplishments is the GIS-based maps that combine new and old He isotope data with thermal feature temperatures, regional heat flow, and locations of young magmatic activity for the Snake River Plain. The new He isotope data is also very intriguing and bodes well for the ultimate significance and utility of the project. The maps and He isotope data provide context for this project and for the collaborative AOP project “Geothermometry Mapping of Deep Hydrothermal Reservoirs in SE Idaho”. Given the complexity of the analyses and the time commitment required of fieldwork, the PI has been very productive. The project earns top marks in this category.

PI Response:

Thanks!

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 24896

Score: 7.0

Comment: The approach taken in this project is straightforward and based on established principles of isotope geochemistry and analytical techniques. The shift in project plan to focus on the Snake River Plain (as opposed to also including the Cascades) is logical given the time and financial constraints and the relatively large extant data set for the Cascades. The initial results of the project have identified some areas of elevate Helium-3. For the most part, these are a consequence of the position of the sampling sites relative to the flow patterns in the Snake River Plain Aquifer; as is the absence of elevate Helium-3 over most of the study area. The results in the Lower Wood River Valley (Camas Prairie) area are intriguing, especially because they lie outside of the influence of the aquifer. The collaboration with other projects working in the area strengthens the impact of these results. The forthcoming focus on tritium monitoring wells that have elevated Helium-3 is also interesting.

PI Response:

We plan to sample selected USGS monitoring wells that exhibited elevated 3He (but which have low tritium) at INL later this year.

Reviewer 23419

Score: 7.0

Comment: The approach is builds on past work and methods by these investigators. The sampling locations capitalize on synergies with other work occurring in the Snake River Plain. Preliminary results suggest that He alone may not really be a proxy for high temperature systems, as at least one location has high He3/4 ratios, but cool predicted temperatures based on the geothermometry. If He is decoupled from high reservoir temperatures it's utility as an exploration tool will be lessened.

PI Response:

We collected an additional sample near the anomalous well (Butte City) to confirm this measurement.

Reviewer 23549

Score: 6.0

Comment: The project is relatively simple, to analyze helium isotopes in samples collected as part of a much larger geochemical study of well and spring samples in the SRP. The analysis is relatively straight forward. The interpretation definitely is not. At this stage, however, they seem content to collect the data.

PI Response:

We agree that the interpretation of the He data is complex. We have engaged in initial interpretation of the data (our presentation did compare He isotopic values with multicomponent geothermometry results). The He data are also incorporated into a more rigorous evaluation of available geologic, hydrologic, structural, geochemical, and geophysical data of the Snake River Plain as part of the SRP Play Fairway project. The integration of the He data with the play fairway analysis provides us with the opportunity to develop more detailed interpretations of the He results.

Reviewer 25423

Score: 10.0

Comment: The scientific approach is sound and consistent with current and best practices. Important components include 1) compiling a database of pre-existing data for context and comparison; 2) collaboration with another AOP project (referenced above); and 3) collecting samples and analyzing/interpreting the data. Spreading the project across two field seasons is wise; it provides the means to self-correct the work effort as the project proceeds. This approach also allows the PI to identify and address data gaps and promising leads. Again, the project earns top marks in this category.

PI Response:

We appreciate the compliment on our approach.

STRENGTHS

Reviewer 24896

Score: Not scored

Comment: The principle strength of this research is that it adds new isotopic data for a geologic province with suspected geothermal potential. These data will be especially useful in light of the other isotopic and geothermometric studies currently underway. Piggybacking on other fluid sampling programs in the area greatly facilitates cross-correlation of results from this study with others.

PI Response:

Collaboration with other projects provides us with an opportunity to develop much better integration of the He data with other geoscience information for this region.

Reviewer 23419

Score: Not scored

Comment: Established techniques build on investigators skills and history. Complementary sampling in Idaho provides multiple tools to understand broad region systematics.

PI Response:

Reviewer 23549

Score: Not scored

Comment: Some interesting results are emerging, but there is not much interpretation at this stage. There is very high value in the integration of the He results with other studies in the SRP.

PI Response:

The He data are being integrated with other studies in the SRP.

Reviewer 25423

Score: Not scored

Comment: The collaboration among Berkeley National Lab, Idaho National Lab, and the University of Idaho is an important strength of this project. An important scientific strength is the use of noble gas isotopes to provide another perspective for geothermal resource evaluation. Collaboration with another AOP project (referenced previously) provides important synergies. The Snake River Plain maps (p. 10-12 of the powerpoint presentation) are informative and very useful. Finally, the PI presented his dataset within context of the bigger picture, making it easier for reviewers to understand the project.

PI Response:

We agree that the He data are much more useful when considered in the context of more comprehensive studies of the region.

WEAKNESSES

Reviewer 24896

Score: Not scored

Comment: The principle weakness of this study at present is the lack of interpretation of helium isotopic results in light of geologic and hydrologic factors influencing this signature. Sampling sites should be interpreted clearly with respect to their relationship to the flow patterns in the Snake River Plain aquifer as well as deep crustal structure. In the latter case, the results in the Lower Wood River Boundary were observed near known deep crustal discontinuities. Are these the source of the elevated Helium-3 or as one collaborator suggested is the source of heat and Helium-3 young lavas in the areas (all of which are sourced distal to the thermal anomalies showing elevated Helium-3).

PI Response:

We are still in the process of intrepreting our He data in the context of available geologic, hydrologic, structural, geochemical, and geophysical data for the region.

Reviewer 23419

Score: Not scored

Comment: Will not accomplish the stated goal of using He to identify new resources in Cascadia.

PI Response:

We made a decision early in the project to focus our efforts in the Snake River Plain, where we could take advantage of other projects being conducted in this region.

Reviewer 23549

Score: Not scored

Comment: Samples are still being collected and there is much analysis yet to be done. The results are ambiguous. High-ish values of 3He/4He are said to all correspond to regions of high heat flow. This is shown on a map, but no direct comparison of He isotope ratio versus heat flow for that location, or versus RTEst temperature are shown. Thus direct comparisons have not been made. (Plotting two variables on a map is not the way to determine whether or not they are correlated – rather plot one against the other). Initial results indicate the He isotope signal is complicated, likely because it has become so diluted by the aquifer. Indeed there is a large extrapolation from mantle value to the observed values of

1-3 R/RA. Given the evidence for strong flow in the aquifer, the pathways from reservoir to sample site could be very complicated and processes occurring during transport will eventually have to be considered.

PI Response:

Our presentation did contain a table that compared 3He/4He values with RTEst results for all areas with elevated (Rc/Ra > 1.5) 3He/4He values. We agree that the interpretation of the He data can be complicated by mixing/dilution with shallow aquifer fluids. However, we believe that the He data may provide one way of seeing through the shallow aquifer, which has significantly affected many components of the geochemistry and masks deeper geothermal reservoirs.

<u>Reviewer 25423</u>

Score: Not scored

Comment: The PI collaborates with INL and with the University of Idaho. Three contacts are listed for the University of Idaho, one is a professor and the other two appear to be graduate students. The PI from the University of Idaho was formally a scientist at Idaho National Lab. These students are under the guidance and mentorship of a former INL scientist. I do not question the quality of the students or their mentorship, but I have to ask, "Is the collaboration with the University of Idaho truly providing the proper scientific perspective?" This is not a criticism of the PI, but a query to the Project Officers.

PI Response:

We have found our collaboration with the University of Idaho to be invaluable. They have provided significant logistical and scientific support for our project, and the students often ask probing questions which help improve our analysis and interpretation of the data. Prof. Tom Wood is extremely knowlegable about the Snake River Plain hydrology and geochemistry, and his students have collected and analyzed water samples at each of our sample locations that have provided important context to the He data.

IMPROVEMENTS

<u>Reviewer 24896</u>

Comment: 1) Collaborate with hydrologists to strengthen the basis for interpreting results in the Snake River Plain Aquifer area.

2) Given that elevated Helium-3 may reflect greater deep crustal permeability (as suggested by the Great Basin results used as a backdrop for this study), lower crustal geology needs to be a component of the data interpretation in this study.

PI Response:

One of the benefits of collaborating with the Snake River Plain play fairway project (of which one of us is also a team member) is that we are privy to the data synthesis and analysis being conducted throughout the SRP. This includes a detailed GIS structural data set of both all mapped faults as well as inferred subsurface structures as interpreted from gravity and magnetic gradient data. These subsurface structures are of particular interest for the SRP, as there are very few mapped surface structures in this area (outside of volcanic rift features, such as the Great Rift). We will also be interpreting the He data in the context of the regional hydrology - we are collaborating with INL hydrologist on this aspect of our study.

Reviewer 23419

Comment:

PI Response:

Reviewer 23549

Comment: Much better treatment of data is possible and will be required before the results will be really useful. Perhaps this will be done (by others?) in the larger collaborative effort.

PI Response:

The data interpretation is ongoing, and will benefit greatly with our collaboration with the SRP play fairway project.

Reviewer 25423

Comment: Aside from expanding future collaborations beyond the LBL-INL network, my suggestions are minor. Indeed, I have only one. It was difficult for someone not intimately familiar with Snake River Plain geology to easily understand and digest the maps and superimposed data. Perhaps keep this in mind for the next review. I'm sure for final reports and papers; this will not be a problem.

PI Response:

The information that could be shared during the peer review was limited by the number of pages and slides that we could share with the peer reviewers. Our final product (manuscript to be submitted to a peer reviewed journal) will provide the appropriate context in which the He data can be interpreted.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Surface estimates of deep permeability
Principal Investigator: Kennedy, Mack
Organization: LBNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 24896

Score: 4.0

Comment: It is unclear how this project addresses GTO goals. While He isotopes do provide insight into mantle sourcing and perhaps even deep crustal permeability, they are probably not ever going to provide sufficient insight into upper crustal processes necessary to impact geothermal development. The modeling undertaken in this study, while a nice extension of extant techniques, cannot overcome the inability to constrain the boundary conditions necessary for this work to provide actionable insights into permeability, fluid flow rates, or their relations to heat transfer. While the fluid residence ages are an interested component of this study, the uncertainties associated with interpreting the He isotope results with respect to heat and mass transfer make it difficult to understand how they will aid in validating the model.

The PI's have undertaken an ambitious research program and made some progress. The observations of He isotope anomalies with respect to crustal discontinuities are intriguing. Code construction for their heat and mass transport models appears complete and valid. While the PI's clearly understand that the state of their modeling activities are preliminary (exploratory might be a better term), these results also demonstrate that the stated purpose of the study may not be attainable.

PI Response:

Reviewer 23444

Score: 8.0

Comment: Because permeability is a fundamental controlling factor in subsurface fluid flow, developing successful strategies for estimating permeability is key to having a successful modeling strategy to understand geothermal systems. Estimating subsurface permeability remains a challenge as hundreds of researchers have worked to develop methods for permeability estimations using a variety of techniques. The use of He isotopes proposed here is novel; understanding He isotopic behavior is a first step to deconvoluting the multitude of interacting factors affecting He isotopic measurements at the surface. Having a mechanism to quantitatively assess subsurface permeability from surface measurements would advance many areas related to fluid flow. As such, the project has potential to lower cost and risk associated with targeting geothermal resources.

Progress has been achieved in meeting objectives such as measuring isotopes and modeling He isotopic behavior generically and in specific systems; because it potentially provides a method to interpret He measurements fulfilling several stated objectives. The new algorithms and data added for the noble gasses appear to capture their small scale behavior and may be a valuable addition to the code. Modeling specific well-constrained geothermal systems provides a first step to a more realistic assessment of the utility of He isotopes. The non-uniqueness of the model parameters and the scaling differences limit applicability to larger crustal scales. There remain significant barriers to relating He isotopes to subsurface permeability that need to be addressed and discussed.

The correlations between He isotopic values, specifically those related to mantle input, and deep crustal signatures are intriguing.

Fluid sampling shared among three research projects is to be commended; sharing of data rather than duplicating leverages funding. Saving both time and cost advances progress simultaneously. The new fluid data is critical to understand the relationships in fluid and He.

PI Response:

Reviewer 23549

Score: 7.0

Comment: Potentially the impact of this project could be extremely high because the use of He isotopes to constrain subsurface permeability represents a highly innovative approach to a fundamental issue. My numerical rating reflects that they are not there yet, but they certainly should be encouraged to continue their efforts. Modeling has begun but can be greatly improved.

PI Response:

Reviewer 25423

Score: 10.0

Comment: Important accomplishments are: incorporation of noble gas isotopes into reactive transport model; and development of a cross section and reactive transport model of the Desert Peak geothermal system (it needs work but it is a good start). Important progress has been made towards developing a robust sampling system for 39Ar and 81Kr. If successful, this will ultimately lead to determination of residence times of crustal fluids.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 24896

Score: 4.0

Comment: The stated goal of assessing permeability in this study points to the fundamental weakness of the approach. First, permeability appears to be both a qualitative and quantitative concept in this study. On one hand the regional scale trends in He isotopes across the Great Basin, as well as the deviations from that trend, are qualitatively treated as an indication of deep crustal permeability. This is fine, but it points to the inability to attain the purported goal of constraining permeability quantitatively by modeling the fate of He-3 during heat and mass transfer in the upper crust. The PI's use available upper crustal geologic understanding to develop numeric grids for their models without understanding how the limits of available cross sections relate to the boundary conditions that necessarily impact the results of their models. Additionally, if I interpret their modeling results properly, at ka or longer time scales the upper crustal aquifers would be largely well mixed in the vicinity of the helium source and have a value equal to that of the input at the boundary. If that is the case, when we collect a near surface sample in the vicinity of a deep crustal discontinuity, are we not just seeing the value of Ra being sourced to the shallow groundwater system? Perhaps this just leaves on with a calculation similar to that mentioned by the PI for the San Andreas system provided we knew the depth extent of the shallow groundwater system. In any event, it makes one wonder whether the stated goals of the project are attainable.

PI Response:

Reviewer 23444

Score: 6.0

Comment: Collecting fluid samples follows carefully established procedures appropriate for capturing noble gasses. Analyzing He isotopic also follows well established protocol whereas new protocols have been developed and tested for Ar, Kr; all are appropriate and rigorous.

Modeling relies on the 'most used code' for geothermal energy development. However, there are conceptual leaps from what is being measured to what is being modeled with little discussion of the associated issues. A 1.5km x 1.5 km grid is used to model a specific system yet to understand permeability of ‘deep crust’ through He requires a much larger area to be modeled. Boundary conditions are ill constrained and need improvements, perhaps from regional model. Realizing that there are modeling constraints from the code, a point source of He has no connection to physical reality. There are too many unconstrained parameters in the model without a discussion of their impact. A discussion of how the local model fits into the large scale regional model is warranted. A model can be run – with precise output but that output may highly inaccurate. Caution should be used when trying to relate a specific model to a generic outcome. The modeling portion of the project is the weakest.

The scientific approach needs to address scaling issue of permeability as well as connectivity between upper and lower crustal regimes, regional vs. local. Permeability measurements scale with the scale of the measurement, consequently permeability measured over larger systems may not reflect the actual permeability at the smaller scale need for geothermal resources. As such, high permeabilities could lead to inaccurate anomalies suggesting highly permeable zones. Helium is being analyzed to find upper crustal perm (important for geothermal systems) yet the permeability of the deeper crust – over a regional scale - is being tapped for mantle He. The discontinuity between these two permeability regimes should be addressed.

PI Response:

Reviewer 23549

Score: 8.0

Comment: For what they are trying to do the approach seems reasonable. However, some of the sampling and analytical challenges are daunting and they are, at this point, far from success. There are two fundamental approaches: 1) measure residence time in fluids, and 2) incorporate noble gas data into reactive flow models. They have made better progress on the second.

PI Response:

Reviewer 25423

Score: 10.0

Comment: The technical approach is robust. The project seeks to incorporate new geochemical techniques (measurement of 39Ar and 81Kr using Atom Trap Tracer Analysis), established geochemical techniques (He isotopes), and state-of-the-art reactive transport modeling. The sampling apparatus for 39Ar and 81Kr failed miserably, and a new technique has been developed and will be tested.

PI Response:

STRENGTHS

Reviewer 24896

Score: Not scored

Comment: The strongest part of this study is the already completed work correlating He isotope anomalies (relative to the Great Basin trend) to crustal geology. The combination of He isotopes, groundwater residence ages, and heat and mass transfer modeling is intriguing. Perhaps the modeling results may provide some insight into what the He isotope measurements reflect (though it will likely not be permeability in any quantitative fashion).

PI Response:

Reviewer 23444

Score: Not scored

Comment: The project has made significant accomplishments, some unanticipated. Correlations noted between plate velocity/strain rate and He isotopes, and regional structures are intriguing. Using these data to infer deep crustal permeability and connectivity is also novel although how these data apply directly to geothermal system remains in the realm of correlation rather than causation. Potentially new uses for He isotopes have been advanced.

Addition of algorithms to model noble gas solubility, partitioning, diffusion and transport in thermal-mechanical flow codes has the potential to add new insights into the development of geothermal systems. In addition, calculating residence times of groundwater may add new constraints to flow models and sources of geothermal fluids. Developing the basic science of and techniques for measuring Ar and Kr at low values is a substantial advancement in technique development.

Working with other groups to maximize fluid sampling and analyses saves time and cost (see accomplishments).

Developing a model of Dixie Valley using known geologic constraints, incorporating the new algorithms provides a generic proof of concept. These models provide beta testing for technique development.

PI Response:

Reviewer 23549

Score: Not scored

Comment: I find this project to be highly innovative and ambitious, which makes it is easy to criticize. Yet the premise is fairly simple: high 3He/4He reflects increased permeability. This is likely true because flow rate should correspond to permeability (and yield less diluted samples) and IF initial He isotopic ratio can be constrained. The determination of residence time in hydrological systems is a first-order problem in the Earth Sciences, and highly relevant to geothermal systems. They have made some progress in comparing data to regional discontinuities and much progress in developing/enhancing THC reactive transport models.

PI Response:

Reviewer 25423

Score: Not scored

Comment: The primer on He isotope geochemistry was most welcome. The PI presented the dataset within context of the bigger picture, making it easier for reviewers to understand the project. The integration of crustal-scale reactive transport modeling with noble gas isotopes to constrain fracture permeability at crustal scales represents a fruitful avenue of investigation.

PI Response:

WEAKNESSES

Reviewer 24896

Score: Not scored

Comment: This project will not clearly address GTO goals, outside of perhaps putting the He isotope work funded by GTO into context. The goal of quantitatively determining permeability is likely not attainable. There appears to be insufficient effort directed at relating the modeling space to crustal realities (having said that, the initial model presented was based on far too much detail within the grid of the model for an initial attempt...the position of the boundaries of the model was constrained by the scale of Fauld's cross section instead of by crustal structure.

PI Response:

Reviewer 23444

Score: Not scored

Comment: The primary weaknesses relate do the modeling portion of the study, as mentioned in the "approach" section. A conceptual model with a single through-going fault tapping the deep crust is unrealistic as are isotropic solids, fluids, and mineral parameters. Because mineralogy along the fault may influence He production, knowing fault materials, their continuity and their likely He contribution is necessary. Permeability likely varies along the fault and is highly anisotropic. Steady state conditions for He production are appropriate at temperatures less than 100C, but the deep crust with elevated temperatures could be a transient source of He.

For improving applicability of the THC model, better constraints on boundary conditions need to be developed and incorporated. Integration of regional flow/He values with small scale crustal features are needed. Elucidating how the regional He patterns are manifest in local He anomalies would enhance the overall applicability of the approach, that is, how do the permeable reservoirs interact. Correlation does not necessarily mean causation. Expand the sensitivity analyses to account for other variables.

While one can estimate permeability, a method to validate that estimate is essential. A discussion of errors, uncertainties, and interactions among reservoirs in a complex geologic setting should be addressed. All of these affect the results. As is, there is much extrapolation with little recognition of pitfalls.

Issues relating to scale are discussed earlier (please refer to those); domain sizes vary over orders of magnitude. Interaction of different zones of crustal permeability i.e. brittle vs. ductile, should be addressed.

With all of the inherent uncertainties in models, how the residence time of fluids validate the non-specific models should be developed.

PI Response:

Reviewer 23549

Score: Not scored

Comment: So far they have been unable to collect samples for Kr and Ar measurements, although they think they have "solved" the sampling problem. For the modeling, there are many assumptions and not enough constraints. For example they seem to be using an initial (mantle?) He isotopic value of 7.5, but it is not clear where this comes from. Melt inclusion data for SRP lavas indicate values closer to 13 R/RA. Is there any reason to believe it will be constant along the SRP? Are there no solids that can be measured to provide constraints? I am not convinced by the claim for correspondence between (reactivated?) crust-scale discontinuities and He isotope anomalies, primarily because two things are plotted against longitude, I think one of which comes from MT but this was not explained, there are lots of lines drawn and I don't see much of a correspondence. This could be evaluated by plotting He isotope anomaly vs distance from discontinuity directly, or He vs MT results directly – my bet is that it is not a very pretty plot. This failure to convince this reviewer does not mean that there isn't a relationship between He isotopes and permeability, only that these, not-that-well-defined discontinuities might not be especially permeable. Permeability structure in the models is well constrained only for the uppermost part. Is there depth-dependent permeability? Deep lateral variations? Modeling results will almost certainly be non-unique.

PI Response:

Reviewer 25423

Score: Not scored

Comment: I could not read the graphics projected onto the screen. It was disrespectful to the reviewers for the PI to not know the contents of his PowerPoints. Please, do not wing it when you present before the next review panel.

I see no weaknesses in the science.

PI Response:

IMPROVEMENTS

Reviewer 24896

Comment: The modeling efforts could be redirected to interpret the time and spatial scales of factors affecting He-3 concentrations measure in shallow systems. What time scales are necessary for obtaining steady state He isotope ratios? Do He isotope ratios reflect the depth of addition to shallow groundwater systems/residence times in the lower crust? A number of related questions come to mind that could be addressed with this model, but few of them allow quantification of permeability.

PI Response:

Reviewer 23444

Comment: See weaknesses; primarily address modeling, discussion of uncertainties, non-uniqueness of the model solutions.

Advancing our understanding of deep crustal permeability and its relationship to surface features is complicated. Relating permeability to a single surface measurement may provide a correlation but recognition must be given to other variables and the problems with such an extrapolation. Otherwise using He isotopes to target potential wells may provide a false positive, thus increasing cost and risk. A full discussion of the inherent uncertainties and problems adds confidence to the outcomes. Identification of barriers to success and limits of the models improves results by critical analyses.

Keep the presentation to the allocated time - it was long by 10 minutes which took away the reviewer's time to ask questions.

PI Response:

Reviewer 23549

Comment: Consider ways to better constrain “initial” He isotope values throughout the study area. If there are no solid materials that can be measured then they are stuck, but it will be a persistent weakness of the effort. Perhaps also consider variable depth-dependent permeability in the models.

PI Response:

Reviewer 25423

Comment: I have one minor recommendation. Is it worth doing some basic aqueous geochem and stable isotope analyses to cross-pollinize with ongoing FOAs targeting the Snake River Plain?

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Integration of Nontraditional Isotopic Systems Into Reaction-Transport Models of EGS For Exploration, Evaluation of Water-Rock Interaction, and Impacts of Water Chemistry on Reservoir Sustainability
Principal Investigator: Sonnenthal, Eric
Organization: LBNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 24896

Score: 7.0

Comment: Although this research investigates interesting geochemical phenomena that take place in geothermal systems, it is unclear that application of the tools and results of this study will have a significant impact on GTO program goals. The models probably capture a lot of the physical and chemical factors at play, but whether modeled Sr and Ca isotope results are sensitive enough to individual properties like permeability and fracture surface area in light of uncertainties and the plethora of variables is not established. The Newberry results are intriguing, and hopefully studies of actual rock chip samples from the system will provide some insight into the sensitivity of these models.

This is a very ambitious and work intensive project. There have clearly been some logistical delays that have hampered analytical plans of the project. The modeling appears well along, at least at the code/database development level. The elemental lithium results are encouraging, and it is a shame that the logistical problems have slowed the lithium isotope portion of this research. A lot of work has been done, but it seems like the rest of the project milestones targeted for completion this fiscal year are a tall order.

PI Response:

Reviewer 23419

Score: 9.0

Comment: Improvements to and application of the models have been published in peer reviewed literature and the TOUGHREACT software has been released. Reactive transport models for Desert Peak have been performed and published. Initial flow through tests on Sr isotopes have been conducted. Measurement of Sr isotopes pre-and post-stimulation at Newberry have been measured and show significant change, though this is likely due to contamination by injecting fluid. Li isotopes have not been measured due to equipment difficulties. The project is establishing methods and protocols that may significantly enhance our understanding of water-rock reactions and history in a variety of real world geothermal environments. The use of real material (Desert Peak tuff) in the flow through reactor is novel and yielding results directly relevant to field measurements.

PI Response:

Reviewer 23549

Score: 7.0

Comment: Incorporation of non-traditional isotope tracers into reactive transport models, along with the measurement of these tracers in well fluids is very worthwhile. They seem to be providing a better picture of reactions occurring at depth in field settings. The experimental work provides critical calibration of models. This study has demonstrated sensitivity to certain processes, such as feldspar and clay involvement. The project appears to have been highly productive although there is still more to do.

PI Response:

Reviewer 25423

Score: 10.0

Comment: The project is in the last few months of a 3.5 year timeframe. The PI has been very productive. Dynamic experiments are complete and appear to have yielded good data. The models are fairly well set up; much care has evidently gone into the construction of the models. Relevant field data has been identified and is being used for validating the models and experiments. On this last point, it wasn't clear to me but I think the fieldwork was performed by the project even though fieldwork was not part of the original work scope. This was a wise use of project resources, but I would ask the PI to make this important detail more apparent to the review panel.

The PI has also achieved many valuable accomplishments, including: incorporated thermodynamics and kinetics of isotopic fractionation into reactive-transport models; released a new version of the reactive transport code; completed dynamic experiments; analyzed flow back waters.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 24896

Score: 7.0

Comment: This is an interested project that attempts to incorporate well-established, but fairly novel isotope systematics into investigations of water-rock interaction in geothermal systems. I generally see no fault with the modeling approaches taken in the study, though wonder if they will be able to actually provide quantitative understanding of subsurface flow processes as claimed in the study. Of the isotope systems, the lithium results, which are unfortunately delayed, are potentially the most useful. Strontium and calcium both are interesting, but I suspect that truly understanding their behavior will require a lot more analytical work on the solid phase side than is proposed.

PI Response:

Reviewer 23419

Score: 9.0

Comment: This project includes construction of a flow-through reactor and improvements to reaction-transport theoretical models to improve geothermometers and geochemistry as indicators of geothermal systems, and to understand fluid-rock interactions during EGS stimulation events. The PI and team clearly understand the methods, models and systematics of the isotopes they are working with. The combination of laboratory, field and theoretical approaches is powerful. The technical approach includes a well thought out progression from flow through measurements to how those measurements will be incorporated into theoretical models and then tested on real field data at Newberry and Desert Peak. Application of Li fractionation could significantly enhance our current understanding of fluid history.

PI Response:

Reviewer 23549

Score: 6.0

Comment: The analytical measurements have now become relatively routine but are a welcome addition to the geochemical arsenal. The enhanced transport solid solution modeling is definitely not routine and represents an important advance. The experiments are useful for some parameters in the model, but the natural system is, of course, far more complex than the experimental system of this project. Nevertheless the experiments are very worthwhile as stand-alone calibration of fundamental processes.

PI Response:

Reviewer 25423

Score: 10.0

Comment: The approach is to integrate state-of-the-art reactive transport modeling with dynamic experiments, validated against field data/perspectives. The use of stable isotopes to evaluate water-rock interactions is incorporated into the models, experiments, and field measurements.

PI Response:

STRENGTHS

Reviewer 24896

Score: Not scored

Comment: The study integrates strong code development with advanced analytical problems. The experimental materials and sites (Desert Peak, Newberry) afford synergy with other ongoing projects.

PI Response:

Reviewer 23419

Score: Not scored

Comment: The project includes many innovations and new approaches that will advance the field of reaction transport modeling as a whole. The project includes new chemical systematics (Sr, Li) that will enhance our understanding of water-rock interactions and changes in active geothermal systems.

PI Response:

Reviewer 23549

Score: Not scored

Comment: Major addition to THC reactive transport models involving Li isotope fractionations seems to be a major advance. New experimental apparatus and measurements therefrom have provided important fundamental properties as functions of flow rate. The overall rigor of the modeling is impressive.

PI Response:

Reviewer 25423

Score: Not scored

Comment: Important strengths are the integration of modeling with experiment and employing non-traditional stable isotopes in the experiments and field. A major strength for the project is that the whole problem started with field observations, the approach is grounded in field reality, and field data are used as a reality check.

PI Response:

WEAKNESSES

Reviewer 24896

Score: Not scored

Comment: The total project is very ambitious and multifaceted, perhaps to a point that it compromises the potential of the study. The Code development and analytical programs point to some interesting comparisons, but more thorough characterization of the individual experimental and field systems is probably necessary to really glean information. For instance, the PI correctly notes the need for analyses of subsurface samples from Newberry. To do this well (by doing it at the phase as well as the whole rock level) is a serious commitment. The flow through experiments on Desert Peak material are another example where resolving the difference between model behavior and observed behavior in a meaningful way will require a lot of work.

PI Response:

Reviewer 23419

Score: Not scored

Comment: While the results of this work are likely to improve our understanding of water-rock interactions, it is unclear that results will significantly change or directly influence EGS stimulation plans or site selection for production wells as suggested.

PI Response:

Reviewer 23549

Score: Not scored

Comment: It is easy to argue that experiments are far simpler than actual field conditions; this is intentional. However, it will limit application to specific field problems.

PI Response:

Reviewer 25423

Score: Not scored

Comment: I see no major weaknesses in the project. I do see details that should be addressed, as I describe in the Improvements section. None of the individual details is a major concern. Collectively, the details could hamper the PI's efforts to relate his work to the field questions he is trying to address. This in turn could diminish the impact of the project.

PI Response:

IMPROVEMENTS

Reviewer 24896

Comment: As PI's also point out, more work on solid phase reactants and products is necessary to constrain and interpret the models.

PI Response:

Reviewer 23419

Comment: None to suggest.

PI Response:

Reviewer 23549

Comment: Using a more realistic brine as injection fluid in the experiments would be worthwhile.

PI Response:

Reviewer 25423

Comment: Recommended improvements are:

A 0.5 molal NaCl solution was injected into the experiment. The lack of other cations in the solution will drive reactions faster. The PI needs to explicitly address this in his modeling. The lack of other cations may also lead to different reactions taking place than would happen if a more realistic solution was injected. I don't think this is the case, but the PI needs to explicitly check this with his modeling. I guarantee that both issues will come up when the PI submits his work to a peer reviewed journal.

Page 11 of the PowerPoint states that "Abundant sericite formed during experiment". My understanding is that the PI bases this statement on SEM work. He needs to quantify "abundant" and verify this statement with quantitative XRD work. The XRD work should also include clay separations and glycolation. Once the clay is identified, how well can the PI approximate these minerals in his models (e.g., will he have reasonably correct thermodynamic data? What rate constants are suitable?).

If I understood him correctly, the PI stated during his presentation that the experiment approximates the reactive surface area a fluid would encounter along a flow path in a fracture. In other words, the combination of high surface area of Desert Peak Rhyolitic Tuff loaded in the reactor combined with the short flow path is a reliable proxy for actual subsurface conditions in which longer flow paths encounter smaller surface areas. I don't think this is true, but I honestly have not developed a quantitative counter argument. Instead, for the purpose of this review, I ask the PI to carefully consider this approach and verify with pertinent calculation.

The subject of flow rates came up during the discussion. Flow rates in the lab do not need to duplicate rates observed in the field. However, the PI needs to explicitly compare/contrast the two rates. The key is to consider is whether potential geochemical differences between field and experimental results are due to flow rates or some other factors. These other factors may include experimental or field factors. An example of the former is the aforementioned surface area vs. flow path comment. An example of the latter is lithologic differences between experiment and field.

And speaking of litholic differences, how heterogeneous is the Desert Peak Rhyolitic Tuff? If it’s homogeneous, the PI will have an easier time of relating his modeling/experimental efforts to the field. If it is heterogeneous, the PI faces some challenges. Either way, he needs to be explicitly aware of the potential for lithologic differences.

Are the subsurface fractures lined with fresh rock or altered tuff? I forgot to ask, but this is another field vs experiment question that the PI needs to at least consider. If the fractures are lined with fresh rock, then the experiments more closely approximate the field setting. If the fractures are lined with altered rock, then the PI will have to expressly address how the experiments do/do not compare to the field setting.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Surprise Valley Geochemistry
Principal Investigator: Spycher, Nicholas
Organization: LBNL
Panel: Tracers / Zonal Isolation / Geochemistry

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 24896

Score: 8.0

Comment: The goals of this study clearly address GTO goals related to identifying exploitable geothermal resources. Whether these efforts will reduce development costs remains to be seen. Remote "sampling" of geothermal systems through studies of extant wells and surface expressions can be a useful tool for reducing exploration risks. There is an ambitious plan to relate observed compositions to surficial and subsurface processes through reactive transport and reaction path modeling that may prove insightful given the fairly constrained geologic problem.

The PI's have made considerable progress in their work. It appears that a new version of their code is near ready and they have applied the methods to a significant amount of extant data. There have been some project delays because of time commitments to other projects. Hopefully the hiring of interns and the increased "burn rate" will help to keep progress on track. I suspect that the time over-commitment noted in the talk may be compromising the care with which the PI is able to interpret data from this study.

PI Response:

We thank the reviewer for these comments. We have completed GeoT V2.0, although the formal release is taking longer than anticipated. We are also in the testing stage of iGeoT. Delays in the schedule are not compromising the care in our analyses (it is rather the other way around).

Reviewer 23419

Score: 9.0

Comment: The project has developed a database of cold and thermal water samples in Surprise Valley, integrated with known fault structures, and submitted to GDR. The project has completed initial integrated analysis of the Phipps #2 well to demonstrate coupled GeoT and iTOUGH2 modeling software. Using data from multiple springs is demonstrated to yield consistent geothermometry. The results from the analysis are being integrated with the Surprise Valley Play Fairway project of McClain.

PI Response:

We thank the reviewer for these comments.

Reviewer 23549

Score: 5.0

Comment: The geochemical data are an important, cost-effective exploration approach. Data have been compiled as expected and have been analyzed with a multi-component geothermometry program, which has been enhanced. These are all very worthwhile endeavors. Analysis/interpretation is underway. This project has identified potential new high-temperature zones in the area. Modeling barely begun.

PI Response:

We thank the reviewer for these comments. The modeling work was delayed in part because the GeoT upgrades took longer than anticipated.

Reviewer 25423

Score: 10.0

Comment: The project has realized several important, relevant accomplishments. Preexisting data for Surprise Valley has been compiled. A database of water chemistry has been integrated with relevant geologic data. The data have been modeled using both classic and modern methods. In-situ temperatures of the deep reservoir have been determined and a deep thermal component identified. A holistic, regional picture of the system is emerging. These results are important for understanding hydrothermal systems and the potential for the geothermal resource. The PI has been very productive to achieve these results.

PI Response:

We thank the reviewer for these comments.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 24896

Score: 7.0

Comment: The geochemical modeling approaches in this study are based on well-established methods that have proved useful in geothermal studies for decades. The approach of combining saturation state calculations (the "multicomponent geothermometry"), reaction path studies directed at understanding the origin of fluid compositions, and reactive transport modeling to put these observations in a system-wide context is far too rarely applied. The study area is very amenable to this approach and there is nice synergy with related projects going on in the area. Generally I would rate the scientific/technical approach of such a project higher than I have done here. What concerns me is the mechanics of the multicomponent geothermometry calculations, which do not appear to be constrained with the same rigor as prior efforts by the PI. Perhaps this is a consequence of the over-commitment noted in the presentation. What is particularly concerning are the apparent non-unique results obtained for samples in this study (cf, the two temperatures obtained for the same sample with different choice of silica polymorph in slide 10). The cause of this is not totally clear to me, but is likely due to a multitude of factors that I detail under weaknesses. What is clear is that the samples in this study do not provide the level of constraint on the calculations that the examples for which the method was recently described through in Geothermics enjoyed. A casual look at slide 11 reveals that CO2 was added in the calculations without even a mineral constraint. Perhaps the minimization of mineral affinities can predict this through the effect on pH, but such poor constraints are likely a significant contributor to the non-unique results curiously provided in the talk. Additionally, the method is often based on considerably more thorough mineralogic data than appears available in this study. The test case example in slide 10 partially (it ignores much of the reported data and misapplies much of it) relies on data from wells studied by Benoit et al. (2005), which provide only a cursory overview of the mineralogy. Much more care needs to be taken in applying this technique for it to yield meaningful results. The PI is clearly capable of more rigor in such work, which might suggest that despite efforts to increase burn rate and personnel, his projects are understaffed.

PI Response:

We thank the reviewer for these comments. We agree that the deep water chemistry reconstruction, particularly for springs, is not as constrained as for other cases we presented in the past. For this reason, in some cases, different interpretations of the available data lead to different temperature estimations. We do not see this as a weakness, however, but as an example of the importance of careful understanding of the data when applying this method (it is not a "silver bullet", and we have been careful to stress this in our 2014 Geothermics paper). In this case the CO2 was constrained by equilibrium of the solution with calcite. The two different temperature interpretations result from the fact that in the first case, the added CO2 amount is optimized to bring calcite near equilibrium with the solution at the temperature at which chalcedony is also at equilibrium with the solution; in the second case, the CO2 amount is optimized in the same manner to bring calcite equilibrium with the solution but near the quartz equilibrium temperature instead. In hindsight we realize we should have made this clearer in the slides and during the presentation. More discussion regarding this non-uniqueness of results is provided in answers to other comments below. We agree with the comment related to understaffing, and concede that we likely underestimated our funding needs.

Reviewer 23419

Score: 9.0

Comment: Approach builds on past published work by PI and collaborators. The PI clearly described the methodology and approach to "reconstituting" the fluid composition at depth. The proposed effort strongly leverages with other work including GIS data integration and past analysis of samples in Surprise Valley by UC Davis students. Work is applying novel methods of multicomponent geothermometry coupled with geochemcial modeling. During the presentation the PI noted that the methods are validated by forward modeling known temperatures of some systems to optimize elements such as gas loss and dilution. The model solutions explore many variables and their statistical variation (e.g. mean and standard deviation) and it was demonstrated how the solutions converge at temperatures that minimize these parameters as well as optimize equilibrium among expected mineral reaction products.

PI Response:

We thank the reviewer for these comments.

Reviewer 23549

Score: 5.0

Comment: The approach is fairly routine, but definitely worthwhile. The geochemical study will be incorporated into a larger play fairway study. Development of GeoT multicomponent geothermometer and newly incorporated parameter optimization software are likely to be useful beyond this project.

PI Response:

We thank the reviewer for these comments. As first reported in our 2011 GRC paper ("Integrating Multicomponent Chemical Geothermometry with Parameter Estimation Computations for Geothermal Exploration"), and further documented in our 2014 Geothermics paper ("Integrated Multicomponent Solute Geothermometry"), combining multicomponent geothermometry with numerical optimisation is a novel approach to geothermometry which cannot be considered "routine".

<u>Reviewer 25423</u>

Score: 9.0

Comment: The project employs a suitable technical approach. It has developed foundational knowledge using available published data, completed fieldwork, and combined classic geochemical perspectives (e.g., Piper diagrams) with advanced modeling techniques. Objectives are being achieved with this approach.

PI Response:

We thank the reviewer for these comments.

STRENGTHS

<u>Reviewer 24896</u>

Score: Not scored

Comment: The project applies established geochemical methods in an integrated way to a well-defined field area. The results could serve as a model for relating the geochemical signatures of surface expressions to subsurface properties.

PI Response:

We thank the reviewer for these comments.

<u>Reviewer 23419</u>

Score: Not scored

Comment: Technical approach is sound, novel, and builds on past successes.

PI Response:

We thank the reviewer for these comments.

Reviewer 23549

Score: Not scored

Comment: Further development of GeoT is a useful tool for estimating reservoir temperatures and alteration mineralogy, and the inclusion of parameter optimization is welcome. New potential high-temperature sites have been identified in the area, which is an important result. This project involved two graduate students from UC Davis to the overall benefit of both the project results and the students' experience.

PI Response:

We thank the reviewer for these comments.

Reviewer 25423

Score: Not scored

Comment: Important strengths are integrating field data with computational methods and using both classic and advanced modeling techniques. Another strength is the collaborative effort with outside institutions and ongoing, related projects. I do not know if it was miscommunication or something else, but it's unfortunate that the PI ran out of time for his presentation. That said, it's a strength that the PowerPoints include data and results that I can digest outside the confines of the formal review meeting. I wish more PIs would do the same.

PI Response:

We thank the reviewer for these comments. Unfortunately the PI's presentation was cut short, not for running over, but because the session's schedule had slipped, which conflicted with some of the reviewer's schedules.

WEAKNESSES

Reviewer 24896

Score: Not scored

Comment: I am very familiar with the PI's previous work in this area, including the recent Geothermics paper describing the code development that is part of this study. The methods are well established. However, the examples shown previously are much better constrained than those in this study.

1) At first glance, it would appear that the optimization scheme used in this study does not produce unique results. For instance, on slide 10 the PI apparently got convergence of his algorithms at two different temperatures assuming equilibrium with two different silica polymorphs. While I would generally agree that quartz should be the polymorph in the system at these conditions, the fact that the same assemblage can be found in equilibrium with more than one polymorph after allowing for a host of fluid modifications indicates that the results of these calculations are non-unique.

2) I like that the PI compares his results to traditional geothermometers like SiO2 and Na-K. I assume that the temperatures indicated on the plots on slides 10 and 11 based on these thermometers are calculated from the raw fluid compositions, since they are the same between the two cased presented on slide 10. What is clear from slide 10, however, is that the thermodynamic data used for the alkali feldspars in the multicomponent equilibrium geothermometry calculation are not consistent with the data used to develop the Na-K thermometer (which is based on equilibrium

between the feldspars). Furthermore, because Na/K in equilibrium with albite and microcline is temperature dependent, and would be independent of the adjustments to fluid composition conducted in order to optimize the temperature fits, it is unclear to me how convergence was achieved at two different temperatures for assemblages containing both these minerals. Something is clearly amiss here.

3)it is unclear to me how these calculations can be fully constrained. I understand that the method advocated purports to optimize even under partially constrained conditions, but the examples that this assertion is based on are all far more constrained than any of the problems described in this study. Calculation of mineral saturation at elevated temperatures requires redistribution of aqueous species at each temperature including solving for pH. If one is going to adjust (or determine in the absence of data) Mg and Al content, adjust CO_2, and correct for dilution, then the calculation ideally needs to be fully constrained per the "mineralogic phase rule", i.e., at a given T,P, the number of components should equal the number of minerals. Taking the nominally 9 member assemblage on slide 10, these minerals can be described by 8 thermodynamic components assuming iron-free monmorillonite as I supposed from the data being used (the components being SiO_2, Al_2O_3, Na_2O, K_2O, CaO, MgO, CO_2, and H_2O). The assemblage in slide 11 contains one fewer component and mineral as calcite is not part of the assemblage, removing CO_2 as a component (though curiously CO_2 loss was somehow corrected for and pH calculated...it is unclear how that was accomplished without a mineralogical constraint). Additional components are necessary to describe the background electrolyte in the aqueous fluid, but these are in theory constrained by chemical analysis (e.g., HCl, H_2SO_4, etc.). Since there are 9 minerals in the assemblage that was optimized, the results in slide 10 appear to present a phase rule violation (number of phases is greater than the number of components). I doubt this is actually a problem as not all nine phases are exactly in equilibrium. In reality, however, neither this calculation nor the ones shown on slide 11 are actually fully constrained as I discuss below.

4) The assemblages in slides 10 and 11 both contain five minerals that represent components in clay mineral solid solutions thought to be present in the Lake City geothermal system. This information is based on preliminary data reported by Benoit et al., 2005 (GRC Trans. v. 29, p. 203-208). As an aside, the Benoit et al., paper identified two distinct mineral parageneses, one with clays, quartz, zeolites and calcite (with epidote at greater depths) and a later paragenesis dominated by quartz (that may replace opal or chalcedony in shallow levels) with minor sericite and calcite (feldspars were not reported, and talc was definitely not in the assemblage). Although the clays were not characterized in this preliminary study, one would presume that they include 2:1 clays like illite and smectite (though at the temperatures suggested by geothermometry is it likely that trioctahedral smectites and chlorites are present in addition to or instead of the dioctahedral clays). The montmorillonite endmembers and talc are often considered to be compositional endmembers in dioctahedral smectites, whereas pyrophyllite may represent a compositional endmember of illites. Pyrophyllite is not an "analog" of sericite, but rather a component in it (muscovite would be a more sensible analog). As components in a clay mineral solid solutions, these five phases (3 montmorillonite endmembers, talc, and pyrophyllite) would not have unit activity as used in these calculations, but would have a reduced activity that is unknown. Furthermore, because four of these substances are actually components in one true phase (dioctahedral smectite0, the phase rule analysis described above should be adjusted by reducing the number of phases by three (three of the four smectite components). Given this, the calculation is not actually constrained, and relies on erroneous interpretation of the clay mineral stabilities because composition-activity effects are not considered.

5) The precision (and given the adjustment parameters in these calculations, the accuracy as well) of these calculations is strongly dependent on the enthalpies of dissolution reactions for the phases in the assemblages. As the PI noted in his talk, minerals whose total dissolution reaction exhibit large enthalpies of reaction are preferred for these calculations. It is also preferable for there to be minerals with both prograde and retrograde solubility. In the case of these mineral assemblages, there are two phases with retrograde solubility, calcite and talc. Unfortunately, components in each of these are fitting parameters in the calculation (CO_2 and Mg) and one suffers from the clay mineral activity problem noted above.

PI Response:

We thank the reviewer for these thoughtful and constructive comments. We addressed some of these in previous responses, and provide more detailed answers below:

1) Non-uniqueness. Any modeling results, regardless of the model sophistication/complexity, is bound to have some degree of non-uniqueness. The more the inputs are constrained, the less are the degrees of freedom and non-uniqueness of the results. In our case, different assumptions for optimizing the amount of CO2 loss result in different temperatures. In the first case the amount of CO2 was optimized to bring calcite equilibrium near chalcedony equilibrium temperature, whereas in the second case the CO2 amount was optimized to bring calcite equilibrium near the quartz equilibrium temperature. Therefore, the two temperatures do not result from a weakness in the method, but from two possible different interpretations. As we concluded in our 2014 Geothermics paper "The method discussed in this study should never be applied blindly or taken as a new fail-proof solution to the challenging problem of solute chemical geothermometry."

2) The "classical" geothermometers are applied to the reconstructed water compositions, not the raw water compositions. In the case of plots on slide 10, there is no dilution/concentration correction applied to the fluid, and no correction applied to measured concentrations except for optimization of Mg and Al. Therefore, both the quartz and chalcedony cases yield the same "classical" geothermometer temperatures. The divergence in Na/K temperatures and albite-kspar equilibrium temperature is not due to inconsistent thermodynamic data. It results from near-equilibrium of the solution with these minerals, and not "exact" equilibrium. At equilibrium, the reviewer is correct, a given Na/K ratio should yield one unique albite-kspar equilibration temperature (and consistent with the Na/K geothermometer). In the present cases, these minerals are not exactly at equilibrium at the two estimated temperatures, and therefore the equilibrium temperature of each mineral depends not only on Na and K, but also on pH, Al, and SiO2. Because the pH differs somewhat in both cases (different amounts of added CO2), and the optimized Al concentrations also differ, both cases show near equilibrium with albite and microcline at different temperatures (with saturation indices actually closer to zero in the quartz case, although this is not visible on the plots). We discuss further below the distinction between near- and "exact" equilibrium and how we regard this a strength of the multicomponent geothermometry approach.

3) The reviewer is correct that the Phase Rule should dictate exactly how many minerals can be at equilibrium with the solution under the same conditions temperature, pressure, and composition. In reality "exact" equilibrium is rarely achieved in natural systems. We have shown with kinetic reactive transport simulations and experiments (in our 2014 Geothermics paper) that water-rock reactions yield a suite of minerals nearly, but not exactly, at equilibrium with each other (and the solution), with near-zero saturation indices that closely bracket the "true" reservoir temperature. In addition, because similar types of minerals have similar thermodynamic properties, the saturation indices of similar minerals are often near zero close to the "true" temperature, even if not truely belonging to the observed assemblage. This allows the use of proxy minerals (e.g. for clays and micas) when detailed mineralogical information or thermodynamic data are not available. This is a significant advantage of the multicomponent geothermometry approach (i.e., relying on the saturation indices of multiple minerals) over "classical" geothermometers. About slide 11, as discussed in our previous response, equilibrium with calcite was used to constrain the amount of CO2 added back in solution; we should have made this clearer and include calcite on all plots.

4) We appreciate this thoughtful comment regarding solid solutions and sheet silicates, and agree (and are well aware) that uncertainties in end-member compositions, activities and type of sheet silicate mineral affects confidence in model results. In this case the assumption of unit activity for solid-solution end-members is likely in part offset by optimizing Al and Mg concentrations. Based on previous applicatoin of the method, we do not anticipate the choice of other, possibly better proxy minerals, to significantly affect computed temperatures (see above reply) and will be further testing this.

5) Please refer to our responses above. We agree that because our geothermometry approach relies on many parameters, the need for constraining all these parameters is an inherent weakness of the method. Simpler geothermometers require less input parameters, but then the reliance on only one or a few parameters is also a weakness. Because both approaches have advantages and disadvantages they should not be applied exclusive of each other.

Reviewer 23419

Score: Not scored

Comment: As noted, and as the investigators understand, even novel methods of geochemistry may not uniquely identify current resource temperature at depth. Many alteration minerals may reflect historical high temperatures recorded in water-rock interactions, rather than current fluid temperatures.

PI Response:

We agree. Also see previous replies.

Reviewer 23549

Score: Not scored

Comment: Modeling of fluid from 170 well yielded reservoir temperatures of either 190 or 230 (favored). What is the explanation for these discrepancies? An overall understanding of fluid chemistry in the region seems to be lacking. The alkali lake compositional treatment is disappointing, perhaps because their compositions appear quite variable and apparently strongly affected by evaporation. Nevertheless, they seem far from deriving a comprehensive understanding of fluid chemistries in this region.

PI Response:

The non-uniqueness of the results in this case was discussed in previous answers. We agree that the treatment of the alkali lake component is difficult because its composition is strongly affected by cyles of recharge/evaporation. We have shown that taking into account dilution, the thermal fluid compositions are remarkably similar across the valley.

Reviewer 25423

Score: Not scored

Comment: There was much discussion during the Q&A session about some of the PI’s modeling methods and assumptions. I think his work is robust. However, several panel members obviously have issues with particular aspects of the work. The PI’s explanations to the review panel needed to be better. Perhaps the PI needs to anticipate a more general audience. Either way, I gave the PI a slightly lower score for Scientific/Technical Approach because of this.

PI Response:

Agreed; one difficulty was also that the PI's presentation time was cut short to make up for the slipping session's schedule, to (rightfully so) accomodate some of the reviewer's schedule.

IMPROVEMENTS

Reviewer 24896

Comment: 1) Understand the origins of the inconsistency in thermodynamic data (and rectify them) that leads to discrepancies between classical geothermometers like Na-K and the results of the multicomponent geothermometry. Also, it would be interesting to know what the classical geothermometers predict for the reconstructed fluids.

2) Determine why the multicomponent geothermometry gives non-unique results.

3) Reevaluate the mineral assemblages used in the calculations with respect to phase rule analysis of the geochemical system. The phase assemblages used in the examples in the talk are not realistic mineral assemblages.

PI Response:

These comments were addressed in our previous responses.

Reviewer 23419

Comment: This reviewer has none to suggest.

PI Response:

Reviewer 23549

Comment: This is another example of investigators preferring one multi-component geothermometer over others that are available. Although parallel developments are not necessarily bad, it would be useful to know how results vary, if at all, with use of, for example, GeoT and RTEst. Furthermore, model independent geothermometers, if there are any, would be useful as comparisons.

PI Response:

To our knowledge there are only two geothermometry codes that integrate the mineral saturation index geothermometry method with numerical optimization (GeoT and Rtest). GeoT is the only one that can do this "globally" with more than one water composition simultaneously, as done with springs in this study.

Further reasons why we preferred GeoT are as follows. We started developing GeoT and reporting on it's development since 2010 (AGU, 2010; GRC, 2011; Geothermics, 2014). RTest followed, and is based on the same approach (i.e., minimization of mineral saturation indices as a function of temperature), however the two codes are quite different. GeoT is a standalone code, incorporating its own geochemical speciation model for the computation of mineral saturation indices, and internally performing its own minimization to solve for temperature. It relies on external minimization software (e.g., PEST, itough2, ucode) only if parameters other than temperature need to be estimated (e.g., if solving for dilution factor; note that soon-to-be-released iGeoT will eliminate the need for external minimization software altogether). It is a standalone code specifically geared for geothermal systems. For example it can use many waters simultaneously; specific gas compositions, steam fractions, dilution factors etc. can be input to reconstruct the deep reservoir fluid; there are various ways to allow any minerals to react along the cooling path while estimating temperature; there are various ways to automatically select or exclude certain minerals from the simulations, etc. A disadvantage compared to Rtest, however, is that it is not currently menu-driven (i.e. no graphical user interface, GUI). In contrast RTest consists of the coupling of a commercial geochemical modeling package (GWB) with the minimization software PEST. As such it requires both the commercial software and PEST to estimate reservoir temperatures, even if other parameters do not need to be estimated. To our knowledge inversions cannot be globally performed using multiple waters at the same time, which was something we wanted to do for our study with spring compositions. It is GUI-driven (as is GWB), which is an advantage over GeoT, however it relies on proprietary commercial geochemical software that may limit is flexibility.

As part of other projects we have run comparisons between the GeoT and Rtest, with single water compositions, and obtained good results. We plan to continue such comparative study in the future, and most notably plan to further evaluate the sensitivity of model results to input thermodynamic data (expanding on our 2011 GRC paper) and optimisation procedures.

Reviewer 25423

Comment: It wasn't clear as to the extent that kinetic modeling would be needed or performed. The PI needs to make this clearer.

I think the plethora of modeling codes and databases that are available confuses the non-specialist and actually plants doubts and seeds of distrust in a reviewer's or stake holder's mind. I sensed this situation during the Q&A for this project and for other projects. Perhaps it would be worthwhile to make a statement in future documents/presentations about why a particular code and database were chosen. I am not advocating a lengthy assessment of individual codes and databases (personally I hate these and find them boring). However, it may be appropriate to provide a simple bullet point(s) on a slide or paragraph(s) in a document about the reasons why a choice was made and potential advantages/disadvantages for this choice.

PI Response:

Exploration Validation / Play Fairway Analysis Projects

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006731
Project: Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways
Principal Investigator: Faulds, James
Organization: Nevada Bureau of Mines and Geology, University of Nevada-Reno
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 10.0

Comment: The impact of this work can be applied to many of the geothermal reservoirs throughout the world.

Previous work by members of this group within and nearby the project area are cited in the application documents of nearly all of the competing projects.

To date the accomplishments, results, and progress on this project have met the schedule and there is no reason to believe that this will not continue until the completion of the project.

This is one of the most likely of the play fairway projects to result in the discovery of geothermal resources that can be developed in a timely manner.

Perhaps the only criticism of this project might be that it is focused on finding more of what we already have and not in making a revolutionary breakthrough to discover or recognize new types of resources.

The project is reported to be on schedule to complete all the tasks in a timely manner.

PI Response:

We agree with most of the comments. However, this project is actually focused on discovering blind and hidden geothermal resources (i.e., systems with no surface hot springs or fumaroles) through a multi-disciplinary effort combining as many as 10 geological and geophysical parameters into one geothermal potential map, much more than in any previous efforts. Several studies indicate that blind and hidden systems comprise the bulk (~75%) of geothermal resources in the Great Basin region. Several operating power plants (e.g., Desert Peak, Stillwater, McGinness Hills) are actually blind geothermal systems and were largely discovered by accident through agricultural wells, mineral resource exploration, or regional gradient drilling programs. Thus, we aim to develop a systematic means of defining and discovering geothermal reservoirs, which may greatly accelerate geothermal energy development in the Great Basin region, as well as other geothermal districts.

Reviewer 29848

Score: 8.0

Comment: This study will synthesize geological and geophysical characteristics of blind geothermal fields in the Great Basin thereby significantly improving the existing technical knowledge gap.

Will identify areas with high potential for hosting blind systems thus helping future exploration for blind geothermal systems in the Great Basin.

Will generate 3D models of two promising basins to serve as benchmarks for future studies in the area.

Statistically based geothermal potential map may serve as prototype for similar efforts elsewhere.

PI Response:

We agree with the comments. However, this project is not only synthesizing geological and geophysical characteristics of blind geothermal fields, but rather all types of geothermal systems (both blind and those with surface expressions). Operating geothermal fields (i.e., those successfully developed and with existing power plants) will be used as benchmarks to help gauge the results of areas that show high geothermal potential on the favorability maps produced in this study.

Reviewer 29849

Score: 7.0

Comment: The goal of this project is "the most detailed geothermal potential map produced for any region to date incorporating more parameters than any other map," to facilitate development of blind geothermal resources, to stimulate greenfield exploration, and to reduce drilling risk. The project in 2014 and 2015 has been the subject of 3 presentations, 1 publication, and 2 publications are in preparation.

The goal is to develop a detailed geothermal potential map of a large portion of central Nevada to find blind geothermal resources. Synthesis of geologic and geophysical data sets is a key goal is to identify areas with high potential of blind geothermal resources based on a statistical model. The hope is that map can serve as a prototype for other areas and reduce the risk of geothermal development of blind geothermal resources. It is an extensional area with fault control, but hot springs may be some distance from the major up-wellings.

The project is on schedule. A preliminary model demonstrated that the multiple data sets can be successfully combined into a "robust favorability map".

There is an existing map of Nevada from 2005 that has 5 parameters. This project is enhancing that map and extending it to 10 parameters notably including dilation tendency. Most systems in the area are hosted in fault interaction areas and associated with quaternary faults with high slip rates and geophysical anomalies. There is a high strain rate across the area with a strain rate gradient. The study is anchored with areas with detailed studies.

The impact question can be asked in two ways -- impact within the study region and in other regions. Within the study region, if the map identifies new areas of high potential that can be commercially developed that should stimulate interest. Beyond the region, the map may be influential if drilling verifies the areas identified in this study as having high potential. If drilling does not confirm the map "sweet spots" it will have less credibility. Also, while many areas with geothermal potential have different geology in which the weighting of geologic factors may be very different, so the map may not provide a good model for them.

PI Response:

The favorability maps developed in this study for the extensional to transtensional Great Basin region should have broad applications, because most of the world's major geothermal regions occur in similar settings, as exemplified by the Taupo Volcanic Zone in New Zealand, western Turkey, East Africa, Iceland, and even some magmatic arcs (e.g., southern Cascades, parts of Japan, Trans-Mexico volcanic belt). We agree, however, that some of the key geothermal parameters identified in this study may not directly apply to different tectonic settings (e.g., some magmatic arcs). However, the methodology in terms of statistically combining multiple parameters and developing applicable statistical analyses to weight such factors will likely have applications to geothermal favorability maps for any tectonic setting. We also agree that drilling will ultimately be necessary to test for geothermal sweet spots identified in this study and that the success of this study will hinge on such testing during a subsequent phase of this project.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23406</u>

Score: 10.0

Comment: The technical approach here is a continuation of previous and ongoing work by the PI and project team that has greatly improved the structural understanding of geothermal systems and their location controls. In fact, nearly all of the other successful Play Fairway project applicants cited this existing work in their original Play Fairway applications. This project represents a clear step forward above and beyond the previous efforts of the PI and the team.

The team was astute is selecting such a large and target rich prospect area already hosting a dozen or so producing geothermal power plants.

They are breaking new ground with trying to utilize 10 or 11 data sets in defining new blind areas.

PI Response:

We agree with the comments and are progressing well in breaking new ground and building on previous work by our group and others.

<u>Reviewer 29848</u>

Score: 8.0

Comment: Will produce GIS geodata bases of geological, geophysical, geochemical, and geodetic data.

Will produce a detailed statistically based geothermal potential map for the study area. New map will incorporate more data and parameters than previous maps.

Innovative aspects of the work will include 3D modeling with slip and dilation tendency, 3D inversion of MT data, and 3D visualization to define play fairways.

Impacts of next generation of detailed geothermal potential maps combined with 3D modeling will improve the analytical approach in selection of well sites.

Methodology will help find permeability sweet spots in the play fairway, which are often one of the keys to successful geothermal systems.

PI Response:

We agree with the reviewer comments. In particular, the combination of developing a statistically based geothermal potential map with 3D modeling has great potential in identifying heretofore undiscovered geothermal resources.

Reviewer 29849

Score: 7.0

Comment: The PI has a detailed plan for gathering specific types of data along with plans to anchor the model on both ends with detailed studies. The PI's have determined which types of data they think are significant as well as those they do not think are important. One concern is the seismic array density and it is being addressed.

In combining diverse sets of data, a key factor is how the data are weighted. Many different approaches can be used. The PI spoke of "putting the data together with different weighting factors to create a geothermal play fairway model". They believe that having recent faulting is very important and believe that they are combining the factors in a logical way. For each parameter they are trying to include a level of uncertainty. The factors can be combined in a plurality of ways, so a single map would only be one possible realization of the data synthesis.

At this point it is impossible to judge the strength and correctness of how the data are being combined and projected from 3D to a 2D map. More details on the rational for the weighting of different factors and their assigned uncertainty would be useful both to reviewers and to future users of the map. The researchers may wish to vary key elements to see how drastically the map changes as a result. Ideally, researchers would present both their best estimate and if there is significant variation between realizations for reasonable assumptions, back-up maps showing other end point realizations that are within the uncertainty limits. Companies interested in exploring the area would like to know how robust the results are and the critical uncertainties.

PI Response:

Seismic array density: The seismic reflection array density is unfortunately relatively poor for this region. Most of the seismic reflection data have been produced by the oil industry and much of it from a few decades ago. These data are now largely in the hands of seismic brokers and not in the public domain. This is why this project has allocated a large expenditure toward purchasing and analyzing such data (about 25% of the total budget). However, large parts of the Great Basin region are simply devoid of seismic reflection data. This project will help to determine the relative importance of such data, and thus lessons learned from this effort can help guide future exploration strategies in terms of determining the cost-benefit ratio of acquiring such data.

Weighting and combining data: The reviewer makes some very good points that the data can be combined in a plurality of ways and that a single map is only one possible realization of the data synthesis. The beauty of having an ArcGIS platform for this project is that we can easily show different maps with different weighting factors. Although we plan to develop a robust logical approach from our experienced team in estimating how best to weight the various parameters and estimate uncertainties for each, one possibility is to publish a web application with an interactive interface (that contains all the data sets) to allow users to combine various factors in different ways depending on local conditions as well as interpretive biases. In addition, our team will pursue publishing several peer-reviewed papers detailing the rationale of selecting weighting factors and describing the uncertainties of each parameter and results of different weighting schemes.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: The area selected for this project is excellent in terms of its large size and number of potential blind or unexplored resources that it could host. It is a target rich area that should be developable or marketable and is amenable to low cost drilling of temperature-gradient holes that will most likely be successful.

The area hosts a number of developed moderate to high temperature geothermal resources which should be good tests of the criteria to be utilized in this project.

The project team is highly experienced in this geographic area and doing this type of research. It is basically a continuation of work they have been doing for the past 8 or 10 years.

PI Response:

We agree with the reviewer comments. This region has great potential for development of additional geothermal resources once blind and hidden systems can be more readily identified. The successful operating systems in the region serve as good tests (or benchmarks) for our analyses.

Reviewer 29848

Score: Not scored

Comment: Awardees appear to be very familiar with the area, the different types of data available in the area, and the problems with identifying successful geothermal systems in the area.

Will provide 3D models and more detailed maps of the two end members (Carson Sink (western part) and Steptoe basin (eastern part)) thereby further reducing risks in these areas and allowing these areas to serve as benchmarks for other sites in the study area.

Also already have 14 developed systems in the area that can serve as benchmarks.

Uncertainty in the various types of data (10 different parameters) will be incorporated into the statistical model used for evaluation.

PI Response:

We agree with the comments. The successfully developed geothermal systems in the region do serve as excellent benchmarks, but it will be curious to see how some of these systems, particularly those that have a history of developmental challenges, rank compared to more robust systems. The 3D models anchoring the transect at each end will also serve as a basis for developing 3D geothermal potential maps in the future, possibly in subsequent phases of this project.

Reviewer 29849

Score: Not scored

Comment: Building on a strong existing base in an area with a lot of data.

PI Response:

We generally agree, but much of this region lacks detailed geophysical surveys (e.g., gravity, MT, magnetic), and only parts of the region has surficial mapping in sufficient detail for geothermal exploration. Thus, significant data acquisition is generally needed for any subsequent phases of this project, as well as other geothermal projects in the region.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: It is difficult to come up with serious weaknesses but one possibility is that this work is being done in an area that has already seen extensive exploration and therefore a great deal has already been developed in this area and therefore less remains to be discovered. Also this project is not likely to be revolutionary in that it discovers a new or different family or class of resources.

PI Response:

We agree that this project covers a region that has seen more extensive exploration than many others, but nonetheless all experts agree that this region contains vast quantities of untapped geothermal energy and that the overall geothermal potential of this region is largely unrealized. For example, only ~600 MW have currently been developed, but well-respected studies suggest at least 30,000 MW of geothermal potential. Experts also agree that most of these geothermal resources are blind or hidden with no surface manifestations. So although we likely will not discover a new family or class of resources, we are likely to significantly refine the methodology for discovering blind geothermal systems, which will facilitate full realization of this region's vast geothermal potential.

Reviewer 29848

Score: Not scored

Comment: Synthesis of multiple data sets into a cohesive assessment of geothermal potential onto a single map using various weighting factors and statistical methods (e.g., weights of evidence, multivariate statistics, classification and regression tree analysis, etc.) could be difficult. Will they compare and contrast the methods using different weighting factors and statistical methods?

There could be problems in accurately measuring some of the parameters they will be using such as recency of faulting, slip-dilation tendency, seismicity, and strain rate.

Is this approach too limited to just a single tectonic regime (Basin and Range; extensional regimes)?

There appear to be gaps in some of the data used to generate their model showing play fairways.

Need to identify the data needs for a potential Phase II.

How many temperature and heat flow measurements do they have? What is the spatial distribution and uncertainty of these measurements?

Don't seem to have documented that the four different fault settings shown in their presentation account for 90% of the known geothermal systems in the Great Basin. Are these 90% all blind geothermal systems?

Don't discuss integration of data and whether the different parameters are in agreement in terms of locating the areas with the highest geothermal potential.

PI Response:

Comparing and contrasting methods: Yes, we plan to compare and contrast the methods using different weighting factors. This will be relatively easy to address given that all the data sets reside in an ArcGIS platform.

Potential problems in measuring some parameters: We generally do not foresee any problems in having access to good databases for these parameters. More data would be valuable, but no new data acquisition is permitted in Phase I. Recency of faulting data is derived from many decades of research on the Quaternary faults of this region by members of our team and other groups. Significant effort has been conducted in the first two quarters of this project synthesizing available data pertaining to recency of faulting. Slip-dilation tendency is readily available due to adequate data on the regional stress field and orientation of Quaternary faults. However, general dip angles were assumed for the normal and strike-slip faults, respectively, in order to conduct this analysis on a regional scale, as it is beyond the scope of this study to carry out slip and dilation tendency analysis on a case by case basis for individual faults. Seismicity data are also readily available thanks to the detailed earthquake catalogue for this region compiled by the Nevada Seismological Laboratory at the University of Nevada, Reno. However, because the accuracy of this catalogue has changed through the years as more seismometers were installed, we have had to use a different threshold of earthquake magnitude for each time period. Strain rate is also readily available on a regional scale due to the extensive geodetic network operated by the Nevada Geodetic Laboratory, which is part of the Nevada Bureau of Mines and Geology. Two members of our team are from the Geodetic Laboratory.

Limiting to single tectonic regime: Our approach is really not limited to a single tectonic regime, as our methodology can be applied to any tectonic setting. In fact, other current play fairway projects utilize a similar methodology and are finding many of the same local structural settings are highly prospective in arc subduction settings (e.g., Cascades and Aleutians). However, as noted earlier, some of the parameters could be applied differently in other tectonic settings. Moreover, it would not be possible in the one-year time frame of this project to expand the scope to other tectonic regimes, although this will be valuable and timely in the future. In essence, we had to start somewhere with this type of approach, and our transect across the Great Basin region is a good place to apply and test the methodologies due to the large geothermal potential of the region and adequate amounts of available data.

Gaps in data: There are gaps in some of the data sets for generating our model. Some of the gaps simply reflect the status of completion at the time peer-review materials were due (e.g., structural settings and seismicity), whereas others reflect limited areal coverage of the data (e.g., seismic reflection and MT data sets).

Data needs for Phase II: There are multiple needs for additional data for Phase II. Depending on the area, these may include detailed geologic mapping, detailed analysis of Quaternary faults from which slip rates and recency of faulting are obtained, detailed gravity surveys, seismic reflection data, and MT data. Phase II will be focused on detailed studies of several promising sites for blind geothermal systems identified on the favorability maps produced in Phase I. Data needs for each of these selected areas will probably differ depending on the status of previous geological and geophysical studies.

Question on heat flow measurements: The study area has abundant well data both from the SMU gradient database (1,424 wells; 1029 of which are ≥100 m) and from several other data sets (oil and gas wells, permitted geothermal wells, state permitted water wells, and miscellaneous observation, test and research wells, primarily from NWIS). Including the SMU wells, we have compiled over 7,000 well entries in the study area that have recorded temperatures and depths. A total of 2846 wells are drilled to depths ≥100 m and contain temperature measurements suitable for calculation of gradients and heat flow (with assumed rock conductivities). These wells will serve as one dataset available in the modeling and will be submitted in the final ArcGIS project files.

Uncertainties of data in the SMU gradient (and other) well databases are not reported on an individual well basis, and uncertainties will be assigned based on professional judgement for well data (perhaps ±5%)

The distribution of the wells covers much of the study area, although there are clearly clusters in areas that have been drilled for other purposes. For example, Carson Sink and many other areas of northwestern Nevada (many water wells), as well as Railroad Valley in eastern Nevada (oil and gas wells), show clusters of wells, with those in the Railroad Valley area having numerous high temperature wells drilled to depths >2,500 m. Many Carson Sink water wells are in the geothermal systems currently under production. Areas of central Nevada generally have more sparse well data.

Documentation of Structural Settings: The documentation for the assertion that four structural settings account for nearly 90% of the known geothermal systems is in multiple papers and in a database that we submitted to the NGDS and DOE Geothermal Data Repository as part of a previously funded DOE-supported geothermal project (mainly EE0002748). Unfortunately, I neglected to show the appropriate citation in the PowerPoint slide. Some of the papers describing this work include Faulds et al. (2011, 2012, 2013, 2015).

Faulds, J.E., Coolbaugh, M.F., Hinz, N.H., Cashman, P.H., and Kratt, C., Dering, G., Edwards, J., Mayhew, B., and McLachlan, H., 2011, Assessment of favorable structural settings of geothermal systems in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 35, p. 777-784.

Faulds, J.E., Hinz, N.H., Kreemer, C., and Coolbaugh, M.F., 2012, Regional patterns of geothermal activity in the Great Basin region, western USA: Correlation with strain rates: Geothermal Resources Council Transactions, v. 36, p. 897-902.

Faulds, J.E., Hinz, N.H., Dering, G.M., Drew, D.L., 2013, The hybrid model – the most accommodating structural setting for geothermal power generation in the Great Basin, western USA: Geothermal Resources Council Transactions, v. 37, p. 3-10.

Faulds, J.E., and Hinz, N.H., 2015, Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA: Proxies for discovering blind geothermal systems: Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April 2015, 6 p.

Data integration: Data integration is discussed in some detail with respect to the preliminary model and the initially employed weighting factors. We would have discussed this in greater detail if more slides and text had been allowed. We also did not discuss whether the different parameters were in agreement with locating areas of greatest geothermal potential due to the preliminary stage of the project (less than half way to completion). The main goals in the initial stages of this project included: 1) compile the data sets; 2) evaluate the data sets; 3) combine the data sets into a preliminary model to ensure that our approach would work; and 4) begin serious analysis of the various weighting factors. We are currently in the process of finalizing the latter and determining if the various parameters are in agreement in the developed operating systems. This is clearly very critical, but we felt that it was important to reserve this analysis to the later stage to avoid potential pitfalls of either biased or circuitous reasoning, especially since some developed systems have faced various challenges through the years.

Reviewer 29849

Score: Not scored

Comment: While a single unified map is a grand target, potential users of the map would benefit from also having maps of the individual components that indicate the uncertainty of those variables.

PI Response:

We agree. The final unified map will be accompanied by maps of the individual components (or parameters), with uncertainty values specified for each as well.

IMPROVEMENTS

Reviewer 23406

Comment: It is difficult to come up with suggested improvements for this project at this time.

PI Response:

No response needed.

Reviewer 29848

Comment: There are still a lot of problems remaining in terms of assessing potential resources.

Need to consider the possibility of "added value" factors such as whether the water chemistry is suitable for removal of lithium or other valuable minerals.

It would help to collect additional MT data other than that clustered around the two end members and along the one line.

Need to fill in gaps in structural setting map.

In one of your introductory slides, you state that your approach will work for low temperature geothermal systems. Could you expand on this and explain in more detail exactly how your approach would work in low temperature systems?

How many different types of risk analysis will they use? Will the results of different types of risk analysis be compared and contrasted?

How well will their approach to risk analysis transfer to other areas?

How will the structural model and regional scale features translate into areas of high and low permeability?

PI Response:

Developing geothermal favorability or essentially permeability favorability maps is indeed complex. We do not expect to resolve every possibility in this study, but we do intend to take a significant step forward in defining geothermal play fairways (i.e., favorable permeability pathways) in this region.

Added value factors: The compiled geochemical database will be critical in evaluating mineral extraction potential of Nevada geothermal systems. However, this topic is beyond the scope of the currently funded project.

MT data: We fully agree that additional MT data are very much needed across the region. However, Phase I did not allow for any new data acquisition. We hope to acquire such data in promising areas in subsequent phases of this project.

Gaps in structural setting map: Yes, the gaps in the structural setting map needed to be completed as of submittal of the peer-review materials, and this has recently been accomplished. This is one of the more time consuming and important aspects of this project. Also, we realized while developing this data set that each setting needed to be rated in a complex way, depending on recency of faulting, slip rate, uncertainty, and slip-dilation tendency. Thus, this part of the project has involved more time than originally anticipated.

Low temperature systems: For low temperature (direct use) systems, our methodology also applies, as even low temperature systems require areas of higher than normal permeability with higher than normal temperatures. The same datasets and models apply to low temperature systems. The threshold temperatures would simply be lower and dependent on the application of interest. For lower temperature (i.e., ~150°C), electric grade systems, an example may be sedimentary hosted geothermal systems in large basins. We plan to broadly evaluate the geothermal potential of those basins with promise (as established by others) in the context of structurally controlled play fairways by overlaying our favorability maps on the published data regarding the sedimentary hosted systems.

Risk analysis: This phase of the project is focused on developing geothermal favorability maps that identify areas with the greatest geothermal potential. Thus, the primary goal of this project is to reduce the risk of geothermal drilling as opposed to a detailed risk analysis that would require thorough analysis of previous, site specific exploration efforts. We will assess risk by building measures of confidence of the data. More specifically stated, we will estimate uncertainties for each data type and combine them in the predictive model to estimate the error of the overall favorability estimate. Our inclusion of the degree of exploration provides a measure of how much detailed exploration data are available in each part of the study area. A more robust risk analysis will be possible after subsequent phases of this project, involving both acquisition of new data in promising areas and eventually drilling of geothermal wells. Once those phases are complete, we can more carefully perform a detailed risk analysis, which may involve comparison of this approach to those previously carried out in the development of operating geothermal systems in the region.

Our approach should translate directly to similar extensional to transtensional tectonic settings, such as East Africa, western Turkey, Iceland, and the north island of New Zealand. The overall methodology should also transfer to analysis of different tectonic settings, albeit the details of individual parameters would likely differ.

Translating regional scale features and structural model into areas of high and low permeability: The structural and regional scale models will translate into areas of high and low permeability in several ways. On the regional scale, higher geodetic strain rates and greater density of earthquakes indicate greater permeability, as even low-level seismicity is enough to keep fractures open and higher extensional strain rates clearly correlate with increased dilation on faults and higher frequency of earthquakes. In addition, regional scale gravity features, such as terminations or steps in gravity gradients, are being used to indicate favorable structural settings (e.g., fault stepovers, fault terminations, and accommodation zones) and thus areas of higher permeability hidden beneath large composite basins. For the structural model, structural setting, age of Quaternary faulting, Quaternary fault slip rates, and Quaternary fault slip and dilation tendency will all be combined into ranking fault zones and in particular individual structural settings, with the premise that favorable structural settings, more recent faulting, higher slip and dilation tendency, and higher slip rates all result in greater permeability. The challenge will be in weighting the various parameters in such a way as to produce a credible geothermal potential map. Benchmarks of successfully developed geothermal systems will help with this determination. Also, we plan to produce a suite of maps using different weighting factors as a means of testing various hypotheses and generating constructive feedback from the geothermal community.

<u>Reviewer 29849</u>

Comment: Provide maps of the individual component variables with their uncertainty.

Provide additional maps showing the impact of the variation of the weighting factors if the weighting factors drastically alter the prospectivity of attractive areas. This could be especially valuable to potential developers, who want to gage the uncertainty of success.

PI Response:

We agree. Maps of the individual components with their uncertainty will be provided with this project, in both publications and data provided to the NGDS and DOE data repository. As discussed above, we also intend to provide additional maps that show the impact of varying the weighting factors for individual or groups of parameters. We are intrigued by the possibility of releasing a web application that would allow users to vary these factors themselves depending on local parameters and their own biases, although we fully intend to publish our own best determination based on the multi-disciplinary background and many years of experience of our team.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006726
Project: Low Temperature Geothermal Play Fairway Analysis for the Appalachian Basin
Principal Investigator: Jordan, Teresa
Organization: Cornell University
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 6.0

Comment: This project is unique among the 11 play fairway projects in that it is focused on deep low temperature or direct use.

It is not intended to identify a new resource but instead will improve the understanding of one very large resource and identify its most prospective sites.

No existing direct use types of projects have been mentioned in the application document or the Peer Review presentation so there appear to be no existing calibration sites to determine which prospective areas, if any, may be economically viable. This project seems to be a very preliminary level in terms of potential direct use developments.

The applicant sites economic studies but doesn't provide any results of these studies. The potential impact of direct use in the heavily populated study area could be high if the economics allow. Certainly more economic information would help the standing of this project.

PI Response:

According to John Lund's recent review for the 2015 World Geothermal Congress, during the last 5 years two new direct use geothermal projects in the United States have come into operation. The first involves Boise State University and the second is a district heating system in Lakeview, Oregon. Buescher (2015) provided information regarding geothermal district heating systems in Europe. Excluding Iceland with its obvious high quality thermal resources, it is noteworth that France has 42 systems and Germany has 27 systems. Considering only the German examples with ≥5 MWtherm installed capacity, their geothermal resource temperatures range between 65 °C and 160 °C.

Separate from this Geothermal Play Fairway Analysis Appalachian Basin (GPFA-AB) project, there has been a series of recent studies published that examine the economic feasibility of low-temperature direct use opportunities, much of it focused on the region of our project. The authors of those studies overlap with the members of this GPFA-AB team. Those studies inform our analyses and our methods.

Beckers et al. (2014) developed and used a software tool (GEOPHIRES) to determine the levelized cost of heat (and electricity) that is suited for feasibility studies. That paper explores the economic viability for cases of low-, medium-, and high-grade thermal resources, and reaches the conclusion that even for what they treat as low-grade resources (30 °C/km), EGS for direct-use heat will be cost-effective in the near future. Their results are pertinent to the Play Fairway Analysis because their analyzed low-grade resource end-member geothermal gradient is found in some parts of the Appalachian basin.

Reber et al. (2014) examined for New York and Pennsylvania the competitiveness of Enhanced Geothermal Energy production for district heating. Their analysis used population and climate data to estimate demand for space and water heating, thermal resource maps, models of surface equipment and reservoir performance, and unit cost estimates, to evaluate the cost of developing EGS resources and supplying heat to each community in the two states. They examined the economic impacts of various cases including: case studies representing points in time along a learning curve, for which learning reduces the cost of implementing a geothermal direct heating system; retrofitting an existing direct heat system compared to constructing new ones tailored to this heat source; tax credits or other incentive structures. A significant difference of the Reber et al. (2014) study compared to Phase 1 of this GPFA-AB project is that Reber et al. assumed that costs include stimulation of reservoirs within crystalline basement. In contrast the current project assesses opportunities to utilize natural porosity and permeability within sedimentary rocks, which might reduce drilling and stimulation costs.

Tester et al. (2015) extended the Reber et al. (2014) study with examination of the economic feasibility of deploying a combined heat and power system that includes geothermal district heating system on the Cornell University campus. The design is premised on retrofitting of the existing district heating infrastructure, a supply of 80–129 °C geothermal water, and a hybrid energy supply that adds biomass burning for peak demand in the combined heat and power system. The result calculated would involve a 15% decrease in Cornell CO2 emissions, a 21% reduction in natural gas consumption, and an increase in levelized cost of electricity by only 0.7-0.8 cents/kWhe. The corresponding levelized cost of heat for Cornell campus ranges from 8–13 $/MMBTU, depending on the assumed temperature of the produced water and the reservoir depth.

He (2015) examined the potential geothermal district heating and cooling (GDHC) systems in either the western U.S. where the resource is hydrothermal or in the state of West Virginia where EGS (inclusive of stimulation) is assumed to be needed. Sensitivity analyses showed that the levelized cost of heat diminishes as market demand increased, water production temperature increases, and project lifetime increases, and among those factors the population-driven market demand is the most important factor. A focused analysis of levelized cost of heat was developed for a GDHC system for the West Virginia University campus. Cost models and supply curves were developed, enabling comparison between the costs with the current steam-based system and the hypothetical GDHC system. This analysis probed the economic trade-offs among geothermal water flow rate, supply temperature, re-injection temperature, and the functioning of the heat exchangers. Inclusion of costs clarifies that flow rate is of greatest importance in the total project cost, through the relationship between achievement of a given flow and drilling costs. This finding is informing our consideration of the viability of the various natural reservoirs in the Appalachian Basin. For case studies that probe a range of physical system parameters and three different assumptions about regulatory and taxation, He (2015) finds that the levelized cost of heat and cooling for West Virginia University ranges from approximately 17– 20 $/MMBtu. Placed on a common basis with the current steam-heating system, the most favorable GDHC case is estimated to cost approximately $2/MMBtu more than steam. With a state-wide analysis using population density as a proxy for demand and a map of geothermal gradient that pre-dated our GPFA-AB project, He (2015) also identified 23 population centers (census tracts) whose levelized cost of heat would be less that 30 $/MMBtu.

The studies summarized above evaluated the economic feasibility using different methods for West Virginia than for New York and Pennsylvania. Given those results and the Play Fairway Analysis program's focus on providing an assessment of geological risks, our team has chosen to limit our economic analysis to examination of the spatial variability of the conditions shown to be of most importance in the levelized cost of heat outcomes, using a uniform method.

Beckers, K. F., Lukawski, M. Z., Anderson, B. J., Moore, M. C., and Tester, J. W., 2014, Levelized costs of electricity and direct-use heat from Enhanced Geothermal Systems: Journal of Renewable and Sustainable Energy, v. 6, no. 1, p. 013141

Buescher, E., 2015, Green District Heating – Actual Developments of Deep Geothermal Energy in Germany: World Geothermal Congress, Melbourne, Australia https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/35000.pdf

He, Xiaoning, 2015, Feasibility and Supply Analysis of U.S. Geothermal District heating and Cooling Systems (PhD Dissertation): West Virginia University
Reber, T. J., Beckers, K. F., and Tester, J. W., 2014, The transformative potential of geothermal heating in the U.S. Energy market: a regional study of New York and Pennsylvania: Energy Policy, v. 70, p. 30-44
Tester, J., Reber, T., Beckers, K., Lukawski, M., Camp, E., Aguirre, G. A., Jordan, T., and Horowitz, F., 2015, Integrating Geothermal Energy Use into Re-building American Infrastructure, in Proceedings: Melbourne, Australia, , Proceedings World Geothermal Congress

Reviewer 29848

Score: 7.0

Comment: The goals of this project fall within the broader goals of the Geothermal Office. Specifically, their approach to Play Fairway Analysis identifies the co-location of heat resources, rocks suitable to circulate water, and potential consumers. In addition, this study identifies major faults to avoid, which might be the sites of induced seismicity. This is something most of the other projects do not do.

The project has done an excellent job of identifying and summarizing objectives, risk, and potential markets.

They have completed the validation/alteration of baseline thermal maps and data.

The project is targeted at providing localized sources of low temperature geothermal energy to areas of high population. Potential users want to know whether their location coincides with geologically favorable factors.

They have compiled the data and completed the maps evaluating the potential to utilize low temperature geothermal resources.

In addition, their co-location of favorable temperatures and documented natural reservoirs narrows the focus of potential favorable areas in the PFA greatly.

The project adapts extensive data collected for fossil fuel activity to basin-scale analysis of geothermal resources and risks.

Their approach could be used in other low temperature basins such as forearc basins including the Central Valley in California.

The project has also done a good job of summarizing the required accomplishments, results, and progress to date.

The project seems to be on schedule in terms of achieving the planned goals and objectives.

PI Response:

We appreciate the detailed comments of the reviewer. Altought there is much work remaining to do as we finish Phase 1, we are pleased that the reviewer is satisfied with what we have accomplished so far.

Reviewer 29849

Score: 8.0

Comment: This project is distinctly different from all of the other play fairway projects in that it is mapping low grade heat reservoirs and combining the geologic information with potential market information. Since in the United States there is far more low grade geothermal heat available than high grade geothermal heat, this project could have significant impact. However, the PI's have not identified other areas in the United States beyond their region that they believe are geologically similar and would directly benefit from their methodology.

Their goal is to delineate parts of their study area that are within 3 to 4 km depth had have formations with temperatures between 80 to 120 C that are co-located with potential users. For some of these locations they are doing levelized cost of heat. In those calculations, they are only considering natural porosity and permeability.

Given the numerous population centers in the region and the cold weather, development of geothermal heating could be an attractive business, if the fluids involved do not involve significant environmental hazards. At this point there has been no discussion of determination of environmental issues associated with the potential reservoir fluids and the issues and costs involved in mitigating those concerns. The PI's should detail the potential risks even if addressing them is beyond the scope of the current project.

PI Response:

The methods developed and used in analysis of the northern Appalachian Basin can be transferred to numerous other sedimentary basins that are mature oil and gas provinces. Mentioning only examples in North America that are not already explored for hydrothermal resources, our methods are suitable for use in the Alberta Basin, Williston Basin, Sacramento Basin, San Joaquin Basin, Gulf Coast Basin, Denver Basin, Anadarko Basin, Illinois Basin, and Michigan Basin.

It is true that the project design focuses only on a single environmental risk, that of induced seismicity. The need to isolate the geothermal fluids from the surface environmental waters is certainly important, as the reviewer implies. In a properly functioning low-temperature heat use system, the geothermal fluids will be entirely reinjected, to reheat while flowing from the reinjection well to a nearby production well. Ideally the system is closed loop over a multi-year time span, with the years of that loop dictated by the subsurface flow through the rocks between the two wells. The reinjection connects this topic to the induced seismicity topic, which is a risk factor that we are evaluating explicitly. The injection design risks will be assessed in the permitting process. The need to mitigate the risk of malfunctions that result in surface spills or flow through casing requires the design of a system that stops and contains spills, e.g., of automatic shut-downs if leakage occurs and entrapment of fluids.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 5.0

Comment: The project is using rather extensive but low quality existing deep temperature data as its primary source of information.

PI Response:

The existence of a small number of equilibrium temperature data has enabled analysis of how to correct the BHT for drilling influence. We have examined the well header data for thousands of wells to identify wells drilled using differing fluids, and to treat wells drilled with air as the fluid as more reliable than those drilled with other fluids. In addition to these efforts to identify the highest quality BHT data and correct BHT data, we omit from the analyses shallow (<1 km) wells and use statistical approaches to identify outliers and remove them from further analysis. Whereas single wells with single point BHT measurements are rightly considered to be very low quality temperature information, the use of thousands of wells and the techniques mentioned above result in greater confidence in the broad outcomes.

It is fortunate that the Phase 1 Geothermal Play Fairway Analysis project has provided the opportunity to utilize and analyze in a critical fashion the body of low-quality existing data, whether for temperature or natural reservoirs or structural features.

Reviewer 29848

Score: 8.0

Comment: The project has a well-defined, innovative technical approach. Specifically, they are combining identification of low temperature geothermal resources with the location of densely populated areas where the greatest market exists for such resources.

They create spatially complete heat resource maps by interpolation between wells.

The project tests the sensitivity of temperature-at-depth predictions to uncertain input parameters using locally-derived conductivity stratigraphy for 50–100 wells and Monte Carlo simulation.

The project incorporates permeability, porosity and pressure to rank intrinsic reservoir quality.

Hydrocarbon occurrences dictate data and knowledge regarding the projected reservoirs.

The project appears to achieve the objectives and goals within the limits of the available resources.

Using large data base of oil and gas data as input into their 3D model.

PI Response:

Although there is much work remaining to do as we finish Phase 1, we are pleased that the reviewer is satisfied that our progress is moving toward accomplishment of the goals.

Reviewer 29849

Score: 7.0

Comment: The PI's are mapping the spatial variations of 4 risk factors: human usage of the area (parks, users, etc.), faults, natural reservoir risk, and thermal resource risk. They are compiling four risk maps.

The study benefits from an abundance of oil and gas data -- over 13,000 borehole temperature for depths from 1000 to over 6000 meters. More than 200,000 wells were drilled in area. They evaluated bottom hole temperatures from 27,000 wells that are deeper than 1000 m. Only half have bottom hole depth recorded, so those without bottom hole depth had to be eliminated. Three areas were used to develop borehole temperature corrections. Corrections in one area added as much confusion as the uncorrected data, so they didn't make corrections to the data in that area. This introduces concern about the corrections in the other areas as well.

They are relying on data collected by the states, so they only have borehole temperatures acquired during drilling of the wells and not fluid temperatures associated with production. Fluid temperatures from producing wells are not being used, because that data is in the hands of individual companies. However, given the high value of temperatures from flowing wells, it would be very informative to attempt to collect flowing well data for the most prospective areas. That data could be very influential in attracting commercial interest.

The reservoir rock assessment focuses on the ability to flow fluids, not heat. The reservoir assessment is also based on the O&G databases have compiled by states; they are mapping the proven O&G fields.

The PI's have complained that the fault maps are not very good, because of heavy forestation. LiDAR could be very useful in mapping the faults in the region.

Census tract information was used to determine demand for heat based.

The presentation also mentioned "Lore that the Appalachian fields are from fracture permeability," but the impact of that observation was not explained. If fracture permeability is that important and existing fault maps are inadequate it is a strong argument for using LiDAR to map the faults.

PI Response:

The corrections for the BHT data are a concern for all of us. We are aware that to select a site and have it be colder than predicted is much more costly than it being hotter than expected. Thus, as we complete the resource assessment there continues to be an emphasis on the risk factor associated with the BHT correction used and the confidence related to the values. An analysis that we are adding into the 4th quarter work will examine the extent to which a BHT value/depth pair and the thermal model correctly predicts the temperature at a second depth for which a BHT value is reported in the same well. Mismatches will provide further insight to the extent to which the BHT and corrections are accurate.

Your suggestion for collecting flowing well data in the most prospective areas is part of our plan for Phase II. As we narrow down the areas with lowest risk for potential development, we will look into what companies own the wells and who operates the oil or gas fields, to be prepared to contact them during Phase II to seek fluid temperature data or to ask them to work with us on obtaining the data to prove out the heat resources.

LiDAR is focused on the expression of faults at the surface of Earth. In the Appalachian Basin study area, which is mostly west of the Valley and Ridge province, most of the seismically active faults as well as faults whose reactivation is a concern have little surface expression. In New York, where much of the basin is farmed or under forest cover, there have been extensive studies by the research group of Robert Jacobi (Buffalo University) using remote sensing. The results reveal thousands of lineaments but little insight into which of those lineaments are faults versus joints. The induced seismicity of faults in the Fort Worth Basin, Oklahoma, Arkansas, Kansas etc are examples of faults below the oil and gas production zones in the basins. To identify those deep faults, subsurface geophysical analysis is needed. The use of the EarthScope findings for currently active faults coupled with the edge-analysis of gravity and magnetic data we think gives us better coverage of the deep subsurface basin. Nevertheless, a Phase II focus on a much smaller study area (i.e., several counties) presents the possibility that we should consider LiDAR analyses in addition to collecting other types of geophysical data.

We agree fully that there is a need to better characterize the fractured reservoirs, as the public domain data have provided little information. In Phase 2 we will target a small set of counties, thereby allowing us to focus on a small number of reservoirs in a small set of oil or gas fields. For these we will seek more direct access to private industry data for the fractured reservoirs.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: The play fairway area is huge and the potential resource could also be huge. There are considerable data of variable quality.

PI Response:

We agree.

Reviewer 29848

Score: Not scored

Comment: Objectives and risks are well defined.

The project identifies potential markets as well as potential economic limitations.

Maps of risk factors are easy to understand and integrate into evaluating market opportunities and barriers.

The reservoir rock quality data were collected and analyzed by state geological survey experts.

Along these lines, they have completed the analysis of natural reservoir quality as well as completed draft maps with reservoir ranking and supporting data.

They have analyzed gravity and magnetic data to detect boundaries between rocks of differing properties in order to identify faults with the size and orientation prone to induced seismicity.

They compare potential field boundaries, seismic epicenters, and previously mapped faults to identify faults with likely surface areas large enough to cause a felt earthquake if slipping occurs.

The project originates out of the Engineering Department at Cornell, so there is likely to be more input and interaction from engineers on pertinent aspects of the project than on some of the other projects.

PI Response:

During Phase 1 the participation of engineers has been especially important in development of methods for evaluation of uncertainty and risk analysis. As the four risk factors are combined in the latter part of the project, and continuing into Phases 2 and 3, the value of the participation of energy systems engineers increases. While there have been prior economic analysis of geothermal district heating and cooling systems developed by our team members, this project provides to them much more insight into the combinations of reservoir properties and thermal resources that likely coexist, which feeds into new perceptions of the designs suitable to viable heat systems.

Reviewer 29849

Score: Not scored

Comment: The project target is addressing the identification and use of lower grade heat for space heating in cold regions.

PI Response:

We agree

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The major weakness of this project would lie within a future phase when it comes time to drill temperature-gradient holes. Such holes would need to be very deep and expensive to develop new insight into a specific target area.

PI Response:

While we appreciate the reviewer's comment about the cost of drilling to great depth, the drilling costs in neither Phases 2 nor 3 will be as high as the reviewer may be imaging. During Phase 2 we do not imagine drilling new wells, but instead are planning around being given access to existing deep wells to log equilibrium temperature profiles. While obtaining permission for access to deep wells may be frustrating and often unsuccessful, there are so many wells and so many operating companies that we anticipate success in a set of useful wells. An important outcome of the Phase 1 project with its strict focus on reservoirs within the sedimentary rocks is that it will inform decisions in the future regarding the economic trade-offs of drilling only to the natural reservoir depths and extracting lower-temperature fluids versus drilling to greater depths where temperatures are higher. During Phase 3, given that we are considering lower temperature/lower enthapy applications for direct use (rather than electricity generation), the well depths and costs cannot be readily envisioned by consideration of the costs of drilling to in the western US to temperatures needed for efficient electricity generation.

Reviewer 29848

Score: Not scored

Comment: There could be some economic problems with developing the low temperature reservoirs.

The risks facing investors are poorly known.

Do they need to do more work on the ability of some of their possible reservoirs to fill with fluids?

There appear to be some gaps that need to be addressed in terms of the data and methodology needed for defining the heat resource.

The heat resource is based on few equilibrium temperature wells and sparse thermal logs collected after known post-drilling time lag. They need to develop corrections for the bulk of BHTs.

PI Response:

This reviewer's concerns are well aligned with the concerns that motivate both Phases 1 and 2 of this project.
The series of recent studies published (reviewed above) that examine the economic feasibility of low-temperature direct use opportunities provide general insight to potential investors. Yet this Geothermal Play Fairway Analysis is vital next step, in that it differentiates communities with differing magnitudes of investment risk.

The economic analyses conducted to date suggest that the economic viability of a geothermal district heating and cooling system will be more sensitive to the cost of establishing an adequate fluid flow through the rock to production wells than it is to the temperature of the reservoir (He, 2015). The public domain data available through the state geological surveys provides minimal information about permeability and fluid transmissivity. Phases 2 and 3 need to be designed to provide data that will better describe the natural permeability and perhaps the work that would be needed to enhance permeability and improve heat sweep as fluids move through the reservoir between paired production and injection wells.

The corrections for the BHT data are a concern for all of us. We are aware that to select a site and have it be colder than predicted is much more costly than it being hotter than expected. Thus, as we complete the resource assessment there continues to be an emphasis on the risk factor associated with the BHT correction used, and we have revised our corrections numerous times because of that added focus. An analysis that we are adding into the 4th quarter work will examine the extent to which a BHT value/depth pair and the thermal model correctly predicts the temperature at a second depth for which a BHT value is reported in the same well. Mismatches will provide further insight to the extent to which the BHT and corrections are accurate.

<u>Reviewer 29849</u>

Score: Not scored

Comment: The study has not accessed data held directly by oil companies. These companies may have large amounts of valuable data.

The study has not addressed environmental issues associated with the production and disposal of the geothermal waters.

PI Response:

Yes, the oil and gas industry has a wealth of data, some of which we seek to acquire during Phase 2. For the first year of the project our focus has been using the publicly available data, in which there is more than enough to quantify the basic parameters to determine where within the basin is it more suitable to geothermal direct use applications. As we move into Phase II we will be contacting the companies within those specific smaller sites and asking to work with them.

The amount of fluids produced for direct-use and district heating applications is in the range of tens of thousands of barrels of water a day. In a properly functioning low-temperature heat use system, the geothermal fluids will be entirely reinjected, to reheat while flowing from the reinjection well to a nearby production well. Ideally the system is closed loop over a multi-year time span, with the years of that loop dictated by the subsurface flow through the rocks between the two wells. The water being produced is below the ground water table and therefore wells will be cased to prevent contamination of drinking water aquifers, similar to the oil and gas wells are in this area.

IMPROVEMENTS

Reviewer 23406

Comment: I have no suggested improvements at this time.

PI Response:

Reviewer 29848

Comment: Could also use the gravity and magnetic data to help identify where changes in basement type occur and where fluids are likely to be moving up from depth.

Need to determine what is causing the localized hot spots in their Heat Resource Map.

PI Response:

The maps shown in the May 2015 Peer Review were from 2nd Quarter. As we have continued to work through the processing of the data, the "hot spots" are being reviewed as well as "cold spot". The gravity and magetics data have been analyzed to identify edges between rock bodies of contrasting properties, and if some of those are fault zones there may be a relationship between advective flow in those zones and thermal anomalies.

During Phase 1 we have used the gravity data to identify natural geological basement domains. These provided criteria for placing boundaries on the areas within which to interpolate well data.

During Phase 1 we have not focused at the small spatial scale at which one would expect localized advection to dominate the thermal field. In Phase 2, when the focus is on a small set of counties and a small spatial area, the analysis suggested by this reviewer will be informative.

Whether or not proximity of a geothermal production project to a fault zone is a favorable choice requires an analysis of trade-offs between several factors that are all, at this point in Phase 1 analysis, unknowns. If fault zones enhance upward advection of hot fluids or if faults result in significantly enhanced reservoir properties, one might favor siting production wells adjacent to those faults. However, if major faults zones (or subsidiary faults within the deformation zones of major faults) are sufficiently near failure conditions that the manipulation of subsurface fluid pressures might trigger enough slip to create a felt earthquake, one would choose to site projects at a significant distance from those fault zones. Goals for Phase 2 work include adding the data and analyses that will better inform the analysis of trade-offs.

Reviewer 29849

Comment: The study should attempt to acquire data from oil companies in the high prospectivity areas.

The study should address potential environmental concerns associated with produced ground water that could greater increase costs and lower the prospectivity of some high-graded areas.

PI Response:

Yes, the oil and gas industry has a wealth of data, some of which we seek to acquire during Phase 2. For the first year of the project our focus has been using the publicly available data, in which there is more than enough to quantify the basic parameters to determine where within the basin is it more suitable to geothermal direct use applications. As we move into Phase II we will be contacting the companies within those specific smaller sites and asking to work with them.

The amount of fluids produced for direct-use and district heating applications is in the range of tens of thousands of barrels of water a day. In a properly functioning low-temperature heat use system, the geothermal fluids will be entirely reinjected, to reheat while flowing from the reinjection well to a nearby production well. Ideally the system is closed loop over a multi-year time span, with the years of that loop dictated by the subsurface flow through the rocks between the two wells. The water being produced is below the ground water table and therefore wells will be cased to prevent contamination of drinking water aquifers, similar to the oil and gas wells are in this area.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006729
Project: Comprehensive analysis of Hawaii's geothermal potential through Play Fairway integration of geophysical, geochemical, and geological data
Principal Investigator: Lautze, Nicole
Organization: University of Hawaii
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 6.0

Comment: The impact of this research has the potential to be significant for the state of Hawaii but outside of the shield volcano environment the impact will be more limited.

At the peer review there was no discussion of possible new insights that have already developed from the work done so far.

The project appears to be on schedule to complete all the tasks.

PI Response:

Regarding applicability outside of Hawaii:
The data presented and the weightings discussed are specific to Hawaii, but the statistical approach we have developed is non-specific to any particular location or geologic setting. Instead the overall methodology is broadly applicable - to any geologic setting - in a case where several datasets exist but a significant 'training' dataset is not available. In the equations presented (slide 8), data type "i" is general, has a value of 'a' that is appropriately scaled, and is weighted by 'w' according to input by experts of any setting. Expert elicitation is a significant element - which we have exectuted for Hawaii - but one which will be required in geothermal prospecting in any specific location. This to say our statistical methodology is applicable to, for example, both the Great Basin (amagmatic) and the Galapagos (another ocean island hotspot enviroment) but would require expert input specific to those locations in both cases. The approach then formally takes the expert elecitation to produce probability models.

Re new insights:
At the time of the presentation, we had completed the compilation, scaling, and weighting of historical and current data relevant to geothermal prospects across the state of Hawaii, and used these data in preliminary probability modeling of heat and permeability for the Big Island. Although the model results may not have demonstrated new insights at that time, they are forthcoming. For example, we can now map better defined outflow plumes using both the updated thermal data and fluid geochemistry compilations. And using groundwater flow models we can trace these back to potential source areas associated with rifts and concealed intrusions. These steps add significant new detail to potential resource areas and will help guide specific steps for the Phase II proposal or other future exploration/development efforts. We also plan to maintain this model as a living entity, such that as new MT, well, gravity, EQ or strain data are collected this PFA is updated.

Reviewer 29848

Score: 8.0

Comment: The goals of this project are in alignment with the GTO goals.

Hawaii has the most expensive cost of electricity per kilowatt/hour of any state, so if the methodology of this project is successful, it could have a significant market impact. Specifically, this group is trying to lower the cost of exploration and development by identifying the highest probability resource areas and lower the cost of electricity in the state that pays the most for it.

In addition, they are trying to accelerate development of undiscovered resources because recent findings suggest resources may exist in previously unrecognized area(s). They have begun mapping areas where undiscovered resources might be found.

The last statewide geothermal assessment (1983) found potential resources on all the islands but there has been little exploration since then. This study then represents a significant step forward in evaluating Hawaii's geothermal resources.

This group has probably done a better job than any other in making the public and geothermal community aware of their work and its potential economic impact.

This group has made significant progress since their last quarterly report in terms of gathering and analyzing data.

PI Response:

We appreciate these comments.

Reviewer 29849

Score: 9.0

Comment: This study could have significant impact in the state of Hawaii, because Hawaii pays 3 to 4 times as much for electricity as those in other states. Geothermal resources are still poorly constrained, but the last study indicated potential resources on all of the islands. This study will produce the first probabilistic map for the state. Outcome could be lowering the cost of electricity in the state that pays the most for it.

The PI's noted that while the shield building volcanism in many of the islands is too old for geothermal, much more recent "rejuvenation" is present on all of the islands and could be a source of geothermal energy.

The Pi's said that they, "want to develop a model that is applicable to other areas as well."

The work is getting press attention in Hawaii. Thus far 6 items in the press. Also two technical presentations.

PI Response:

We appreciate these comments and offer a simple point of clarification. Certainly the rejuvenation stage of volcanism is more recent and offers a potential geothermal heat source that is not commonly discussed, however we have not ruled out the possibility that residual heat from the shield stage of volcanism for the older islands is also a potential heat source. Uncertainty is due to unknowns regarding the total volume of intrusive magma and the rate of heat loss, as well as additional complications such as the fact that post-shield volcanism can follow structures (rift zones) formed during the shield stage (especially true for Haleakala volcano, Maui). On several islands, groundwater temperature and chemistry values near shield building structures suggest a magmatic influence (even in the absence of post-shield activity). We are looking at these interesting data in more detail.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 6.0

Comment: The technical approach suffers from one obvious weakness in that the single producing geothermal field on the island is apparently not going to be well characterized as a possible calibration point for other resources along the rift zone. The application document specifically mentions utilizing key known characteristics of the KERZ as a metric but not going the next step to use the geothermal field to try to recognize what parts of the KERZ are most likely to host additional geothermal systems.

The remaining technical approach is reasonable given the geologic conditions of a shield volcano surrounded by the ocean and the relatively limited amount of geothermal data.

PI Response:

We understand and appreciate the reviewer concern, but wish to point out that at the time of the presentation our methods were not finalized, and time constraints limited the extent to which we could present each data type. In fact, we are using data from the KERZ to the complete extent possible. Such data include water well temperature and chemistry, groundwater flow models, nearly a decade of geochemical data from the discovery well (HGP-A, located less than 1 km from currently producing wells) and other exploratory wells drilled by PGV and other exploration ventures in the area, gravity, geologic structures, geodetic strain, seismicity, etc. We further note that the well chemistry data from within KERZ were used to develop the geothermometers used to define geochemical anamolies throughout the rest of the state (although we recognize that using just KERZ data to calibrate the entire statewide study would be problematic due to unique circumstances in Puna - high rainfall, active rifting, recent volcanism). The only data we are unable to use are those from PGV which are proprietary - and in this regard we are in discussion with Ormat regarding mutually agreeable circumstances in which data exchange and/or discussion of their 'conceptual model' may occur. In sum, the data from KERZ has become one of the center pieces of our study.

Reviewer 29848

Score: 6.0

Comment: To identify, obtain, and compile existing relevant geothermal data across the state of Hawaii. However, this group is somewhat limited by the data that is available.

Apply geostatistical modeling to: 1) Rank each data set in terms of its ability to indicate subsurface heat, fluid, and permeability, 2) identify high priority areas for collecting new data, 3) be generally applicable to other settings.

To develop broadly applicable geostatistical methods to produce statewide Play Fairway map(s). Data integration will be undertaken and result in a probability model/map of the state.

Compiled groundwater data will facilitate current and future investigations.

Understanding aquifer capture zones and hydraulic pathways will assist with the interpretation of geochemical data.

Despite having limited data, this group is doing a good job of integrating data, identifying and ranking key parameters, and then analyzing these data using a Bayesian statistical approach. This group provided more detail than many other groups regarding how they will do the statistical analysis and then apply this analysis to identifying undiscovered resources.

PI Response:

We thank the reviewer for their recognition of our efforts to develop a robust approach to integrating a variable and, to some degree limited, amount of data into a coherent assessment of geothermal potential for a unique, ocean island, environment. With respect to the limitations of the available data: we concede that our 'training set' is small, with only one producing geothermal facility statewide. However we have made a concerted effort to be inclusive of any data that may be relevant to geothermal, and the amount of data being incorporated into this study is substantially more than was so in the last (1983) statewide resource assessment. Slide 4 of the presentation lists the >15 datasets we have compiled, and we continue to build on this with projects ongoing concurrently. Our hope is that our approach, of using a broad and diverse set of data that is appropriately weighted, will serve as a guide to other exploration efforts conducted in "greenfield" environments where traditional geothermal exploratory data is limited in extent and coverage.

Reviewer 29849

Score: 8.0

Comment: The data are being compiled into a GIS project. Addressed concern with data quality and how to incorporate it into the geostatistical model. Each data set is being weighted in terms of relevance to heat, fluid and permeability. Probability of a successful plan is weighted based on three properties heat, fluid, and permeability. Each property is weighted on a scale of 0 to 10 with regard to the impact of that property.

A new gravity map is very important in recognizing areas of new intrusives. These are events that happened after the shield building phase. This provides impetus to look at potential in the older islands.

Only one proven resource plus army water well (the drilling of which had to be halted, because temperature at the bottom was much higher than anticipated). That well is in an area of high gravity, which is interpreted as being due to magma.

Challenges: 1) Some data is concentrated in just a few places. 2) Showed examples of use of water well chemistry. 3) Don't have many deep wells or geothermal thermometers, so using Iceland data as a surrogate.

Focus of the work to date is the modeling using a generalized linear model with logistic inverse-link function. That modeling currently shows highest potential at the most obvious areas - on top of the caldera, but they hope to find other resources. They think can find some prospects by refining color scale and eliminating areas that cannot be developed.

All aspects of data quality are being incorporated including when the data were acquired.

Clever use of Hawaiian place names.

They will add some weighting to the probability of future development due to cultural sensitivities, National Parks, etc.

PI Response:

We appreciate the reviewers comment regarding our efforts toward integrating a diverse set of data into a coherent evaluation of geothermal potential.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: Any new potential resources discovered in Hawaii as a result of this project are likely to be seriously considered for development.

PI Response:

Reviewer 29848

Score: Not scored

Comment: This group provided more detail than many other groups regarding how they will do the statistical analysis and then apply this analysis to identifying undiscovered resources.

The geostatistical modeling has already provided provisional maps of the probability for heat and permeability on the island of Hawaii.

This group is applying some innovative approaches to acquiring novel types of data in an area where many types of data typical of a geothermal project are lacking.

The models used by this group will cover and include the various stages of volcanism.

Hundreds of thousands of data points are available for the gravity data.

This group has probably done a better job of any other in making the public and geothermal community aware of their work and its potential economic impact.

PI Response:

Reviewer 29849

Score: Not scored

Comment: Attractive market because of presence of high temperature heat and high cost of electricity.

Attractive new model targeting recent volcanism on all of the islands.

Clever use of Hawaiian place names.

PI Response:

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The area selected for this project consists of shield volcanos which are not particularly representative of the bulk of geothermal resources throughout the world.

This project does not have access to much geothermal data such as temperatures, MT, etc. that are normally used to recognize or characterize geothermal resources.

The sole active geothermal operator on Hawaii is not involved in the project to bring its existing expertise and knowledge into the project.

PI Response:

Re shield volcano environment not being representative:
While our work is focused on Hawaii's shield volcanoes, we have developed a process that can be applied broadly. Clearly, others working in, for example, the Basin and Range, will not be able to directly apply the weighting factors that we use for each of the data sets that we are using; but the structured approach that we are using to compile diverse data sets, and the expert elicitation that we are using to define weights and statistical values, will be applicable in that environment as well as in any other environment where geothermal potential may be present.

Re data availability:
Per the RFP we are necessarily working with the data available. We note that this includes >1500 water well temperatures. Most of the MT surveys were completed in the past 2-3 years; the resultant data are being incorporated as they become available.

Re discussion with Ormat:
We have open lines of communication with Ormat however the information that they can release is limited. We have discussed an NDA with representatives of the company but, as a public institution, we are expected to find an appropriate balance between our obligation to make our findings available to the public in a transparent way and Ormat's need to protect proprietary data and knowledge. And, in fact and practice, our University requires administrative scrutiny and review of any NDA or information sharing agreements entered into by its research faculty. We are working through these details.

Reviewer 29848

Score: Not scored

Comment: Hawaii has a very unique geologic setting, and the methodology developed here may not be applicable elsewhere in terms of discovering and developing undiscovered resources.

Obtaining data from diverse sources could be a problem. The variety of data available may be more limited for this project than for some of the others.

To develop models that incorporate disparate data types pertaining to different resource qualities and with variable quantities and spatial relevance could be difficult.

Fluid indicators of heat may originate some distance from wells; flow paths are also not well established.

Much well chemistry data is dated; prior test methods may have reduced analytical accuracy.

Although the geothermal resources are deep, there are no deep wells.

There are no detailed geothermometers for Hawaii; Iceland studies (e.g. Arnorrson et al.) provide the best surrogate.

PI Response:

Re applicability of methodology:
We disagree. The methodology is here being applied to Hawaii, but is designed to be generally applicable to other geothermal resource settings, where a training dataset is limited or lacking. In fact, the method is not only relevant to geothermal prospecting, but could be applied to natural resources of many different types. We are confident the utility of the method will be appreciated by the geothermal community - and we have already garnered interest from Ormat and following our Peer Review Presentation as well as at the Near Surface Geophysics Meeting earlier in July. Please also see our reply to the related comment on P. A-1.

Re data variety and compilation:
The compilation of the >15 datasets listed on slide 4 of the presentation has been a challenge - but one which we have largely overcome. We now have multiple surface geology, geophysical, geochemical, and water temperature data layer(s).

Re the model development:
Although our presentation and the review was conducted at an early stage of this effort, the members of our modeling team are working very closely with the discipline-specific data analysts (geochemists, geologists, etc.) in a process we referred to as "expert elicitation" to ensure that the model accurately incorporates their expertise into the probability modeling. We feel confident in our statistical approach, and have heard similarly from other teams .

Re groundwater flow paths:
We are in fact limited by what is known here, however flow paths are commonly complex and not well constrained - such that this will be true for most other geothermal prospect areas in which hydrologic and structural data is incomplete.

Dated well data and chemistry:
This again will be true for any diligent compilation of fluid chemistry data. We are incorporating age and reliability factors in the probability modeling that will minimize the impacts of these uncertainties on the resource probabilities.

No Deep Wells:
We disagree. There are a number of deep wells that have been drilled in the Kilauea East Rift Zone (KERZ) as well as well away from the known geothermal area. These include the HSDP well, drilled to 3500 m below sea level, as well as deep wells in the center of Hawaii Island, and deep monitor wells that have been drilled through the basal freshwater lens on Maui and Oahu. We have data from all mentioned with the exceptions of recently drilled geothermal development wells along KERZ.

Reviewer 29849

Score: Not scored

Comment: Scarcity of data. Use of remote sensing data may be a low cost way to fill in some gaps. LiDAR can be very useful in areas with heavy ground cover.

PI Response:

Please see above comments regarding scarcity of data.

Re remote sensing: The blind and deeply buried systems in Hawaii render many of the traditional remote sensing techniques (e.g. hyperspectral, satellite) less useful than some other locations. No LiDAR exists for the vast majority of the state; where it does it is of moderate resolution and therefore does not demonstrate high utility. We are still considering LiDAR for Phase 2 however we are concerned about its cost-effectiveness (for high resolution especially).

IMPROVEMENTS

Reviewer 23406

Comment: The presentation of the project at the Peer Review would have benefitted from some discussion or presentation of data defining the Puna resource as a Hawaiian operating analog.

PI Response:

We agree, and apologize for not including this discussion. The Puna resource highlights an area with colocation of high gravity defining a rift with obvious water chemical and temperature anomolies.

Reviewer 29848

Comment: One of the goals of this group is how to find less obvious but more accessible resources.

This group needs to more precisely determine the age distribution of volcanism.

It is a challenge to recognize exactly which processes cause some of the variables to be related.

If available, they may want to consider incorporating additional low cost data such as magnetics and remote sensing into their data base and undertake statistical analyses of those data.

PI Response:

Re the age distribution of volcanism: We apologize for not being clear on this point. The age of volcanism has been studied extensively and is quite well constrained. Two of the map legends on the presentation slide 7 show the age of vents for each volcano on Hawaii Island. Similar ages exist for volcanism across the state (USGS state map, 2007).

Re inter-relation of variables: We certainly agree that this is a challenge! It is also scientifically very interesting. Our approach has been to design the statistical methodology such that it allows us to incorporate the relationships in a relatively simple way. The Q3, Q4, and final reports will explain this in more detail. We are also in the process of putting together a formal paper (for peer review publication) on this.

Re additional data: See above comments. We are incorporating MT data as it becomes available and anticipate additional magnetics will be a large part of Phase 2. Only very minimal remote sensing data exists in Hawaii, which have not proven substantially useful in geothermal prospecting given Hawaii's anticipated deep (~2 km) resource. Work to date suggests that gravity is most reliable potential field dataset; to date our work has focused on this.

Reviewer 29849

Comment: Leverage low cost remote sensing data to supplement other data sets. LiDAR could be very useful in mapping structure and thermal imagery may also be of value.

PI Response:

We appreciate the comment, and agree, although anticipate remote sensing techniques to be less informative in Hawaii (where the resource is expected to be quite deep ~2km) relative to some other locations. We note also that LiDAR data can be quite expensive, given the remoteness of Hawaii from service providers, and may be quite challenging in areas of dense vegetation coverage where the illuminating beam simply cannot reach the ground surface.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006734
Project: Geothermal Play Fairway Analysis of Potential Geothermal Resources in NE California, NW Nevada, and Southern Oregon
Principal Investigator: McClain, James
Organization: University of California-Davis
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 4.0

Comment: The project suffers from a bit of an identity crisis and a lack of a clear focus. It covers NE California, NW Nevada, and Southern Oregon; but in reality it is mostly a study of Surprise Valley, which is where the majority of the detailed data the project will utilize are located. Surprise Valley is not geologically representative of the Modoc Plateau located west of Surprise Valley or of the plateau region located to its east. It is unclear as to how this project will lead to the discovery of new geothermal resources outside of Surprise Valley or have much of a research impact.

At the peer review the presentation emphasized tasks and schedule but not any new insights gained into the project.

Geothermal resources within the Modoc Plateau such as Alturas and Canby were named but no data or insights from them were presented at the Peer Review.

It is too early in the project to tell if the proposed paramaterization tools will be successful or not. The project claims to be on schedule.

PI Response:

The reviewer is quite correct when he/she points out that our region is relatively large compared to the area that normally would be covered in a geothermal exploration effort. But this is exactly the point of the Geothermal Play Fairway Analysis (GPFA) that was announced in the FOA. Play Fairway analysis in the petroleum industry is usually defined by a project that has two components:

1. First is the concept of a regional (or basin-wide) model. In the petroleum industry this is generally related to knowledge of the depositional system.
2. The second issue is the integration of a wide variety of data (geological-geophysical) into the analysis.

The original FOA for GPFA phase 1 called for an analogous regional approach. In fact, at the start of the Phase 1, our "region" was the smallest among those advocated by the 11 groups. This has led some groups to reduce their regions to a few isolated and known geothermally active areas. Thus, this drastic reduction of the goals of a project runs the risk of it reverting to a typical geothermal exploration effort. Furthermore, it does not advance the goal of exploration for so-called blind systems.

For our project, we have not given up on the GPFA concept, but we did have to develop an approach permitting us to retain our original goal of looking at geothermal resources in the transitional areas between primarily volcanically-hosted systems and those in extensional-hosted systems. Even though our area is small compared to the other projects it is still very large, and our project consists of the following elements:

1) We have selected an unequivocal volcanic system (Medicine Lake) and an equally unequivocal extensional system (San Emidio) as our test examples. In addition to examining geological, geochemical and geophysical characters of the whole region, we have focused on several subregions, where the data are more plentiful.
2) We are using these data to establish important characteristics of the two types of system, and to develop a hybrid set of characteristics to transitional systems.
3) We are applying the results of (2) to two test areas that are in or near the "transition" zone. One of these test areas is Surprise Valley (SV), alluded to by the reviewer. The concern expressed that this was the only area we were really looking at is inaccurate. We are using SV as a model "unknown" area; that is, we are attempting to use results from the two “end-member” calibration sites (San Emidio and Medicine Lake) to see if the SV area would be identified as a geothermal exploration target. In other words, would we reduce the risk of drilling if we did not already know much of the information about SV. Thus, we take issue with the criticism that we are concentrating on SV; collecting as much information from SV is important as it is a key site where we are testing our model. Our second test area is a more broadly defined and poorly characterized Modoc Plateau west of the Warner Mountains. This is a generally poorly explored area and might be termed as a possible blind system. Successful application of our PFA model to SV will raise our confidence in its application to the Modoc Plateau.

Reviewer 29848

Score: 4.0

Comment: Although the goals of this project are very ambitious, it seems like the group is behind in the progress towards their goals, and consequently it is difficult to judge the quality of their accomplishments and results. Either that or the awardees have pushed the completion dates for various parts of the project beyond the time during which this May conference is being held so that they will not be behind on those portions of the project.

Regarding productivity, it is again difficult to judge such items as the value of the accomplishments compared to costs and achievements against planned goals because the presentation appears to be lacking in the display of significant concrete results.

The awardees state that they plan to focus on a new type of play: that of geothermal systems lying in the transitional regions between those systems hosted by extensional regimes and those hosted by volcanic regimes. They state that such transitional regions are common but do not cite references documenting this. It is hard to see how this project will successfully help achieve the GTO's objectives and goals.

They have identified many of the key characteristics for Medicine Lake (volcanic end member) and started identifying key characteristics for San Emidio (tectonic/extensional end member).

In the presentation they state, "The results of this project will be to create an approach to transitional (and sometimes blind) systems throughout the western U.S. and the world." But, not all transitional systems will have volcanic and extensional end members. Will their approach work for transitional systems that have different types of geologic end members?

In the presentation they state, "We would hope to make our results useful to geothermal companies that have or will explore the region." Do they already have any specific companies in mind, and, if so, who are these companies?

It seems like they are leaving a lot of work to be done in Q3 and Q4.

What are they doing to promote and make people aware of their work?

PI Response:

We are attempting to follow the approach of the GPFA outlined in the FOA. We have found that indeed we do not have the analogous "depositional model" that are available to the fossil fuel industry. Our project does rely on a regional model (transitional environment region), and that indeed is a regional model. The Play characterization of two geothermal "end-members" to explore "in-between" systems is indeed ambitious and time intensive. This is not the type of approach that is commonly used in geothermal exploration, which typically relies on very local exploration that does not easily apply to blind systems.

The reviewer asks the question if the approach we have advocated (essentially interpolation between two geological endmembers) might be applied to other "transitional" problems (not just extensional versus volcanic systems). It is certainly a logical approach that should be applicable for any such effort, however at the current time we are confining our study to the transition at hand.

To make our work more visible, we will be presenting a poster on our project at the upcoming GRC annual meeting in Reno. We have been in touch with Roy Mink, who is involved in a drilling project in the SV area, and will be contacting ENEL Green Power, who is also conducting studies in this region.

Reviewer 29849

Score: 7.0

Comment: This study may have more technical impact than commercial impact. The surprise valley is isolated, so it is expensive to get power over the mountains to larger markets. The target is powering resorts and other local power users. It may be difficult to attract developers because the size of the resource would have to be large to justify the cost of a power line over the mountains to larger markets.

As a scientific study of an extensional transitional zone interpolated between two test areas, it could influence studies in similar locations.

PI Response:

We agree that Surprise Valley is isolated. However, it is not the only test case we have identified. We have also identified a segment of the Modoc Plateau, which is more likely than SV to be "truly" transitional, and does not have the same issues of power transmission. The reason for using SV as a test case is to determine if our approach will predict known or new potential drill sites

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 4.0

Comment: The technical approach to the overall project does not appear to mesh well with the geothermal data available within the overall area. By example in the application document the goals are "to establish that regional context, and to identify crucial gaps in data needed provide a full assessment of the risks and opportunities for geothermal resources." It is difficult to understand how identifying obvious data gaps is a technical/scientific approach that will lead to new discoveries in a timely manner. The lack of data is already widely known and recognized.

At the Peer Review Medicine Lake was shown as a volcanically hosted end member but Medicine Lake is highly unrepresentative of the overall Modoc Plateau. There has been no mention of the quantity or quality of the geothermal information from Medicine Lake that will be made available for use in this study. From the maps in the original proposal the Medicine Lake area is outside of the proposed study area.

San Emedio has been selected as the Basin and Range end member site. However, there has been no mention as to what data from San Emedio are available and can or will be used in this project. It is obvious that no person from U. S. Geothermal, the operator of the San Emedio power plant is included as a project participant. The San Emedio gravity map presented at the Peer Review is of poor quality and did not advance the argument that San Emedio will be a viable test case or calibration.

The application document states "We will focus on a new type of play; that of geothermal systems lying in the transitional regions between those systems hosted by extensional regimes, and those hosted by volcanic regimes." However, the great majority of the geothermal information in the area comes from Surprise Valley.

PI Response:

We agree that the available data is not uniformly available across our entire region. This is why we have chosen end-member sites, and why we have chosen two relatively small test subregions. We take issue with the comment that the great majority of the geothermal information in the area comes from Surprise Valley. A great deal of data are available for Medicine Lake and San Emidio as well. Given the significant number of mandatory slides and short amount of time for the review presentation, we regret that more of our synthesized data for the entire play fairway region could not be presented.

<u>Reviewer 29848</u>

Score: 4.0

Comment: Although the awardees have taken on a very ambitious project (focusing on a new type of play; that of geothermal systems lying in the transitional regions between those systems hosted by extensional regimes and those hosted by volcanic regimes) they do not appear to have either the data or the expertise to undertake the requisite play fairway analysis for this problem. Either that or the data, expertise, and methodology are not adequately shown or explained in this presentation.

The premise of this project is that in regions that display a transition between two types of geologic systems, a weighting scheme that is itself transitional between the schemes used in the two end member cases is needed. If so, exactly how will they develop the transitional weighting scheme and then, in turn, develop a (hybrid) PFA model for transitional areas?

What areas are they going to use as test sites for their methodology?

How are they going to determine and handle the uncertainty in each of the various types of data they are using?

PI Response:

The two test sites were clearly discussed in the presentation and in the preparatory material submitted in March (Surprise Valley and San Emidio). The "interpolation" weighting scheme between the two end-member sites is currently being developed. We take issue with the comment that we lack the data or the expertise to undertake this analysis. Our team consists of scientists with varied and well established backgrounds in the field. We agree that this is an ambitious project, and so is the premise of the GPFA.

Reviewer 29849

Score: 7.0

Comment: The study has a technical focus with its primary value a greater understanding of transitional zones. The approach of having two well characterized end members, the volcanic Medicine Lake and extensional San Emidio with interpolation between them is good.

Since there was mention of limited deterministic data between the two end members, the researchers should elaborate on how they will test the validity of their modeling of the transitional zone.

The use of fuzzy logic and other statistical methods is highly beneficial in this case. Those wishing to learn from this case study would benefit from seeing the uncertainties in the data and significant differences in interpretation depending on the weighting of the parameters and the uncertainty.

The PI's should discuss how they will validate their modeling of the transitional zone.

PI Response:

As described during our presentation and materials submitted for the review, we will test the validity of the GPFA for the transitional zone starting with Surprise Valley, with its known and relatively well characterized zones of thermal activity. Once we are successful with Surprise Valley, we will then test the method to the Modoc Plateau, which is the likely location of a transition zone, but is comparatively much less explored. It is there that we may be able to use our GPFA rubric to explore for so-called “blind” resources.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: Surprise Valley has relatively abundant data available for a credible play fairway study. Surprise Valley, by itself, would appear to qualify in terms of size as a legitimate play fairway basin or regional study. Surprise Valley is a location where there are abundant low to moderate temperature resources at accessible depths that could be put to use.

PI Response:

As stated above, the GPFA approach itself was meant to be regional in nature. Although we are initially focusing on smaller subareas, the use of our risk analysis will be applied to our entire study area. Part of our review will identify data gaps that would need to be filled to reduce uncertainties for regions with sparse data coverage.

<u>Reviewer 29848</u>

Score: Not scored

Comment: The UCD part of the team undertaking this project appears to have experience in the area.

PI Response:

<u>Reviewer 29849</u>

Score: Not scored

Comment: This study could provide insights to those working in the numerous other transitional areas around the world. The study has two strong end members.

The PI's have a concept for development of smaller resources in the valley so that there can be local benefit if only small resources are located.

PI Response:

We have observations that apply to the Surprise Valley, and this project is to determine if our transitional GPFA will identify the already-known local geothermal sites at Surprise Valley as an exploration target. Other sites that may be known in SV, or that are not known in the Modoc Plateau will also be evaluated, as well as other known geothermal features (such as Susanville) within our study area.

WEAKNESSES

<u>Reviewer 23406</u>

Score: Not scored

Comment: Weaknesses of this project have already been emphasized in the Impact and Approach criteria.

PI Response:

<u>Reviewer 29848</u>

Score: Not scored

Comment: Few concrete examples of specific data interpretation are shown in the presentation.

The variety of data types available are limited and appear to be highly variable geographically.

The awardees have still not determined where the transition between the extensional and volcanic regimes is located in their study area. Furthermore, the awardees state, "Regions that display a transition between the two types of systems must exploit a different weighting scheme, one that is itself transitional between schemes used in the two end member cases." Consequently, how can the characteristics for the transitional system be weighted differently if the awardees can't determine the boundary/transition between the two regimes?

The awardees also state, "The challenge with this project will be to determine which subset of characters can be applied to transitional regions. Another significant challenge is evaluating areas with significantly different amounts of data coverage." However, it is not evident that they have addressed either of these two challenges.

Another of the issues recently identified is the need to evaluate the reliability of regional heat flow and temperature-gradient data in order to determine subsurface temperatures in specific areas.

Need to explain 3D Visualization Analysis more clearly, how it will be used in this project, and what its benefits are compared to other methods of data analysis.

Need to attain a better understanding of the hydrology in various parts of the study area. The geothermal resource may be masked by dilution from groundwater.

When asked after his presentation whether the group has MT data, the presenter answered "Yes.", but there is no mention of MT data in the presentation.

PI Response:

Because we are working from plays established at two end-members (volcanic versus extensional), the need to know exactly where the transition between the extensional and volcanic regimes is located is not required. Surprise Valley exhibits characteristics of both extensional (e.g. graben) and volcanic systems (e.g. elevated ^{3}He/4He isotopic ratio) and will be used as a test case to determine whether zones of hydrothermal activity in this area can be implied from play characteristics identified at the two end-member sites (Medicine Lake and San Emidio).

<u>Reviewer 29849</u>

Score: Not scored

Comment: Commercial weakness: The local market for power is limited and it is difficult to export power from the valley

Technical weakness: The methodology for testing the modeling of the transitional zone has not been explained in light of the admittedly limited deterministic data available.

PI Response:

We agree that exporting power from Surprise Valley is difficult. However our study encompasses a much larger area with zones of larger market for electricity. Also, commercial viability should not only be based on demand for electricity as direct geothermal use could play (and has played) an important role in many areas within our study region.

IMPROVEMENTS

Reviewer 23406

Comment: It may be a good idea for the team to get together and reassess the overall concept of the project as to whether it can successfully be a transition zone type of study or if the available data are better utilized toward a different focus such as Surprise Valley.

PI Response:

Again, Surprise Valley is only used here as a test area for identifying key geothermal play characteristics established at the volcanic and extensional end-members. The methodology should be applicable to other types of transitions.

Reviewer 29848

Comment: So many improvements are needed in this project that it is beyond the scope of this review to list all of the needed improvements. That being said, it might help to have some engineers on the team.

PI Response:

Providing a constructive answer to this comment is difficult without more specifics. We hope that our replies to other comments have alleviated some of this reviewer's concern. The application of the Play Fairway concept to geothermal exploration is in itself challenging and controversial, and we wonder if this may be part of the concerns raised by the reviewer. We are attempting to go beyond some sort of "geothermal exploration as usual" and to investigate GPFA as an approach. We recognize that such exploratory research is bound to raise some questions.

Reviewer 29849

Comment: Share the plan for testing the validity of the modeling in the transitional zone.

Provide maps showing the variability in the modeling depending on the weighting factors and also on the uncertainty in the data.

PI Response:

We are in that process.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Hydrogeologic windows: Regional Signature Detection for Blind and Traditional Geothermal Play Fairways
Principal Investigator: Middleton, Richard Stephen
Organization: LANL
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 3.0

Comment: The overall hydrogeologic window concept was not strongly developed or convincingly presented in either the original application or at the peer review. This concept has not gathered a significant following within the geothermal community since being presented in 2002. Only one obscure reference is cited in the original application for the existence or importance of hydrogeologic windows and there was no supporting discussion by the applicant at the peer review meeting to bolster the case for the importance of the overall concept. Figure 1 in the original application shows a long deep flow path for geothermal fluid from the Magdalena Mountains to the Socorro Basin that seems highly improbable (long lateral flows through fractured bedrock) and no discussion is presented as to why the fluid could not have flowed on the surface to the Socorro Basin and then commenced its subsurface journey. The structures shown in both the original application and the peer review showed rather typical Basin and Range normal faulting and the work of Faulds and others is cited as support of this concept yet in the northern portion of the Basin and Range the concept of hydrogeologic windows has not gained any evident popularity or followers.

The producing Lightening Dock geothermal system is described as "likely another example of a hydrologic window geothermal system" but no evidence or references are presented to support this statement.

Using boron or lithium in the groundwater to try to trace geothermal fluid flows is not a new concept and it is difficult to see how this is particularly innovative or will appreciably advance our understanding of geothermal systems.

The importance of crustal heat flow modeling to the industry and future exploration is not developed. The source of heat in a geothermal system is relatively unimportant, especially when magmatic heat sources are not nearby.

The remote sensing component is not well described in the original application and was not discussed at the peer review.

For the above reasons this project is unlikely to have any significant impact on the geothermal community.

PI Response:

Reviewer 23406 raised several important concerns that are used to question the potential applicability of our hydrogeologic windows conceptual model. Although our work is somewhat foundational, our goal is to produce insights and new approaches that will find use in the geothermal community. We hope to develop methods that result in significant improvements in exploration, in part by adapting techniques used elsewhere, including in the oil and gas community.

Reviewer 23406 had five specific concerns that we address in detail below. But, in short, these concerns and our response are as follows:

- *The concept has not gathered significant following in northern portion of the Basin and Range.* We agree with the reviewer's observation on the northern portion of the Basin and Range province. Our initial work is focused on the southern portion of the province, where the methodology is quite applicable and has shown promise. We believe, however, that our efforts will ultimately lead to a methodology that is applicable throughout the Basin and Range province.
- *No evidence is given to support Lightning Dock as a hydrologic window geothermal system.* Lightning Dock has been shown to be discharge from a hydrologic window because confining aquitards are missing or breached over a buried horst block or structural high that hosts the upflow from a deep-seated advective groundwater flow system (Witcher, 1988 and Witcher, 2008).
- *It is difficult to see how the B and Li work will advance an understanding of geothermal systems* Our new approach to the use of boron and lithium is expected to improve our understanding of geothermal systems through our innovative upwinding method that traces observed B and Li concentrations upgradient to their likely higher-concentration source.
- *Crustal heat sources are unimportant in the analysis of geothermal systems, yet the study includes crustal heat flow modeling.* We include crustal heat flow analysis in our effort because elevated heat generation from plutonic rocks at shallow levels in the crust creates measureable increases in heat flow and temperature (e.g. Reiter, 2008).
- *Remote sensing is not well described (and presumably not emphasized in the effort)* The remote sensing component of the original application was removed when we were informed that the funded budget was 20% less than the proposed budget. The removal of this component will not impact our effort because all of the other signatures of a hydrogeologic window are direct characteristics of the subsurface.

Detailed Explanation to Reviewer 23406 Comments

The hydrogeologic window play fairway is based on a simple conceptual model of a generalized hydrothermal system, which is a groundwater resource with sufficient heat and fluid fluxes to be economically useful for direct-use heating or for electrical power generation. All hydrothermal geothermal systems have six general characteristics:

1) Heat source.
2) A surface recharge source or zone.
3) Flow path or circulation framework that may include a deep-seated reservoir.

4) Chemical attributes from water-rock interaction at elevated temperature and sometimes fluid and gas inputs from magma or deeper crust or upper mantle.

5) A shallow discharge zone that may include a shallow reservoir and in many cases an outflow plume with or without hot springs.

6) In some cases an alteration cap or zone of silicification may exist in association with hotter systems.

Our geothermal play or exploration model is a specific type of geothermal system with typical parameters fitting the six general characteristics outlined above. Our geothermal play focuses upon the most common type of convective geothermal systems, advective geothermal systems, occurring in the Rio Grande rift and Southern Basin and Range (SBRP) in a cratonic crust with a relatively thin Phanerozoic cover and no silicic magma heat source. Advective systems are known in virtually all tectonic settings.

We recently published an article documenting the applicability of the hydrologic windows concept in in the Truth or Consequences geothermal system, New Mexico (Pepin et al. 2013). The hydrologic windows concept was based on two prior studies published in the Journal of Geophysical Research (Barroll and Reiter, 1995) and in Water Resources Research (Mailloux et al., 1999). The latter two references were included in our proposal. We would be happy to provide this reviewer with all three peer reviewed papers.

The advective (forced convective) geothermal systems in the rift and SBRP have the following geologic characteristics (Barrol and Reiter, 1995; Mailloux et al, 1999; Pepin et al., 2015; Witcher, 1988 and 2008):

1) Discharge at low elevations and frequently near or adjacent regional surface water drainage.

2) Discharge out of structurally-higher terrains (horsts) where confining aquitards are missing or thin.

3) Discharge in areas on or adjacent to rhyolite mid-Tertiary caldera ring fracture zones (not a heat source).

4) Reservoirs include Paleozoic carbonate aquifers, fractured Tertiary intrusives (not heat sources), and volumes of fractured rock associated with Laramide basement-cored reverse faults and drape folds.

5) Rift accommodation zones and normal fault transfer zones; fault tip splays are common discharge sites.

6) Structures that show tectonic inversion frequently host geothermal systems.

7) Discharge from partially buried or low relief horst blocks within or on the margins of rift basins is common.

Advective geothermal systems are single-pass flow-through, large-scale, deeply-penetrating regional groundwater systems in fractured bedrock (Smith and Chapman, 1983) rather than local density or thermally-driven free convective flow systems (Lopez and Smith, 1999).

Geothermal play fairways can include analysis of a gamut of geologic, geophysical and geochemical parameters and approaches that include heat flow, seismicity, young faulting, aquifers, aquitards, aqueous geochemistry, water table elevation maps, structure mapping, geomorphic analysis using hypsometric mapping techniques to understand favorable discharge and recharge areas, gravity surveys, aeromagnetic surveys, SP surveys, and MT surveys, to name a few. Our unique integrated framework combines six of these signatures to focus on the need for heat, permeability, and fluid, under the organizing principle of a Hydrogeologic Window. As Reviewer 29849 under Scientific/Technical Approach below states, we are integrating various types of data, "in contrast to the other projects narrowly focused on one type of data." Please see our response to Reviewer 29848, beginning with the paragraph beginning that starts with "The framework for this project…" for more details on this integrated framework and with the organizing concept of a Hydrogeologic Window.

Petroleum exploration play fairways frequently focus on the quality of hydrocarbon source rocks, reservoirs, and traps. In contrast, a Rio Grande rift advective geothermal system play clearly requires the opposite of traps; this geothermal play focuses on hydrogeologic windows. Open recharge and discharge zones are required components for a regional groundwater system with the long-lived flow required to sweep up heat and chemistry in order to maintain an advective geothermal system (Smith and Chapman, 1983).

Subcrop mapping is used to identify potential hydrogeologic windows for discharge on a regional scale. Discharge hydrogeologic windows are zones at relatively low elevation where regional or local aquitards are thinned or breached by faulting, erosion, or fractured intrusions, allowing relatively rapid vertical flow of geothermal water toward the surface. On a regional scale, subcrop mapping is used to delineate areas with best potential for the occurrence of windows. Subcrop mapping takes advantage of the geologic history of a region and specific structural and stratigraphic-tectonic packages associated with major geologic events and shows where major stripping of regional aquitards is most intense. The subcrop map has been updated since the time of the Peer Review using published geologic maps of the mountain ranges and formation top data from oil and water wells drilled into the intervening basins (see third quarter report). The rock units present beneath unconformity between older rocks and the middle Cenozoic rocks were identified and the subcrop map was constructed in ArcGIS.

In southwest New Mexico, a period of epeirogeny deposition starting in Cambrian left a package of rocks that began with marine sandstone, then carbonate rocks, and finally with shales in the Devonian and Mississippian. The shales represent aquitards and the older Ordovician and Silurian carbonates rocks may act as aquifers today, especially where dolomitization or temporary subaerial exposure contributed to karst or solution permeability. Later, Ancestral Rockies deformation of late Pennsylvanian and Permian, the Bisbee rift of Jurassic and early Cretaceous, and the Laramide Orogeny compression during late Cretaceous created bedrock highs and syndeformational lows or basins. The end result on uplifts was erosional stripping of Devonian and Mississippian aquitards and the thick Mesozoic shale aquitards of the Triassic and Cretaceous that capped potential early Paleozoic carbonate aquifers and highly-fractured WNW and NE trending Precambrian basement zones. The numerous parallel elements of the Texas Zone (lineament) and Santa Rita and Morenci Zones are examples and the Texas Zone structures were repeatedly reactivated, some with major tectonic inversion. The basins culminated in fine-grained deposits that formed additional aquitards. Latest Cretaceous through Eocene andesitic arc volcanism left an average 1 km thick layer of altered andesite flows, lahar, and mudflows across the landscape that act as aquitards. Mid-Tertiary volcanism and extension deposited additional aquitards as early rift basin packages. These aquifer units were stripped during Neogene horst block uplift during the latest stages of Rio Grande rifting. We focus on the subcrop units beneath Paleocene-Eocene rocks that bury the unconformity at the end of the Laramide Orogeny, arguably one of the most profound tectonic events that deformed the region.

Virtually all thermal wells and thermal springs occur in the region delineated by a Paleozoic or Precambrian subcrop beneath Eocene rocks. Areas outside the region of the Paleozoic or Precambrian subcrop have little or no potential for advective geothermal systems. The thermal wells and springs represent known local discharge hydrogeologic windows of advective geothermal systems.

The geothermal system at Lightning Dock discharges from a hydrogeologic window that allows flow across kilometer thick and altered Eocene andesitic flows and volcaniclastic rocks and Neogene basinal silt, clay, and evaporates that form a confining aquitard over deep-seated advective ground water flows in fractured granitic Precambrian rocks and/or mid Tertiary high silica rhyolite. The hydrogeologic window is found in a buried horst block that is structurally very high that is covered by alluvial basin fill (Witcher, 1988 and Witcher, 2008).

Although the use of boron or lithium to understand geothermal fluid flow may not be new, our methodology to analyze these data is new. This approach has three related components: (1) upwinding, (2) forward modeling, and (3) modified spatial frequency distribution analyses to estimate spatial probabilities associated with the upwinded boron and lithium concentration paths.

We have developed an "upwinding" approach to track mathematical particles through the flow field. This new exploration concept considers the dynamics of fluid flow and geochemical tracer transport. Typically, geochemical geothermometers are used to estimate reservoir temperatures in a zero-dimensional analysis. Fluid flow and advective-dispersive solute transport are not taken into consideration. We have developed an "upwinding" approach to track mathematical particles through a water table aquifer. This concept is not new; a similar concept was successfully used in the ore deposits exploration industry to locate diamond-rich kimberlite pipes within glaciated regions of the Canadian Shield (McClenaghan and Kjarsgaard, 2001). Our upwinding approach also builds on the ideas presented by Neupauer and Wilson (1999) to use solute tracers to identify the location of up gradient contaminant sources. We are unaware of any previous work that has applied these concepts to the geothermal industry. In our application, mathematical particles are introduced at the location of the wells that have lithium or boron measurements. Each particle is assigned the measured boron or lithium concentration of their respective well. By examining the trajectories of adjacent particle through the groundwater flow field, the location of the upwelling zone can be inferred provided that there is a relatively high number of wells.

This upwinding approach focuses solely on advective transport. We also developed an approach that takes into account both advective-dispersive solute transport in a formal inverse analysis. A multiple realization-based methodology for locating geothermal upflow solves for numerous realizations of advective-dispersive transport taking into account different source locations was considered (Person et al. 2015). By comparing simulated tracer concentrations to measured values, a source likelihood map is drawn, and the tentative source locations of upflow zones are identified. These approaches require a relatively high density of wells, which we have in our study area.

The forward modeling methodology estimates the source locations by running hundreds of forward models. In this is particular method, we perform multiple realizations (similar to Monte Carlo method) by placing the lithium and boron sources at different locations in the domain. We then perform forward transport simulations using these source locations. By comparing the tracer concentrations at the observation locations to the observed data, we derive 'likelihood' maps that estimate the likelihood of the geothermal source location. A separate approach to estimating uncertainties and the spatial probabilities of the blind geothermal resource is based on spatial frequency distribution analysis and is described in more detail in our response to Reviewer 29848 in the Scientific and Technical Approach section. This spatial association analysis will create maps containing probabilities of the presence of geothermal resources based on a systematic evaluation of all of the observations of the tracers in relation to known geothermal resources. These spatial probabilities will be combined with the uncertainty quantification from the forward modeling and with the upwinding to estimate the likelihood the source of the tracer being a geothermal system.

The primary goal of the "crustal heat flow" component of the project is to identify Proterozoic basement or Tertiary intrusions in New Mexico that might have elevated heat generation using gamma ray logs from deep oil wells that penetrate crystalline rocks. Elevated heat generation from plutonic rocks at shallow levels in the crust does create measureable increases in heat flow and temperature (e.g. Reiter, 2008).

We argued in our proposal that new thinking and approaches are needed in geothermal exploration, beyond the typical approaches used in the geothermal industry. We see a lot of value in using hydrothermal models to help constrain plausible exploration targets. For decades, the oil industry has similarly tracked the formation and migration of hydrocarbons using basin evolution models from kitchen to trap as a routine part of petroleum exploration to reduce risk (Welte and Yukler, 1981). Their success rates are high and oil companies are profitable. While it remains to be seen whether or not transport based hydrothermal models advocated in our proposal can be used successfully in frontier areas, it is worth trying this approach and we appreciate DOE giving us Phase I support to pursue these ideas.

REFERENCES:

Barroll, M. W. and Reiter, M. (1990). Analysis of the Socorro hydrogeothermal system: central New Mexico: Journal of Geophysical Research Solid Earth. v. 95, p. 21949-21963.

Lopez, D. L., Smith L (1995). Fluid flow in fault zones: analysis of the interplay of convective circulation and topographically driven groundwater flow. Water Resources Research, 31, 1489–503.

Mailloux, B. J., Person, M., Kelley, S., Dunbar, N., Cather, S., Strayer, L., Hudleston, P., (1999). Tectonic controls on the hydrogeology of the Rio Grande Rift, New Mexico. Water Resources Research, v. 35, p. 2641-2659.

McClenaghan, M. and Kjarsgaard, B. (2001). Indicator mineral and geochemical methods for diamond exploration in glaciated terrain in Canada, Geological Society, London, Special Publications 2001, v. 185, p. 83-123.

Neupauer, R. M. and Wilson, J. L. (1999). Adjoint method for obtaining backward-in-time location and travel time probabilities of a conservative groundwater contaminant. Water Resources Research, v. 35, p. 3389-3398.

Pepin, J., Person, M., Phillips, F., Kelley, S., Timmons S. , Owens, L., Witcher, J., and Gable C. (2015). Deep fluid circulation within crystalline basement rocks and the role of hydrologic windows in the formation of the Truth or Consequences, New Mexico low-temperature geothermal system. Geofluids, v. 15, p. 139–160.

Person, M., Kelley, S., Kelley, R., Karra, S., Harp, D., Witcher, J., Bielicki, J., Sutula, G., Middleton, R., and Pepin, J., 2015 (in press). Hydrogeologic windows: detection of blind and traditional geothermal play fairways in southwestern New Mexico using conservative element concentration and advective-diffusive solute transport. Transactions, Geothermal Resources Council, v. 39.

Reiter, M. (2008). Geothermal anomalies in the crust and upper mantle along Southern Rocky Mountain transitions, Geol. Society America Bulletin, v.120; p. 431-441; doi:10.1130/B26198.

Smith L, and Chapman D. S. (1983). On the thermal effects of groundwater flow: 1. Regional scale systems. Journal of Geophysical Research, 88, B1, 593–608.

Welte, D. H., and Yukler, M. A. (1981). Petroleum origin and accumulation in basin evolution--a quantitative model. AAPG Bulletin, 65(8), 1387-1396.

Witcher, J. C. (1988). Geothermal resources of southwestern New Mexico and southeastern Arizona. New Mexico Geological Society 39th Field Conference Guidebook, p. 191-197.

Witcher, J. C. (2008). Evidence for large-scale Laramide tectonic inversion and a mid-Tertiary caldera ring fracture zone at the Lightning Dock geothermal system, New Mexico. New Mexico Geological Society 59th Annual Fall Field Conference Guidebook, p. 177-187.

Reviewer 29848

Score: 4.0

Comment: The quality of the accomplishments at this point in the project seems low. This may be because of sub-contracting delays and/or time line compression resulting from these sub-contracting delays. Alternatively, it may be because this project is very heavily weighted toward geologic (and geomorphic) data and has very little geophysical data (gravity, magnetics, MT, seismic etc.). In addition, some of the more quantitative data particularly the geochemical tracer work, which is supposed to identify areas or geothermal upwelling, is hard to evaluate from the presentation, and when asked how unique the results of the geochemical tracer work done to date are, the reply was: "We are working on evaluating this."

It is also difficult to determine from the two slides illustrating the geothermal modeling (2D & 3D hydrothermal modeling framework to assess the role of hydrologic windows) whether this task is, as stated, on schedule. In addition, it is not easy to see from these two slides that the preliminary results are "promising" as stated in the presentation.

The level of productivity for this project at this point also seems low. Again this may be because of sub-contracting delays and/or time line compression resulting from these sub-contracting delays.

Bottom line: It is difficult to determine from this presentation and the work done to date how helpful this project will be in successfully developing methodology for Play Fairway Analysis that can easily be transferred to other projects and areas.

PI Response:

Yes, the reviewer is correct about our subcontracting delays affecting progress by the time of the Peer Review. We have made substantial progress since the Peer Review.

Regarding the comments on the geochemical tracers, please see our response to Reviewer 23406 above, specifically the paragraph beginning with "Although the use…".The work presented at the Peer Review was preliminary, and we have made significant progress in the tracer modeling since the presentation. For example, we have developed two new east-west, cross-sectional hydrothermal models for the southern Albuquerque Basin in the vicinity of the Socorro Magma body and to the north across the Acoma Pubelo that document additional regions containing hydrologic windows. Preliminary model results from these cross-sectional models will be presented in the third quarterly report. A third cross-sectional model for the Rincon geothermal system is under construction as part of this project.

Regional scale gravity and magnetic data available from the U.S. Geological Survey and from the PACES web page through the University of Texas at El Paso have now been incorporated into our structural analysis that also includes the mapping of Quaternary faults, older faults, fault density, dikes, volcanic vents (Quaternary and pre-Quaternary), and earthquakes (see third quarter report). Much of the published MT data in New Mexico lies outside of our area of interest (Española, Santo Domingo, San Luis basins in northern New Mexico). Published AMT data from Kilbourne Hole, MT/AMT data from the Acoma Basin, resistivity and MT data from the southern Albuquerque Basin, and the Socorro, Las Cruces, and T or C regions have been gathered and are currently being evaluated.

The framework for this project integrates outputs from individual analyses in order to enhance the physical understanding of the geothermal system and reduce the risk associated with any future exploration projects. By following this framework, future projects can gain detailed information about the physical properties of geothermal systems—the fluid flow path, the regions that form a reservoir within the flow path, the magnitude of heat in the source, and the areas where there is sufficient fluid/gravitational potential energy to create an advective geothermal system—as well as a means of ranking the regions that have geothermal potential based upon risk (see third quarter report).

Using the physical properties of a hydrogeologic window as the inspiration for this framework, we have identified what each data type provides to the framework. Earthquakes and faults identify regions of potentially increased permeability. Gravitational and magnetic anomalies provide information about the depth of potential resources. The basement map also reveals areas that have been uplifted, resulting in increased permeability as aquitards are eroded. The subcrop mapping reveals the areas that could contain advective geothermal systems (see the reply to reviewer 23406). By analyzing these layers we can exclude large swaths of the study region that do not fit the criteria for a hydrogeologic window. We have created a surface connecting drainage bottoms throughout the region that defines local base level. Combining this surface with the topographic surface, and water table elevation, we can establish which regions are recharge zones and which regions are discharge zones... The water chemistry data is useful for both geothermometry and particle tracking, which will provide information about the magnitude of the resource and the path that the fluid takes to reach the discharge zone. Heat flow and discharge temperature can also be used to estimate the magnitude of the resource. Upon completion of the above analysis, we establish regions that are not hydrogeologic windows, identify regions that are likely windows, estimate the amount of discharge and heat content of each potential window, and locate most likely path that the fluid in the window takes. After determining the error associated with the analysis, the regions can be fully quantified and ranked based upon the risk of failure for exploration.

With all of the above analysis completed, we will have confidence in which regions do or do not contain hydrogeologic windows, the approximate magnitude of each potential window, and the most likely path that the fluid in the window takes. After determining the error associated with the analysis, the regions can be ranked.

Reviewer 29849

Score: 7.0

Comment: This project seems to focus primarily on developing a new technique, upwinding of geochemical data. This technique involves identifying discrete areas in which "breached aquitards" exist. Their deliverables are geothermal and geochemical modeling (open source codes) with a stretch goal of a geothermal energy development code with a hypothetical well with a robustness metric to learn where to get more data. The technology would probably only work in arid environments (e.g. NM., Utah, Nevada, Arizona), but some of those are important potential locations for geothermal resources in the United States.

They have no publications or presentations to date.

Report delays in developing subcontracts and project that resulted in the project starting about 3 months late and a new timeline.

They have produced a water table map for all of New Mexico from almost 90,000 observation points that may have multiple applications in a dry state. They have also created a map of geochemical upwinding tracing flows back to their source.

PI Response:

We thank the reviewer for these comments, including the acknowledgment that we are developing a new upwinding technique as a part of our integrated approach to identifying blind geothermal resources using the conceptual framework of a Hydrogeologic Window. We have described the technique, the integrated framework, and the hydrogeologic window concept above in our responses to Reviewers 29848 and 23406. We refer the reader to those sections for more information.

Regarding publications, we presented a poster at the New Mexico Geological Society Annual Spring Meeting in April (Witcher et al., 2015) and we wrote a paper about upwinding that will be presented at the Geothermal Resources Council Annual Meeting in Reno, NV in Fall 2015 (Person et al., 2015). Other papers about the analysis geothermal gradient/heat flow information derived from the bottom-hole temperature and formation top data from oil and water wells drilled the southern Basin and Range and the Acoma Basin are in preparation. Given the short one-year timeline for Phase I projects, we expect that many of these documented products will be produced near the end or after Phase I. We will add our chemistry and BHT data to the National Geothermal Database System (NGDS). While these outputs are not papers or reports per se, they do contribute to the overall capacity of geothermal researchers to investigate topics of their own. We believe that these contributions to the NGDS will be quite useful to the community.

REFERENCES

Person, M., Kelley, S., Kelley, R., Karra, S., Harp, D., Witcher, J., Bielicki, J., Sutula, G., Middleton, R., and Pepin, J., 2015 (in press). Hydrogeologic windows: detection of blind and traditional geothermal play fairways in southwestern New Mexico using conservative element concentration and advective-diffusive solute transport. Transactions, Geothermal Resources Council, v. 39.

Witcher, J., Person, M., Kelley, S., Kelley, R., Bielicki, J., Sutula, G., and Middleton, R., 2015. Hydrogeologic windows: detection of blind and traditional geothermal geothermal play fairways in southwestern New Mexico. Proceedings, New Mexico Geological Society Spring Meeting, Socorro, p. 66, (poster).

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 3.0

Comment: The technical approach is to a high degree based on stratigraphic control of hydrothermal fluids. This is an overall concept that has not gained any significant following in the Basin and Range province. Unfortunately, the area selected for this prospect is presented by the applicant as a basin and range area.

The technical approach as presented in the application document will most likely be completed by the team but as noted in the above comments the significance of the results likely to be obtained are questionable.

PI Response:

Yes, confining aquitards are relatively impermeable packages of rocks. The "discharge" hydrogeologic windows are "structures" that allow upflow of hot water through fractured or permeable rock. The structures can be folds, faults, horst blocks, fractured dikes and intrusive plugs or any structure that provides important vertical permeability that is structurally high, and at low relative elevation in the landscape. Forced convective or advective systems don't discharge on mountain tops, but they may be effectively recharged by a hydrogeologic window at high elevation.

Great Basin explorers (GBEs) should try our concept. GBEs are encouraged to pay attention to stratigraphy, aquifers and aquitards, and to consider the role tectonics plays in breaching aquitards through faulting, erosion or formation of carbonate karst, etc. GBEs might like it if they try it. It works in the Southern Basin and Range, Rio Grande rift, Colorado Rockies, West Texas, and Wyoming (outside Yellowstone).

We expect that this reviewer's moderate skepticism of the usefulness of our approach and products will be turn around after reading our Final Report for Phase I.

Reviewer 29848

Score: 4.0

Comment: Although the geologic and geomorphic approaches appear reasonable and sound, it is difficult to evaluate the quality and rigor of the geochemical tracer work and geothermal modeling. More detailed information is needed regarding the: 1) methodology, 2) uncertainty, and 3) amount, quality, and spatial distribution of the data used in the geochemical tracer work and geothermal modeling.

It would be useful to have other types of data and analyses that would help verify the applicability and accuracy of the present methodology used in this project.

The number and spatial distribution of the data points for the various types of analyses need to be provided as does the uncertainty of the various data types.

It is uncertain at this point whether the scientific and technical approach employed by this project is adequate to develop accurate PFA models that can successfully be applied to exploration for geothermal resources in other areas.

PI Response:

We appreciate this comment, in part because it helps us to alleviate some unintended confusion. Our responses above address the multiple types of data that we are using and how they are being integrated together under the hydrogeologic framework perspective. We refer the reader to those sections above.

Regarding the tracer work and related confusion, there are 5,493 boron concentration points, 2,104 lithium concentration points, and 3,126 bromide concentration points being used for the geochemical tracer work. These data points have been combed through numerous times during our work. We have taken into account the spatial distribution of the data, we are developing a method to analyze and use the spatial association that the data values have with known geothermal locations. We are using a technique described as Spatial Frequency Distribution Analysis. This method has been used before to provide information about the distances at which geological features have positive spatial association with known geothermal resources (Carranza, Wibowo, Barritt, & Sumintadireja, 2008). Positive spatial association is the positive difference between the cumulative frequencies of observed data and randomly distributed points; when there are more observations within a set distance of a geothermal well than would be expected under a random distribution, this is positive spatial association.

The method described in Carranza et. al, 2008 does not deal with data types that have values associated with locations. We have adjusted the method to fit with spatial statistics literature (Waller & Gotway, 2004) about categorical data in order to identify the degree of positive spatial association of different geochemistry values with known geothermal resources. The categories are adjusted with each value, x, to represent "≥x" and "<x". Upon obtaining the positive spatial association vs. distance curves for these values, we then overlay filled circles onto each point with the coloration at each radial length dependent on the amount of positive spatial association at that distance. Regions of overlap sum together, similar to multiple ripples intersecting. Areas with higher spatial association values have higher probability of a geothermal resource. Using this novel spatial statistical method, blind regions releasing heightened geochemical values may be more easily detected based upon the positive spatial association that such values have with the known geothermal resources in the state of New Mexico.

The geochemical tracer modeling that was shown represented only two of the many realizations that we ran to identify the likelihood of the source location. The general methodology is described under response to reviewer 23406 in the previous section. For uncertainty evaluation we are currently in the process of linking from framework to LANL's RAREDGE which is a uncertainty quantification tool. The details of the resolution and data distribution can be found in the quarterly reports.

REFERENCES:

Carranza, E. J. M., Wibowo, H., Barritt, S. D., and Sumintadireja, P. (2008). Spatial data analysis and integration for regional-scale geothermal potential mapping, West Java, Indonesia. Geothermics, 37(3), 267–299. doi:10.1016/j.geothermics.2008.03.003

Waller, L. A., and Gotway, C. A. (2004). Applied Spatial Statistics for Public Health Data. Hoboken, N.J.: John Wiley & Sons.

<u>Reviewer 29849</u>

Score: 7.0

Comment: These PI's are developing an innovative approach of mapping hydrogeologic windows. The model assumes that water forced low in an area of elevated heat that picks up heat and ions and then may or may not breach the surface. They are looking for a releasing mechanism where fluids can reach surface as opposed to a seal. This geochemical upwinding is their key focus in back-tracing conservative ions to their source to identify blind systems.

The innovation is subcrop mapping of where breaches are located. A "pen and paper approach" is being used with the digital database. Working on finding areas of charge and discharge. Can eliminate charge and discharge areas as being prospective areas for geothermal potential. Currently they mentioned that they are looking at a lot of low grade heat that may have minimal value in a sparsely populated state.

They are collecting all of their data together into a single database that is aligned with national geothermal data system.

Doing inverted modeling to find source to trace outflow back to its source of conservative ions.

Geospatial statistics analysis. Pulling out spatial anomalies and hot spots.

Identified five specific targets with a potential industrial partner. Started conversations with potential partner.

Geochemical tracer, upwinding approach. Focused on hydrogeological modeling. (In contrast with the other projects narrowly focused on a single type of data.) Do have the other type of data and plan to incorporate other data by September.

PI Response:

We appreciate the acknowledgement of the innovative approach that we are developing, and this brief summary of some aspects of our approach. We have emphasized the applicability of our approach, and while it is being developed on sparsely populated portions of the state, its usefulness is not limited to these areas or to areas with low grade heat. Besides, identifying low-temperature resources in rural areas of New Mexico can provide clean, environmentally friendly, low-cost, localized energy to places far from transmission lines and other energy sources.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: It is uncertain as to what the real or innovative strengths of this project are.

PI Response:

We appreciate that Reviewer 29849 above in "Scientific/Technical Approach" states that "These PI's are developing an innovative approach of mapping hydrogeologic windows…" We agree and have emphasized the uniqueness of the methodology elsewhere in our responses to the reviewers. The project combines a real world geologic model for a forced or advective geothermal system as a geothermal play with a variety of fairways such as hydrogeologic windows for recharge and discharge using regional geologic strato-tectonic analysis such as subcrop mapping, geophysics, geomorphology, groundwater flow modeling and analysis, geochemistry and then gives a statistical or probability weighting to the meld the approach into a viable exploration tool to find new geothermal resources. The geothermal source identification inverse method is unique in that we are not aware of any previous works which use this methodology to obtain 'likelihood' maps.

Reviewer 29848

Score: Not scored

Comment: The construction of the subcrop maps appears to be reliable.

PI Response:

Thank you. We appreciate this comment.

Reviewer 29849

Score: Not scored

Comment: They are developing a new concept that could be applied in other arid areas. The concept is applicable to identifying blind geothermal resources.

PI Response:

We appreciate the acknowledgment that we are developing a new concept. Rather than relying on existing and inadequate techniques, we believe that the spirit of the FOA is to add to the repertoire of approaches that the geothermal community may use to find blind resources.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The resume of the PI of this project shows no geothermal experience or geothermally related background.

PI Response:

The PI has conducted and coordinated numerous investigations that require integrating various aspects of subsurface energy approaches. All of the co-PIs have substantial experience with geothermal energy research and applications, and thus the PI is serving the much needed role of an integrator.

Reviewer 29848

Score: Not scored

Comment: More information needs to be provided on the geochemical tracer work and geothermal modeling in terms of the methodology, input data, examples where the specific approaches used in the project have worked elsewhere etc.

How unique are the results obtained from the geochemical tracer work and geothermal modeling?

How many data points went into constructing the La Jencia basin water table diagram?

PI Response:

All the details can be found in the quarterly reports. Uniqueness of the tracer modeling can be found in the response to Reviewer 23406 under Impact of Research, Accomplishments, Results and Progress section.

Reviewer 29849

Score: Not scored

Comment: The uniqueness of the upwinding process was not discussed in depth. The value of the work is strongly dependent on how unique the upwinding paths are or the probability assigned to the existence of specific upwinding paths.

PI Response:

In other areas of this response, we have described the upwinding process and its uniqueness, as well as the two methods for estimating probabilities. See, for example, the paragraph beginning with "Although the use of boron or lithium to understand…" in response to Reviewer 23406 in the section entitled "Impact of Research, Accomplishments, Results and Progress" as well as the response to Reviewer 29849 in the Scientific/Technical Approach section, starting with the paragraph that begins with, "Regarding the tracer work and related confusion…"

IMPROVEMENTS

Reviewer 23406

Comment: At this stage of the project I do not have any viable recommendations for improvement of the project.

PI Response:

We appreciate your other comments and have used them to clarify and focus how we present and explain our approach, its innovativeness, and its potential to complement existing approaches rather than applying the same existing techniques to different areas.

Reviewer 29848

Comment: Provide more information and detailed results for the geochemical tracer work and geothermal modeling work.

What specific type(s) of risk analysis will be used in the project?

PI Response:

The details of the data and the methodology can be found in the quarterly reports. Our tracer methodology will be coupled to LANL's RAREDGE uncertainty quantification toolkit. RAREDGE uses a set-based, information gap approach to quantify geothermal development robustness. This approach uses an ensemble of model simulations.

Reviewer 29849

Comment: The researchers should provide maps showing the probability of mapped upwinding and other potential realizations. The researchers should also compare their method to other geochemical tracing approaches including providing examples of situations in which it would be more beneficial and why.

PI Response:

The usual approach with tracers involves conducting tracer tests on site which are more cost and labor intensive. Our approach involves mining existing lithium and boron data that exists in the literature and using two approaches for source identification, namely: a) upwinding and b) performing multiple forward simulations to obtain source likelihood maps.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006730
Project: The Convergence of Heat, Groundwater, & Fracture Permeability: Innovative Play Fairway Modelling Applied to the Tularosa Basin
Principal Investigator: Nash, Dr. Greg
Organization: Ruby Mountain Inc.
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 7.0

Comment: This is a solid small play fairway project being performed by a small team of four technical people. The one modest sized basin selected for analysis has a reasonable amount of available data to hopefully allow the project to reach credible conclusions in an area where development is viable and desired.

The relatively small size of the project area is a significant challenge to this project identifying multiple new blind resources.

PI Response:

Our study area is larger than the State of Connecticut and is spatially equivalent to many petroleum fairways. Its spatial extent could easily accommodate multiple plays, making it a great test area for PFA. We believe that new resources will be located. This is enhanced by the fact that the basin is a graben with Quaternary faults bounding both sides creating structural zones of enhanced permeability.

Reviewer 29848

Score: 7.0

Comment: The goals of this project are in line with the GTO's Play Fairway Analysis missions and goals.

Although the area is largely unknown from a geothermal resource perspective, the awardees appear to have done a good job with their initial assessment.

The awardees are making reasonable progress. Milestones 1 to 3 have already been met, and a preliminary basin-wide PFA has been completed.

Greater data collection than expected. Lots of unpublished data discovered. PFA uncertainty is based upon data availability.

Addressed issues of potential market. Much of the project area is owned by the Department of Defense, who is very interested in developing local energy grids that are easy to secure.

Technical knowledge gap: Two strategies for PFA. Will create a hybrid model if the training sites for the two models are too limited (which is possible in this area).

Cost benefit analysis will be performed for the identified plays. This is a critical step because the areas for the five plays identified thus far are small and need further refinement to determine their true size.

Market transformation will be initiated by presentations at meetings, in journals, for key stake holders, and on EGI's website.

Further market transformation can be completed by concentrated outreach to the DOD end user community and industry.

PI Response:

Several distinct potential markets for geothermal energy exist within the Tularosa Basin, including three of our nation's premier military installations (Fort Bliss, White Sands Missile Range and Holloman Air Force Base) as well as the El Paso, Texas metropolitan area (home to over two million people). In large part, the project team developed the project due to the potential marketability of geothermal power to these distinct areas. As an example, due to the vastness of both Fort Bliss and White Sands, both installations require power in numerous remote training locations and currently purchase power from several different small electric cooperatives. The power purchased is costly (up to 17-21 cents per kWh) and is subject to frequent interruption.

Reviewer 29849

Score: 7.0

Comment: Their business model is their strongest attribute: The model of looking for resources on military bases is attractive because of the mandates that the military become energy independent. They are probably the closest of any of the projects to drilling a well, even though the underlying interpretation has only been revealed at a very superficial level.

They report that they have made one poster presentation at the GRC meeting in Portland in 2014 and have submitted a paper for 2015 GRC meeting. They have also posted a "PR" piece on EGI's website and had some coverage in the El Paso regional business publication. They talk about plans to publish results in scientific, peer-reviewed journals and state that data collection efforts have exceeded expectation, but it is difficult to verify. The data is described as "not perfect, but sufficient to get good meaningful results." Three single pixel anomalies and two single pixel step-out anomalies near the well that they drilled in Fort Bliss in 2013 are not that persuasive. The two single pixel step-out anomalies may not qualify as defining a play fairway and the other three pixels were in an area of high data uncertainty. Single pixel anomalies could have credibility if they are due to hot springs that have been ground truthed. The PI did not reveal if this was the case.

Their strength is relationship building with local stakeholders. They report that they got access to more data than they knew existed.

The technical presentation was more like a promoters pitch. Single pixel anomalies in areas with little data were discussed as targets. Two of the single pixel anomalies where close "step-outs" from an existing geothermal well, which was identified in by their modeling.

PI Response:

With all due respect, we do not understand what is meant by single pixel anomalies. The plays were constrained by structural geometries known to produce critical stress. In the preliminary PFA model these areas were conservatively spatially constrained by a buffer with a radius of 3 km. This would have contained numerous input data pixels had the model been based upon raster rather than vector data. As new models are developed and further structural analysis is done, the areas will be modified by the results which may increase their size. For instance, the two plays identified in the McGregor Range area have already been merged into a single play that is approximately 5 km x 12 km based upon structure, because it is generally the limiting factor. This area includes the presence of a Quaternary fault, other older normal faults, and an accommodation zone that has been interpreted from gravity data. Accommodation zones are known to produce long-term critical stress and can make good drilling targets. Further work on the other identified plays may or may not suggest extending them and it may be prudent to increase the buffer radius to 4 km.

As for the promoters pitch presentation, this is what happens when you have a very nervous and extremely introverted presenter -- he channels Ron Popeil!

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23406</u>

Score: 8.0

Comment: The technical approach using two methods for the PFA is unique and hopefully will provide some insight as to the relative strengths and weaknesses of the methods.

The project is built on previous geothermal exploration projects in the area which give it a known training site within the basin.

While the Tularosa Basin is small relative to some of the other project areas, it is large enough to qualify as a true play fairway project.

PI Response:

None

<u>Reviewer 29848</u>

Score: 6.0

Comment: Most of scientific/technical approach is based on the development of two modeling strategies for PFA:

1) Composite risk segment maps (CRS; modified from petroleum industry; knowledge-based): The geothermal CRS = Heat, Fluid, and Fault Related Fractures. Risk input and mapping are easy to understand.

2) Weights of evidence (Data-driven stochastic): CRS maps are developed using training sites, however, local training sites (known geothermal systems) are sparse, may need to use additional input to augment the models.

Ultimately, results of the two models will be compared and contrasted to determine which provides the most useful information (never done before). However, the awardees need to show that they have developed and validated a reusable methodology that can be transferred to other areas.

Success/Failure maps will also be developed that couple a heat-in-place model with a business model for each play identified.

PI Response:

We believe strongly that the "best" model developed by this project will be directly applicable to other areas, especially in extensional terrains. In andesitic hosted systems some tweaking of CRS development may be necessary, but the basic logic should prevail. The ultimate validation would be to apply this model in another fairway and have it locate one or more successful plays. Since a similar petroleum industry logic approach is being used in Phil Wannamaker's PFA project in Utah, these two projects may well provide cross validation.

Reviewer 29849

Score: 7.0

Comment: They are making good use of remote sensing that many of the other projects are not utilizing. ASTER analysis - 10 images of nighttime temperatures and mineralogy. The analysis revealed some hot single pixel anomalies (with a temperature cut-off of 80 C). The data is described as "not perfect, but sufficient to get good meaningful results." Three single pixel anomalies and two single pixel step-out anomalies near the well that they drilled in Fort Bliss in 2013 are not that persuasive. The two single pixel step-out anomalies may not qualify as defining a play fairway and the other three pixels were in an area of high data uncertainty. Single pixel anomalies would have credibility if they are due to hot springs that have been ground-truthed. The PI did not reveal if this was the case.

They have specifically targeted military bases and much of Tularosa Basin is military bases.

Their approach is very pragmatic. They are creating risk maps with high, medium and low risk. The uncertainty due to data availability is shown on the maps with cross-hatching indicate where data is needed to reduce uncertainty. They are using training sites in other areas in the basin and range to supplement the sparse training sites within the Tularosa Basin.

A low-cost, pragmatic approach was taken to data gathering -- using personal meetings and the internet. Some of the other projects would also benefit from this approach. Stakeholders meetings yielded significant data results including heat flow, temperature gradients, water chemistry, volcanic ages, Quaternary faults, Bouguer gravity data, total magnetic intensity, ASTER multispectral imagery, DEM, earthquakes, top of ground water, wells. All data was integrated into a GIS database. Areas with data missing were flagged as being high risk, but in their view were in a trend that would indicate low overall risk.

They are using petroleum industry knowledge based standards and data-driven stochastic, weights of evidence.

Success/failure map development couples heat-in-place model with a business model for each play identified.

They describe their approach as, "not brain surgery by any means" but believe that they support development of best practices in using GIS data processing to facilitate an accurate analysis.
They plan to get all stakeholders together to demonstrate what they have done.

PI Response:

Again, the term “single pixel anomalies” is not understood by the team and the plays were not determined by single pixels. Additionally, the plays were not based upon surface geothermal manifestations. In fact, we believe that it is the purpose of PFA to identify plays whether surficial manifestations are present or not, after which they can be validated. The plays identified by the initial model were based upon heat flow, temperature gradients, ground water availability, and structural geometries known to produce critical stress to facilitate fracture permeability. If this project moves on to Phase 2, surface geology mapping may reveal evidence of old hot springs activity that could lend additionally credibility, as could additional geothermometry, temperature gradient data, and geophysics. However, ground truth was, by necessity of the DOE rule of using only existing data, not part of Phase 1 work.

A note on uncertainty: for the weights of evidence model, CRS input layers are being developed using Kriging. This facilitates the development of probability and standard error maps which will be used to develop a final quantitative uncertainty layer for this model.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: Nearly all of the area should be amenable to relatively shallow and low cost future temperature-gradient hole drilling.

PI Response:

It is likely that a large part of the area could support direct use. We are, however, trying to emphasize plays with hotter temperatures that could be either used directly for electrical production or be coupled with solar for electrical production.

Reviewer 29848

Score: Not scored

Comment: Greater data collection than expected.

The data will be incorporated into a GIS database for processing. The processed data will be entered into both raster and vector formats for PFA.

Heat of the earth (heat flow, temperature gradients & geothermometers, potential fault-fracture permeability, fluid for heat transfer) maps have been created.

One of the methods of risk analysis (weights of evidence, a data-driven stochastic approach) is supposed to be a superior data-driven method.

PI Response:

None

Reviewer 29849

Score: Not scored

Comment: The approach to this project is low cost and pragmatic. They have done an excellent job persuading stakeholders to share data and finding supplementary data on the internet. They are making use of remote sensing data.

PI Response:

None

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The project area is relatively small, consisting of only one B+R basin so the quantity of potential resources to be discovered must be relatively small.

PI Response:

The area does constitute a fairway, albeit smaller than some, but as large as many petroleum fairways. Additionally, the resources within can help achieve military energy goals. Even the placement of a relatively small generation facility would have a very positive impact. As an example, McGregor Range - one of Fort Bliss' primary training areas - has a 4-5 MW peak power need. The training range is significant and hosts both U.S. and foreign military trainees year round as well as trainees from several federal agencies such as the FBI, DEA, Customs and Border Protection and others. The project team estimates that the geothermal resource located at McGregor, once developed, could supply all or almost all of the power needed to take McGregor Range off the grid. This would be a significant step for the military toward achieving their Net Zero energy goals.

Reviewer 29848

Score: Not scored

Comment: Although more data may have been collected than expected, the variety and types of data collected may be limited.

The five plays identified to date using the composite risk segment maps are all very small and will need further work to determine their exact size. Three of the five plays are at White Sands Missile Range, and the other two are on Ft. Bliss. One of the plays on Ft. Bliss is the only known geothermal system in the study area. While it is encouraging to know that the analysis did select the only known geothermal system, it is likely that the second point that is "near" this only known system is probably not separate from the known system. In addition, none of the five plays may be large enough to generate economic amounts of energy.

The transferability of their Play Fairway Analysis risk model to other areas also requires more detailed assessment.

The training sites for the risk model evaluation are likely to be limited and small.

Wells penetrating groundwater are concentrated to the northeast and southwest.

PI Response:

Yes, data is limited, but not so much as to preclude PFA. Data is always limited in under-explored areas until interest in geothermal production rises to spur investment for more data collection. This project will identify areas lacking in data, which is an important step in early exploration. This project is also geared toward raising this interest in stakeholders and Phase 2 could provide more data in data sparse areas to locate new plays and help validate identified plays.

The currently identified plays are small, but the size is based upon structural controls and productive geothermal systems are often constrained to relatively small areas based upon fault related fracture permeability. Production wells in several geothermal fields fall within an area of just a 2 or 3 of square kilometers, however, increasing the structural buffer radius to 4 km may be prudent. As for training sites, this area is very similar geologically to many other areas in the Basin and Range that contain known geothermal systems. We believe that we can utilize this to our advantage by using training sites outside of the Tularosa Basin for weights of evidence PFA.

<u>Reviewer 29849</u>

Score: Not scored

Comment: Their identified targets are single pixel anomalies (although they are in what the researchers consider to be low risk trends). It would be useful to see if they can verify these anomalies in some way). A single pixel anomaly due to a hot spring is possible, and could be checked out with a site inspection or perhaps Google Earth.

PI Response:

Again, we are still perplexed by the term "single pixel", but we wholeheartedly concur that play validation is needed. This will be the primary goal of Phase 2.

IMPROVEMENTS

<u>Reviewer 23406</u>

Comment: I have no suggested project improvement comments at this time.

PI Response:

None

<u>Reviewer 29848</u>

Comment: The current key issues are adding additional data to the database, creating two final PFA models, and developing the success/failure ratio map (cost/benefit).

PI Response:

None

Reviewer 29849

Comment: Provide more information on exactly which data they used in their analysis and how they weighted it. Explain in greater detail why they have confidence in single pixel anomalies and how they plan to ground truth them.

PI Response:

The data used in CRS development included (1) heat flow, temperature gradients, and chalcedony geothermometers to represent the presence of heat, (2) water wells, which have penetrated ground water, and the expanse covered by Pleistocene Lake Otero were used to represent areas where fluid is likely to be present, and (3) areas with structural geometries known to produce critical stress/fracture permeability that are associated with Quaternary faulting were used to represent fracture permeability. The three resultant CRS layers were then classified according to risk as follows: (1) temperatures expected for an economic geothermal system, including that of hybrid electrical generation, (>=80 degrees C = low risk, 40-80 degrees C = medium risk-- direct use, and <40 degrees C = high risk, (2) the presence of fluid (binary -- low/high), and (3) the presence of fracture permeability (Quaternary fault present and favorable structural geometry = low risk, Quaternary fault present = medium risk, no Quaternary fault and favorable structural geometry = high risk). Heat flow data classification was done by relating average heat flow values found in known producing geothermal systems in the Great Basin with those in Tularosa Basin. The three datasets were fused in to their respective CRS layers using the ArcGIS Union method. The final three CRS layers were then fused using the ArcGIS Union method to create the PFA model. No weightings are used for this type of PFA.

Single pixel anomalies were not identified – again we are unclear on the meaning of this. Ground truthing identified plays will not be done in Phase 1 because no new data collection is allowed. However, Phase 2 will be geared toward collecting data that will provide significant ground truth. This will include (1) surface geology mapping (this very often results in the discovery of surficial geothermal manifestations if present as well as a better understanding of the geology), (2) collection of additional water samples for chemical analysis to support further geothermometry, (3) temperature gradient drilling. We would also suggest high resolution gravity surveys over the high priority plays to facilitate enhanced structural model development and MT and microseismicity surveys at the McGregor Range play to help better characterize the system, which will help us develop a better 3D geothermal system model.

Review: 2015 Geothermal Technologies Office Peer Review
ID:
Project: Iceland Geophysics: Advanced 3D Geophysical Imaging Technologies for Geothermal Resource Characterization
Principal Investigator: Newman, Gregory
Organization: LBNL
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 7.0

Comment: There is no question that this project addresses the GTO objective of "new and innovative technology development". MEQs and resistivity gleaned from MT surveys have long been used to try to identify geothermal fields. However, MEQ's can be caused by non-geothermal events and MT-revealed low resistivity zones can be caused by clays, metallic mineralization as well as non-thermal brines. This project seeks to create inversions that combine MEQ and MT results so as to minimize these ambiguities. Moreover, the project is testing their inversions by using actual field data from three Icelandic geothermal fields and one USA field (Coso).

The Coso data is especially helpful because there was existing MT and MEQ data as well as long term production from the field. Accordingly, the researchers could use the data, create their inversions, and try to correlate the results with known productive zones, known low resistivity zones, and focused MEQ zones.

The project has employed the services of Swedish, Icelandic, and American experts, so the quality of the work is very good. A great deal of progress has been made towards the achievement of the objectives, but overcoming scale-related problems is still a challenge. (The imagery produced is still too large to be of practical use in the field).

The principals have worked diligently and have produced a great many publications and inversions that are getting close to accurately mirroring actual conditions. There is more to be done to refine the inversions, but every degree of accuracy is harder to achieve than the last. This is an excellent project and it may have significant impact on geothermal exploration in the future.

PI Response:

Reviewer 29850

Score: 5.0

Comment: Objective was to develop improved electrical and seismic imaging methods to 1) characterize subsurface structure, 2) identify fluid locations, and 3) characterize fractures. Five year project was concluded at the end of FY14.

If successful, project could provide a non-invasive method to better characterize the subsurface. As to the project objectives:

1) Characterize subsurface structure, the project has made progress on mapping subsurface structures, the joint inversion while constraining the geologic structure.
2) Identify fluid locations, this object “map fluid bearing structures” was not met. Some progress was made with identifying magma bodies.
3) Characterize fractures was not met, some consistence was illustrated between micro seismic and resistivity but not “charactering the fractures”

1. Quality – The project has produced 3 students, 1 PhD, 2 MS and a number of journal articles suggesting that the quality of developing the methodology was high. Too little data was submitted for this review to independently assess.

2. Productivity – A number of theory/applied papers were produced in association with this project. I will assume the subcontracts were responsible for these results.

PI Response:

Reviewer 23532

Score: 9.0

Comment: This project has made notable progress in showing the efficacy of utilizing advance seismic and MT analysis for exploration of geothermal systems in high-temperature environments. Project goals were, or will soon be reached. Some delay in completion was outside of the control of the PI. Of particular impact was the utilization of several advanced MT analysis codes allowing direct comparison of their results. It is likely that these methods will be utilized by geothermal developers and their geophysical contractors.

PI Response:

Reviewer 23554

Score: 5.0

Comment: The original SOW proposed development of a coupled imaging process using micro-earthquake recordings and electrical resistivity surveys to map fluid bearing fractures. The project accomplished the coupled interpretation; however, "fluid" is still largely an inference and each inversion is unique to an individual system.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 8.0

Comment: As previously stated, this project has been conducted by experts in the seismic and electromagnetic fields from Sweden, Iceland, and the USA. They have access to and have employed state-of-the-art techniques, instrumentation, software, and out-of-the-box thinking to reach their objectives. The group has carefully reviewed the field data from four geothermal sites in different geologic provinces, re-processed the data where appropriate, and undertaken multiple inversions to test the similarity of the predicted results with actual field conditions.

To date, with funding used up and the project suspended, the results have been promising. The next step will be to hone predictions down to smaller scales so that the predicted interest areas (high temperature and fluid-filled fractures will be small and accurate enough to be useful to field explorationists in the future.

PI Response:

Reviewer 29850

Score: 5.0

Comment: It is hard to present 5 years of research in a 20 minute talk. The geophysical inversion problem is poorly constrained. Coupling the inversion of independent geophysical measurement is one way to better constrain the problem.

PI Response:

Reviewer 23532

Score: 9.0

Comment: The approach was very good. It was well thought out and benefitted greatly by the strong technical team. Coupling of advanced MT modelling and seismic studies has provided new insight into the structure of the geothermal systems studied. Utilization of more than one MT code also strengthened interpretation and provided a direct comparison of the codes.

PI Response:

Reviewer 23554

Score: 5.0

Comment: The project illustrated inversion of joint data sets. Asserting that something new has been done does not necessarily demonstrate the applicability or utility of the process.

PI Response:

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: A strength of this project is the novelty of the idea to jointly invert data from two very different geophysical techniques so as to produce new imagery that will accurately display the results of both techniques together with the mapped subsurface geology and the known geothermal fluid production characteristics. Another strength is the use of real data collected at four discrete geothermal fields at which many different MEQ and MT signatures have been recorded. The researchers have created joint inversions and then been able to test their validity under different field conditions.

A final strength of the project is their use of experts from different institutions where the technical approaches can differ from one-another. This assures that there will be little "rubber-stamping: of ideas going on and that multiple techniques will be used to create the inversions.

PI Response:

Reviewer 29850

Score: Not scored

Comment: High quality team members work on the problem.

PI Response:

Reviewer 23532

Score: Not scored

Comment: A very well thought out and conducted cooperative study utilizing state-of-the-art seismic and MT models to investigate structure, alteration, fractures and fluid pathways.
The results of this study directly impact the ability to understand high-temperature, volcanic hosted geothermal systems. Similar work should be continued utilizing these geophysical methods and the joint analysis process in order to develop

similar techniques for use in geothermal system of a different nature (i.e. Basin and Range and Cascades) and lower temperature systems.

PI Response:

Reviewer 23554

Score: Not scored

Comment: Coupled interpretation.

PI Response:

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The primary weakness of this project, and one acknowledged by the researchers, is the matter of scale and accuracy. In drilling for geothermal resources, one must have well defined targets such as major faults that may not be obvious on the surface. This project appears to be accurate to within about 0.5 kilometers (1640 feet, or more than 5 football fields). This is really not accurate enough to be useful to field drilling planners.

Also, not all geothermal fields have MEQ signatures. In these cases, there can be no joint inversions. Therefore, the plan is going to be somewhat limited in its potential use internationally.

Finally, it appears that a very powerful and expensive computer must be available to run thousands of iterations of data inversion. This means that the technique will be limited to developers with enough money to be able to access such computing power. This may also reduce the practicality of using the inversions in third world country with small financial resources.

This technique has great promise, but needs to be further refined. Funding should be provided for renewed accuracy attempts.

PI Response:

Reviewer 29850

Score: Not scored

Comment: Although the methodology has been applied to several geothermal sites, it is not clear if the GTO has a tool that is applicable to other sites with less data.

PI Response:

Reviewer 23532

Score: Not scored

Comment: The only weakness may be that the geophysical methods and the approach to analysis may not be appropriate for lower temperature systems in different geologic setting. This could be remedied by additional funding for similar studies in different environments

PI Response:

Reviewer 23554

Score: Not scored

Comment: The stated promise of imaging fractures is misleading. From a geophysical standpoint, the methods may image a large bulk volume that could be fractured. This is not a significant improvement over other bulk MT or MEQ interpretation. Useful imaging of individual fracture zones and drilling productive wells to intersect those fractures is still an unrealized promise. While the joint inversions provide some refined imaging of large-scale bulk features, the refinement changes a series of fuzzy blobs into a series of slightly less fuzzy blobs. The promise of the SOW was to image fractures and fluid distribution in geothermal systems. The reality, as with many previous studies, is that bulk geophysical characteristics in 6X10km blocks are used to infer fractures and infer potential fluid distribution but not necessarily to directly image individual fluid bearing fractures. The work presented still does not uniquely "image fluid distribution" as stated in the SOW and project objectives. Instead, as in many geothermal systems, the method maps alteration, mineralization etc. and the effects of heat and fluid circulation are inferred but direct fluid detection is still not accomplished.

The surveys were done in producing geothermal fields but there was precious little if any attempt to correlate the interpreted geophysics with well data. More than 100 wells have been drilled within the Coso field but the summary documents use circulation losses from only one well in that system and the majority of the loss zones in that well are not mapped as faults on the geophysical cross-section. Instead the cross-section was presented as a cutting edge result based on the assertions that the new joint interpretation agreed with an earlier interpretation of seismic data. This is not validation of the geophysical method or the processing. As presented, the methodology may be numerically impressive but has no ground-truth constraints.

PI Response:

IMPROVEMENTS

Reviewer 23478

Comment: 1. Improve the inversions so that they can identify fluid filled fractures within a few meters horizontally and vertically

2. Design software that can be obtained at a reasonable cost and can be run on computers readily available world-wide.

3. Simplify the inversions so that "average" field personnel can enter raw data from MEQ and MT surveys in order to obtain fault locations accurate enough to be of practical use to them in designing drilling patterns and targeting.

Sorry, there is no way that I can use 500 words on this section!

PI Response:

Reviewer 29850

Comment: Reviewer did not provide comments for this criterion.

PI Response:

Reviewer 23532

Comment: Continue similar work on systems in different geologic settings and at lower temperatures,

PI Response:

Reviewer 23554

Comment: Three of the four interpretations were done for geothermal systems in Iceland. How is this a rational use of US DOE funds?

One of the interpretations required processing in a Cray supercomputer. Impressive. How could this ever be considered transferable to industry?

The final project cost was $4,807,839 (slide #26); roughly the cost of drilling a well. Would that be a better way to actually achieve the stated objectives of characterizing subsurface structure, identify fluid locations and characterize fractures plus measuring reservoir characteristics, establishing productivity and confirming an actual resource?

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006728
Project: Geothermal Play-Fairway Analysis of Washington State Prospects
Principal Investigator: Norman, David
Organization: Washington Division of Geology and Earth Resources
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 3.0

Comment: This project is really not a play fairway study as described in the FOA. It is basically a geological study of three separate geothermal prospects in two much different geologic settings. One setting is classically on the sides of active volcanos and the other is a structural setting not near a volcano. One area, Saint Helens, is largely within an area that would be impossible or very difficult to develop if a resource were to be recognized. The three areas are not of a regional or basinwide extent covering thousands of square miles, they cover tens of square miles. These three areas all lack any existing plays, other than thermal springs with minimal previous surrounding exploration efforts. No specific models for these plays were presented in the application document. For these reasons it is difficult to see how there will be a significant impact from this research project.

The progress to date is reported to be on the proposed schedule. Accomplishments to date primarily consist of gathering data so no comments on the results can be made.

It is very difficult to see the results of this study leading to the discovery of new resources.

PI Response:

1. Our project as a Play Fairway study: the FOA states that “A geothermal play can either be based on the characteristics of a known field or prospect, or on a concept… Some play types are well documented with actual examples, while other play types may be conceptual or speculative in nature”. This project focuses on under- or unexplored regions (the GTO target areas for the PFA) in the Washington Cascade Range, a region with no documented examples, but within a volcanic arc setting that we speculate to have high favorability for hosting a geothermal system. Other volcanic arcs around the world (such as Indonesia) have been successful in a similar geologic play fairway setting.

Why only three areas?: This project builds off of the larger statewide geothermal favorability analysis conducted by Boschmann and others in 2014, where they analyzed the entire state for geothermal favorability based on a variety of heat and permeability factors to locate areas to focus future research. The proposed and approved scope of the current project focuses on three promising plays identified within the previous statewide study in an attempt to understand and develop end-member benchmark resource types within the region that will be useful for identifying additional plays within the Cascade Range. The FOA states that "this analysis should be conducted on a regional (basin) scale, with the resulting maps covering areas up to several thousand square miles". Since we are not researching basin- and range-type systems, but an active volcanic arc setting, instead of analyzing a basin, we are looking at geothermal potential around active volcanoes and in other promising areas along the Cascade Arc.

An important goal of this project is to develop viable methodologies for exploration based on existing data sets that work in the three distinct plays represented by these sites within the volcanic arc fairway. Despite high potential for geothermal reservoirs implied by active volcanism, the lack of systematic exploration, identification, and testing of plays in these areas is precisely why this study is needed.

Feasibility of Play-Fairway Analysis in the Washington Cascade Range: Because no resources are developed in Washington State, or in the northern Cascade Range, there is no existing model or cookie-cutter approach that can delineate favorable areas; instead we are using the existing data and the statewide model to analyze the three most promising sites identified in that study. Our approach starts with existing data sets, characterizes these three promising end-member sites to benchmark methodologies, then based on this initial assessment identifies both locations for increased scrutiny, and which parameters the assessment of geothermal potential is most sensitive to. This methodology and uncertainty model will guide the acquisition of new data (e.g., temperature gradient wells, geophysics such as MT, or LiDAR to improve fault trace resolution) which, as required by the FOA, is part of the next Phase of the Play-Fairway project. From this systematic approach, we are working towards an exploration methodology tuned by application to the three areas, which can then be extended to other locations. .

In the U.S., the magmatic arc has yet to be exploited for geothermal resources unlike extensional settings. For geothermal to be a viable resource base in the long term, such a larger and potentially significant region cannot be ignored. Without exploring for new resources and testing innovative modeling techniques on the readily available data, nothing could get developed. We are hopeful that our research will lead to the discovery of a new geothermal site, and a model that can help guide future exploration efforts.

Status and Progress of Work: The work to date includes data gathering, but also includes extensive analysis, modeling of all the three sites, as well as beginning the uncertainty analyses. The Mount St. Helens seismic zone study area was the focus of the presentation because it was the first of the three areas that was modeled, and the limited time precluded detailed discussions of multiple areas. As might be expected, development and implementation of new methodologies at the first site took the longest. Building on this initial development, the work at the remaining two sites is progressing rapidly.

Feasibility of the Mount St. Helens seismic zone study area: The Mount St. Helens seismic zone study area was the focus of the presentation because it was the first of the three areas that was modeled. The actual volcano lies within the Mount St. Helens Volcanic Monument, but the study encompasses the seismic zone, an area that surrounds the monument where the Department of Natural Resources (DNR) and USFS manage lands, and Weyerhaeuser and AltaRock hold leases that have the potential to be exploited for geothermal development. The seismic zone is a north-northwest trending zone of enhanced seismicity that extends 30 km south of Mount St. Helens (into the north end of the Wind River valley, one of our play fairway study areas) and 60 km north of the volcano. Our study area includes Mount St. Helens as a heat source, but the volcano is NOT being considered for exploration.

<u>Reviewer 29848</u>

Score: 5.0

Comment: Appear to be trying to evaluate geothermal prospects in Washington state using PFA but: 1) are only looking at three areas, 2) are only looking at two main parameters (heat and permeability), 3) amount of data going into their models is limited, and 4) although they said during the question and answer period that they are looking for industry partners and trying to identify potential markets, these items were not mentioned in the talk.

Given some of the unique characteristics and problems of the study area (high precipitation, dense vegetation, high relief, volcanic regime), it is difficult to see how these awardees will develop a PFA model that is easily transferable to other areas.

It is disappointing that at this point in the study; they have only begun working on a model for Mt. St. Helens. The progress of these awardees toward the GTO goals appears to be limited at this point.

PI Response:

2. If conducting a Statewide assessment, Why only three areas?: The statewide geothermal potential model was already completed in 2014. This model already includes a majority of the available heat data within the Cascade Range. We are currently building off of that analysis and looking in more detail at three of the most promising areas from that study, concentrating on improving the methodology used in analyzing permeability.

Please also see the response to this question in the responses to Review 23406 Comments above concerning the Why only three areas?

Why only heat and permeability?: The factors influencing heat and permeability are the two main components of this study. We are not addressing the fluid component in this part of the study because we have no operating geothermal reservoirs or wells to test.

Lack of data: This study represents a largely green field exploration scenario where data is limited and the majority of data is at a regional scale. Despite that, promising plays are evident from the 2014 regional analysis and this study provides an effort to characterize them by improving the resolution of the analysis and directly addressing the structural/geomechanical controls on permeability, again using existing data. Once characterized, meaningful, targeted acquisition of new data can be conducted.

The magmatic arc of the Cascades represents a potentially huge resource base, which is currently poorly explored. We expect lessons learned from the characterization of the three plays to be transferrable within the larger fairway setting. We also expect that our measured approach to data gathering guided by prior analysis should reveal which data sets are most beneficial, inform how to deploy them, and thus cut the overall cost and increase the likelihood of success of exploration. Thus we will provide a tested exploration methodology and key play models, which do not currently exist within the region. In addition, our modeling methodology utilizes data that is typically available in most states and our approach to identifying unknown, or underexplored geothermal targets can be used in other magmatic settings around the world.

Industry partners: Our project partners, AltaRock Energy Inc. hold geothermal lease areas in two of the three plays in agreement with the Weyerhaeuser Company to perform geothermal exploration work. AltaRock also has additional leases in Oregon and Northern California, to which methodologies and lessons learned from this study can be applied. The Snohomish Public Utility District no. 1 is also supportive of our exploration, as is the USFS, who recently consented to lease many parcels of land in the Mount Baker area for geothermal development. We are working with our local industry partners, and will continue to talk to the geothermal industry to look for support and potential collaboration in the future.

Addressing precipitation and vegetation: The high amounts precipitation and vegetation are two difficulties of working in this area, and they are challenges that exist in the whole Cascade Range, as well as in other parts of the country. Many of the geologists who mapped in these areas used LiDAR to map structures and to help see past the vegetation. The parameters of our current model are not affected by precipitation and vegetation, and so we are not addressing them in this study. However, in the future we hope to acquire LiDAR coverage for the entirety of the study areas to help delineate new structures.

Why only the Mount St. Helens seismic zone study area was presented at the Peer Review: When the presentation was made (one month before the actual presentation) we only had results for the Mount St. Helens seismic zone study area. Since then we have modeled all three plays and have begun the uncertainty analysis. Our modeling methodology utilizes data that is typically available in most states and our approach to identifying unknown, or underexplored geothermal targets can be used in other magmatic settings in the cascade arc, as well as other areas around the world. There are many more volcanoes and seismically active areas within the Cascade volcanic arc that are also promising for exploration. The lessons we learn with this study and the modeling methodology we establish can be applied to other sites within the Cascade volcanic arc.

Please refer to the response to Reviewer 23406 above concerning the Status and Progress of Work.

Reviewer 29849

Score: 5.0

Comment: The impact of this study may be limited, because of limited data and missing some important data sets. The team should make use of available LiDAR for fracture mapping.

Better cooperation between the project Play Fairway PI's would be beneficial. In his presentation on the central Cascades, Wannamaker played "gotcha" with the Washington State PI's including pointing out that he had gotten access to some proprietary data covering their area. Since he knew that the existence of the MT data was not widely known, he should have shared that with the Washington State Team. Since the projects are competing in the downselect process, examples such as this of the projects competing rather than supporting each other can occur.

Their use of a tool that incorporates psychology and statistics could be a best practice. It would be good to document how much difference use of that tool made in their results.

PI Response:

3. Impact of study and lack of data: The FOA stated that the goal of this project is to explore areas that are under or unexplored, and the entire Washington Cascade Range as well as our three plays fit into this category. The purpose of the PFA is to use the available data to learn as much as possible about a region and then to determine what data is missing and would be beneficial for further exploration.

A limited data set is expected at the onset of exploration. Our study will clearly have an impact because it organizes existing data, implements a new methodology to refine assessment from this data and will identify what data sets will provide the greatest improvement to the geothermal assessment on a per site basis.

Please also see the response to Reviewer 23406 above concerning the Feasibility of Play-Fairway Analysis in the Washington Cascade Range.

Use of LiDAR: This addresses the comment about utilizing LiDAR for fracture mapping. We agree that LiDAR is a vital tool for exploration in the densely vegetated Cascade Range, it is one of the tools geologists who mapped in these study areas have utilized in the past to aid in their mapping, and it is one of the tools that we hope to use in future analyses. However, at the present time we do not have enough LiDAR coverage to map fractures/lineaments without biasing our results by having only some portions of the study area mapped at this scale. Washington State is committed to collecting LiDAR coverage for the entire state and we will incorporate LiDAR data as we move forward with this project. Additionally, the time and field work required to accurately analyze and field check the lineaments seen in the available

LiDAR was out of the scope of this project. That work would be welcomed as a part of Phase 2, and could be guided by the work of the current phase to rank the priority of data and regions for characterization at each site.

Cooperation between PI’s: We agree that there should be better cooperation between PI's of different PFA projects and projects within the Cascades range in general. We have been in contact with other PFA studies. The WADGER team did contact Phil Wannamaker in January to ask about any MT data he may know of in our study areas. He was helpful and shared the available data he knew of; he also told us about the Mount St. Helens MT study. Unfortunately, that data is proprietary (and he was not the one who collected it) and so he is not allowed to share it. We will actively seek all data sources to constrain our analysis, but must also realistically operate within the limited project timeline and budget as we seek additional data.

Analytical Hierarchy Process: We agree that the Analytical Hierarchy Process (AHP) is a great way to incorporate expert opinions and to assign weights to different variables. We will do a sensitivity analysis to see what difference it would make to evenly weight the input parameters instead of incorporating the weights.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23406</u>

Score: 3.0

Comment: It is disconcerting that neither the PI nor the second person on the team list attended the Peer Review. Instead, the presentation at the Peer Review was given by a person apparently not involved in the preparation of the application. By no means is this statement intended in any way to denigrate or downgrade the quality of that individual who made the presentation or the presentation itself.

The three areas largely lack significant temperature, MT, etc. data that are normally associated with geothermal reservoir studies.

It is difficult to see how this approach will lead to the kind of results that the geothermal community wants and needs.

It is too early in the project to determine how the overall interpretative tasks will work out.

PI Response:

4. Discrepancy between person giving the talk and the PI: The person giving the presentation was specifically hired to work on the project after the application was prepared and approved. She is now coordinating project components, reporting to the DOE, and conducting research in collaboration with the PI. 100% of her effort is on this project, therefore she was the best person to present at the Peer Review. Please note, that several Co-I’s were present at the Peer review and in the audience to provide additional details about specific sub-components as might have been necessary.

Lack of data in the three study areas: The three areas, like the majority of the state, have not previously been explored in detail, and thus some traditional data sets are not available (such as MT, extensive down-hole temperature, geophysics etc.) to incorporate into this preliminary study. We hope to incorporate such data if the project moves forward into the next Phase when next data can be gathered. Gathering MT, high resolution magnetics, complete LiDAR coverage, detailed geologic mapping, and temperature gradient data would substantially improve exploration in these areas. Of course, these are expensive and time consuming, so having a clear set of priorities for where such data is needed is critical and a result of this Phase I analysis.

Please also refer to related responses to concerns about available data by Reviewer 23406.

Scope and implications of the study: We would appreciate your feedback of precisely what the geothermal community wants and needs. We do feel that making a start on a vast and as yet largely unexplored geothermal region is one thing the geothermal community absolutely does need.

A critical impediment to resource development in general is the identification of specific locations where heat and permeability coincide. Providing a clear approach to addressing that problem in this setting both addresses the problem as it manifests in an important resource area, but could also apply wherever faulting plays a significant role in geothermal reservoir behavior.

Reviewer 29848

Score: 5.0

Comment: Why did this team of awardees decide to limit their investigation to only 3 areas (Mt. St. Helens, Wind River, and Mt. Baker) when the title of their presentation is, "Geothermal Play-Fairway Analysis of Washington State Prospects"?

Why did the team limit the major parameters they are considering to just heat and permeability?

Determining how to deal with the high precipitation, dense vegetation, and high relief in the study area is a major problem, and it does not appear that the team has done an adequate job of explaining how they are going to handle these problems.

Their modeling methods build on other geothermal exploration studies. Favorability layers commonly used include: hot springs/ fumaroles, hot wells, geothermometry, Quaternary volcanic rocks and faults, fault geometry, paleo-surface manifestations, earthquake epicenters, temperature gradient, heat flow, high rates of crustal strain, and proximity to known geothermal systems.

ArcGIS will be used to weight the heat inputs.

How are they determining the sensitivity to input parameters?

Stated in the talk that innovative 3D permeability modeling techniques and quantitative heat potential modeling highlight heat and permeability at 200m and 3km depth are underway but did not provide the details of this modeling or why the modeling techniques are innovative.

Stated that rigorous uncertainty analyses of the favorability models are underway but again did not provide details on how uncertainty was determined and why the uncertainty analyses of the favorability models is "rigorous".

Stated that uncertainty modeling determines which study area is the most promising and will guide the Phase 2 go/no-go decision point, but at this point have only done the initial modeling for Mt. St. Helens.

Has the team calibrated the Mount St. Helens to existing data from hot springs?

PI Response:

5. Why only three areas?: Please see comments above (nos. 1 and 2) about why we chose to look at only three areas within the Washington Cascade Range. We could alternatively change the name of the study to “Geothermal Play-Fairway Analysis of Several Washington State Prospects” if that would make the topic more clearly understood.

Innovative modeling for heat and permeability: Heat and permeability are two of the main factors influencing the viability of a geothermal system. Data pertaining to surface manifestations associated with these two parameters are also the most abundant, and easy to model. In our study, heat is analyzed using: temperature gradient wells, water wells, hot springs and fumaroles, inferred reservoir temperatures using geothermometry calculations from hot spring temperatures and chemistry, volcanic vents, and Quaternary intrusive rocks. The permeability analysis uses the geometry and structural setting of faults mapped at the surface, as well as faults inferred at depth based on seismicity. By incorporating fault data with GPS velocity measurements we can then predict the permeability potential at different depth slices by using the GPS derived stress orientation and magnitude to calculate for: slip and dilation tendency, fault displacement and displacement gradient, the maximum Coulomb shear stress and sigma three (both proxies for the deformation or fracturing proximal to the faults), and dilational and maximum shear strain rate (high strain rate commonly coincides with high temperature geothermal systems). GPS derived strain rate data was collected and interpolated for the entire Washington and northern Oregon Cascade Range for this study. The results of the strain rate analysis will help guide future exploration in the Cascade volcanic arc.

The innovative modeling technique (Poly3D) used in this study relies on the assumption that geothermal resources are strongly dependent on faults. A global survey of 822 faults at 25 different sites by Curewitz and Karson, 1997, indicated that the majority of hot springs and hydrothermal upflow zones are dependent on faults; in particular, fault tiplines, and the mechanical interaction between multiple faults that kinematically maintain permeable fracture networks. Modeling fault slip in an elastic half-space (our modeling approach) can indicate where stress/strain favorable to fracture formation is localized in proximity to faults that can be useful to geothermal exploration. This method was successfully applied to the fault system at the Desert Peak geothermal field, and showed favorable stresses at the location of the most successful injection and production wells at that facility (Swyer and Davatzes, 2013).

Precipitation and vegetation: The precipitation and vegetation are two difficulties of working in this area, and they are challenges that exist in the whole Cascade Range, as well as in many other parts of the country. Complete LiDAR coverage, in addition to other geophysical surveys such as MT, magnetic, and gravity will help to see past the vegetation and hopefully aid in identifying structures of interest. The high amount of precipitation is a problem in the sense that groundwater flow may mask any hydrothermal upflow and potential surface manifestations. It may be beneficial in the sense that there is abundant meteoric water to recharge the system. This is one of the reasons we are looking at heat and permeability potential, so that we can try and see past the effects of groundwater and look at the regional parameters that are known to host geothermal systems in other arc settings around the world.

Uncertainty and sensitivity modeling: For the uncertainty modeling, each layer (13 heat and permeability layers for each play area) will have an uncertainty map that demonstrates the quality of the individual data points based on the parameters that delineate each data set (for example, the number of earthquakes used to map a fault and number of sample points in a temperature gradient well, etc.), as well as the certainty of the data itself (hard/measured data vs. interpolated, etc.). A Euclidean distance analysis will be used within the buffered points, polygons, and lines to demonstrate decreasing certainty away from the hard data points, transitioning into the area where there is no data and the uncertainty is highest. These uncertainty maps will be summed together to come up with an uncertainty or risk map for each study area.

Fault geometry uncertainty will be quantified by how many events were used to constrain fault geometry, and by the range of the residuals from the regression function used to define fault planes. Because the boundary conditions for the numerical fault model are derived from GPS strain rates, the uncertainty of this model can be quantified by the uncertainty of the GPS station velocities. For this reason, BOS technologies, who were contracted to derive strain-rate data for most of Washington and Oregon for this project, derived strain rates using the GPS station velocities +/- one standard deviation. During the sensitivity analysis this range of strain-rate values will be used to determine the uncertainty of the model, and values that show a best fit to GPS strain rate data not used to define the boundary conditions as well as earthquake focal mechanisms located away from the fault model will be used in the final calibrated model.

Reviewer 29849

Score: 5.0

Comment: Wannamaker pointed out in his Cascade project presentation, that the team failed to leverage remote sensing LiDAR data that would have mitigated to some extent the limited information on faults. Knowledge of the faults is essential; because the assumption is that the permeability is based on faulting. Their modeling is based on looking for permeability along fault trace. This project is severely handicapped because there are very few faults mapped in the area. They have relied instead on mapping and inferring faults based on seismicity and velocity data. The LiDAR data is very useful in areas with massive precipitation and heavy ground cover. This study area receives up to 260 inches of rain a year and has up to 100% vegetation coverage.

They are using MATLAB to model faults from earthquake data to incorporate mapped faults and model slip and dilation tendency on fault planes in 3D. Poly#D software to model GPS strain rates to determine where faults are causing proximal damage zone that enhance fault permeability.

Wannamaker also revealed in his Cascade project presentation that MT data was available for the region. Since the existence of that data was not generally known, it would have been better for him to have shared that information with the Washington State team than to play "gotcha" in the reviews. Wannamaker collaborates on many of the projects, so it would have been more appropriate for him to alert them to the presence of the data and to see if it was possible to work together.

Most of the existing maps are from Mt St Helens area. The PI's want to build three comprehensive models: Mt. St. Helens, Wind River Valley and SE flank of Mt. Baker. They have completed the Mt. St. Helen's model and nearly done with Wind River model.

Around Mt. St. Helens they are using the most recent temperatures in their modeling.

The PI's are using analytical hierarchy process (AHP) as a structured technique based on math and psychology for organizing and analyzing complex decisions. Program tells you when you are being inconsistent with yourself.

PI Response:

6. Leveraging LiDAR: LiDAR data are not readily available for a majority of the study areas. Utilization of the scant coverage we do have would bias the study results, and would require field checking the interpretations, which is not something covered in the scope of this project. Please see comments above regarding available LiDAR coverage, use in previous geologic mapping, and plans to incorporate it in the future.

Response no. 3 addresses PI participation

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: The Analytical Hierarchy Process is an interesting and unique feature of this project.

The project has some industry component, even if it is relatively limited.

PI Response:

7. Analytical Hierarchy Process: We are happy with the use of the Analytical Hierarchy Process for weighting our data. It is useful and interesting to see how everyone weights the various parameters. Each expert can have a say based on their experience, but it is nice to not have to argue about the differences in our individual weights, but to combine them. This program is unique in that there is a function built in to the spreadsheet that tells the user when an individual is being inconsistent with their weights, and when the weights of multiple experts are inconsistent with each other.

Industry: The team is comprised of industry, state, and academic partners. We are open and interested in including more industry partners in the future.

Reviewer 29848

Score: Not scored

Comment: The team has chosen a difficult area in which to find geothermal resources that will be economically competitive. Any information they can come up with regarding some of the numerous obstacles that they have to overcome could be helpful in promoting geothermal resources in areas with similar problems.

PI Response:

8. We realize that this area is difficult to explore, and we agree that any information we can find to help overcome such obstacles will be beneficial to geothermal development in such locations.

Reviewer 29849

Score: Not scored

Comment: The PI's are using analytical hierarchy process (AHP) as a structured technique based on math and psychology for organizing and analyzing complex decisions. Program tells you when you are being inconsistent with yourself. This group seemed to be the only one using this type of approach for evaluating their weighting decisions. It could potentially be a best practice.

PI Response:

9. The team agrees that the AHP is one of the many strengths of this project and we appreciate that you recognize that it is a useful tool for analyzing complex decisions.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: All three areas are most likely too small to host more than the one geothermal system upon which each area is centered.

The geology, which forms the basis for much of the geological model, is poorly known and the absence of Lidar over much or most of the area(s) is another factor that makes development of convincing models unlikely for this project.

PI Response:

10. Geothermal prospecting and local geology: Each area was chosen with the goal of identifying at least one location to focus future exploration efforts as long as that area was deemed viable from the uncertainty modeling. Understanding the local geology is critical to understanding the geothermal potential in an area. While some of the faults mapped at the surface are questionable, we used seismic catalogs for the region to constrain fault geometry at depth. In some cases, the seismic catalog is robust enough to show clear planar alignment that can be used to construct a very well-constrained fault geometry. Areas with a robust seismic catalog were used to develop the methodology and select a regression function appropriate for defining fault planes—very useful in areas with fewer data. The regression function also defines the residuals of the fault geometry which will be used to quantify uncertainty. Washington State is very seismically active, and lends itself to this modeling technique.

Reviewer 29848

Score: Not scored

Comment: Why are they only looking at three areas (Mt. St. Helens, Wind River, and Mt. Baker)?

Why are they only looking at two main parameters (heat and permeability)?

Determining how to deal with the high precipitation, dense vegetation, and high relief in the study area is a major problem, and it does not appear that the team has done an adequate job of explaining how they are going to handle these problems.

Have they resolved their questions and concerns regarding: 1) the quality and reliability of the geothermometer data, and 2) the size of the buffer zone for limiting the areal extent of the data gathered around each individual hot spring?

There is so much inexpensive hydroelectric power in the area, how is geothermal going to effectively compete in the market for power?

PI Response:

11. Please see comments above in response to why we are looking at three areas (nos. 1, 2, and 5), why we are looking at heat and permeability (nos. 2 and 5), and the precipitation and vegetation issue (nos. 2 and 5)

Preliminary concerns regarding geothermometry and buffer size: We have resolved our concerns regarding the reliability and quality of the geothermometry data by weighting it much less than the other heat parameters and incorporating a quality value in the uncertainty modeling. We used a 0.5-mile buffer zone for the springs based on other similar studies and expert opinions from our team.

Competing with hydropower: As stated in the U.S. Energy Independence Act (EIA) for Washington State, “large utilities are required to obtain 15% of their electricity from qualified new renewable resources by 2020 and to undertake cost-effective energy conservation”. Interestingly, most water-driven electric generation (hydroelectric power) is not considered renewable, and may not be used to meet this target. In a state like Washington where solar is not an option for much of the year, geothermal energy is a promising solution for helping to meet the EIA goals.

<u>Reviewer 29849</u>

Score: Not scored

Comment: The group failed to locate and leverage LiDAR data that could make a big difference in their fault mapping, which is critical to their analysis.

PI Response:

12. The currently available LiDAR coverage was shown in slide 14 of the power point presentation. Please see comments in the responses above as to why we did not incorporate this data in our analysis.

IMPROVEMENTS

<u>Reviewer 23406</u>

Comment: Given the time constraints and the overall character of the project I have no recommendations that would be of value in salvaging it to a true play fairway type of analysis.

PI Response:

13. We appreciate this point of view, and realize that our methodology and scope of analysis are unconventional. We can only hope that the apparent negative opinion of this reviewer is ultimately found to be incorrect.

<u>Reviewer 29848</u>

Comment: The awardees state in their summary that, "Future efforts will focus on siting temperature-gradient wells and (or) identifying where collection of new geophysical data is warranted." Both of these items are needed to improve the project, and the group also needs to consider what additional geological data might be helpful.

Why was the project limited to just three study areas?

Perhaps investigating what techniques are used in the tropics might help them deal with such problems as precipitation and dense vegetation.

It might be helpful to show how the data from Mount St. Helens has changed over time.

There is also considerable variation in the amount of rain fall that occurs in each area, and this could affect the evaluations and data.

Have they resolved their questions and concerns regarding: 1) the quality and reliability of the geothermometer data, and 2) the size of the buffer zone for limiting the areal extent of the data gathered around each individual hot spring?

Are they now working with Rick Blakely at the USGS to acquire high resolution aeromagnetic data in this area?

Has the team located the magma chamber for Mt. St. Helens?

Can the team differentiate between earthquakes caused by the movement of magma vs. earthquakes caused by other mechanisms?

PI Response:

14. Future efforts will focus on geophysics, LiDAR acquisition, detailed geology, and siting temperature gradient wells.

Please see comments in the responses above regarding three study areas, precipitation and vegetation, geothermometry weighting, and buffer size.

Why these three study areas?: This project was limited to only three study areas because of the amount of time it takes to model each area at the level of detail we are analyzing. The three areas that were chosen were the most promising from the preliminary statewide geothermal potential model. They are end members of the Cascade volcanic arc and serve as guides for other sites within the arc. The end members are: a historically active volcano along a very active seismic zone (Mount St. Helens seismic zone), the continuation of the seismic zone to the south in a tectonically transitional environment with high temperature gradient data (Wind River valley), and a relatively unexplored but active volcano with the highest temperature gradient in the state (Mount Baker).

We are not currently working with Rick Blakely (USGS), but there has been communication and the door is open for possible collaboration in the future.

Mount St. Helens magma chamber: The location and geometry of the magma chamber at Mount St. Helens was determined by Barker and Malone (1991) by calibrating an elastic stress model similar to the fault modeling technique being used in this project. The stress model was calibrated to earthquake focal mechanism solutions in close proximity to an aseismic gap underneath the Mount St. Helens crater, assumed to be where the magma chamber is located. Our project makes use of earthquake focal mechanisms in a similar manner to constrain the geometry of faults away from the magma chamber. The distinction between focal mechanisms associated with the magma chamber and focal mechanisms associated with faults is relatively clear. Fault-related focal mechanisms show a clear planar alignment of their hypocenters, have similar fault plane solutions, and have a similar sense of slip, whereas focal mechanisms associated with magma movement above the magma chamber show no clear planar alignment or consistent fault plane solution and sense of slip. This concept was demonstrated by Weaver and others (1987), who also formulated a conceptual fault model within the Mount St. Helens seismic zone. This project utilizes the catalog of relocated seismicity and this conceptual fault model to construct a detailed fault model which in some cases is extremely well defined. The development of this method and lessons learned became very useful when constructing the fault model for the Wind River valley, which is proof positive that it can be applied to other areas.

Reviewer 29849

Comment: The PI's should acquire LiDAR data. They also should contact Wannamaker about whether they can access the MT data set that he has acquired and interpreted.

PI Response:

15. Why we didn't acquire LiDAR: No new data acquisition was allowed in this project. We agree that LiDAR coverage of these areas would be very beneficial, and is something we hope to see happen in the next phase. Washington State is committed to acquiring LiDAR for the state and in the recent legislative budget the division was awarded $4.6 million to help with such tasks. Additional funding for LiDAR coverage for geothermal prospecting would be key for future exploration in the Cascade Range.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006733
Project: Play Fairway Analysis of the Snake River Plain
Principal Investigator: Shervais, John
Organization: Utah State University
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 8.0

Comment: This project has the potential impact to help open up a large geothermal province, which has been lightly explored by the geothermal industry in the past, to more modern exploration activities. The high potential impact is somewhat reduced by the uncertainty of this actually happening. There certainly is abundant water for geothermal reservoirs and there most likely is adequate heat somewhere as shown by the recent Mountain Home well which found 150 C temperatures. The study area is large enough to potentially host many geothermal reservoirs.

The progress to date is reportedly meeting the proposed schedule.

PI Response:

The SRP Fairway team met at the end of June and made significant progress towards its Q3 goals. We held a Team meeting at Lawrence-Berkeley National Lab (LBNL) at the end of June, at which we made considerable progress on our CRS and CCRS maps. We now have a protocol in place for applying data uncertainty estimates to each data layer, and for combining the resultant risk layers into a single CRS map for each resource characteristic (heat, reservoir, seal). This work is proceeding on target.

Reviewer 29848

Score: 7.0

Comment: Project objectives align with GTO's goals. That is, the ultimate goals of this project are to lower the risk and cost of geothermal exploration and development, not just in SRP but throughout the geothermal industry and to stimulate development of new geothermal power sources in Idaho.

Another project objective is to build a geothermal play fairway model for the Snake River Plain that will make it possible to identify the most promising plays and formulate a strategy for identifying prospects for further exploration.

The key factors for defining geothermal resources in the area are locating places where the SRP intersects with Basin & Range faults (this is where permeability is likely to be the highest).

It is likely that the methodology developed by this group will be able to apply in other areas. However, the group is still working on how in incorporate varying degrees of uncertainty and risk into the model.

They have defined 3 key elements of the Play Fairway concept for Geothermal Systems: (1) Source (heat is the critical component for geothermal plays), (2) Reservoir (geothermal reservoirs require permeability), (3) Seal.

They have identified 3 main play types.

PI Response:

We made great progress at our Team meeting in June on how we will incorporate risk, as well as on weighting for different data types, data interpolation and aggregation, and how data layers, evidence layers, and uncertainty will be combined to create a series of risk layers.

Reviewer 29849

Score: 7.0

Comment: Their goal is to create a work model and process that will work anywhere. Their goal is to have methodology that is scalable and can be used by others. "Play fairway concept thinking."

They are adapting petroleum industry software to geothermal applications, but note that is proving more difficult than expected.

The PI's have the ability to generate multiple maps to see which observations are most robust.

They have two publications on the work.

PI Response:

Our work so far suggests that most petroleum industry software is too specialized to adapt well for geothermal use. In addition, the expense of acquiring this software commercially (we have academic license) will likely deter most companies from using it extensively. We are now working to produce our own tools in Arc GIS, using Python scripts that can be integrated into the Arc toolbox, that will automate much of the work involved in this process. Since we did not budget for this in Phase 1, we are just developing the basic protocols and scripts at this time. In Phase 2 we plan to continue this work to produce a mature toolset that can be used easily by anyone with good GIS skills. The goal is to produce a "turnkey" system, as far as that is possible, that incorporates all of the important data types used in geothermal, but still allows for expert intervention in the process.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 8.0

Comment: The entire Snake River Plain is large enough and has abundant indications of heat and water to make it a truly viable Play Fairway kind of project. It does not have the past exploration discouragements that downgrade the central Oregon Cascades.

This project has a particularly large and strong set of technical team members, some of which have solid past geothermal development expertise and in play fairway analysis. The team is building off of a recent success at Mountain Home Airforce base where a blind moderate temperature resource was discovered.

A downside to the Snake River Plain is that no electrical grade resources have yet been discovered in it.

PI Response:

It is true that no electric grade resources have been developed in the SRP, but the work of Project Hotspot showed that thermal waters exist in the western SRP (at least) with temperatures and thermal gradients that are essentially identical to those at Raft River. This implies that electric grade resources are present, but remain undeveloped by the risk-adverse geothermal industry. It is hoped that our work on this project will reduce the perceived risk and encourage development of new resources in this region.

Reviewer 29848

Score: 8.0

Comment: Innovative aspects of this project include the use of petroleum industry software tools, as well as a new conceptual model for basaltic plays, and GIS processing scripts developed by the USGS.

The project team will construct critical element charts that assess the probability of success versus the data confidence for each play type.

One of the challenges of this project is to take different types of data into a single resource assessment.

The group is using a wide variety of data including: 1) fault dilation tendency and slip tendency, 2) equilibrium reservoir temperatures, 3) 3D stratigraphic models, 4) 3He/4He ratios, 5) maps showing active faults, 6) volcanic vents-age, 7) gravity, 8) magnetics, 9) seismic, 10) MT, 11) heat flow, and 12) aquifer thickness.

Critical element matrices will combine probability of success with data quality to produce a risk assessment that will be used to construct the common risk segment maps.

A mantle hot spot is likely driving the heat flow in the entire area.

PI Response:

See previous responses. Our June Team meeting established a protocol for incorporating data uncertainty layers and evidence layers to produce risk maps for each data layer. One important point is that this must be done separately for each data layer, since the uncertainty distribution and type for different data layers may be different. Once the evidence layer and uncertainty layer have been combined to form a single risk map, these can easily be combined with other risk maps (with separate weights for each) to produce the CRS maps.

Reviewer 29849

Score: 8.0

Comment: They are developing techniques to automate the process as much as possible. The PI's are using Google Earth to review data sets and a cloud drive to share and transfer information. They are using Phython scripts in ARC GIS to automate how evidence layers are put together. They are using 3D stratigraphic maps in Petra. They are applying confidence limits first before merging datasets.

They have the benefit of a huge database and are mapping all of the known vents in the region. Maps showing heat at different depths show impact of the aquifer. They are using high resolution gravity data. Their key challenge is getting everything together and weighting it. They are monitoring chance of success vs data quality for each factor -- each with its own risk.
They are using a common extensive GIS database.

They plan to coordinate work with Northwest Volcanic Aquifer study of the USGS.

On schedule with no performance or technical variances.

Their major downside is that they don't have training sites for their model.

PI Response:

See other comments regarding training sites; we plan to use Neal Hot Springs and Raft River as the nearest and best models. We have already begun to work with USGS on extending the NW Volcanic Aquifer study, and Erick Burns attended our Team Meeting in June.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: The strengths are abundant data, a strong team, and a large interesting area with a considerable variety of geology to work with.

PI Response:

We agree, and are working towards what we hope will be a successful Phase 2 proposal.

Reviewer 29848

Score: Not scored

Comment: The SRP is characterized by high heat flow, voluminous young volcanism, and a range of structural settings that may enhance permeability.

There are probably undiscovered geothermal resources in the western SRP and along the eastern plain where effects of the aquifer bringing cool water into the system are minimized. Undiscovered geothermal resources may also exist at lineament intersections in the central SRP.

There are engineers on the project staff, which may help with certain aspects of the project.

PI Response:

Our work confirms that undiscovered thermal resources are likely present, and that at least some of these are of electric grade. And having an experienced reservoir engineer on staff is a distinct advantage that will become critically important during Phase 2.

Reviewer 29849

Score: Not scored

Comment: They recognize that the statistical representations are non-unique and are incorporating processes to acknowledge the uncertainties and non-uniqueness.

They are developing rigorous work processes that can be replicated and used in other areas.

They have an abundance of data.

PI Response:

See previous responses. Our June Team meeting established a protocol for incorporating data uncertainty layers and evidence layers to produce risk maps for each data layer. One important point is that this must be done separately for each data layer, since the uncertainty distribution and type for different data layers may be different. Once the evidence layer and uncertainty layer have been combined to form a single risk map, these can easily be combined with other risk maps (with separate weights for each) to produce the CRS maps.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The most obvious weakness of the project is its lack of any operating geothermal fields and not much in the way of known high temperatures to serve as training sites.

A secondary weakness may be that temperature-gradient holes in the eastern Snake River Plain will likely need to be relatively deep and expensive to get beneath the aquifer.

PI Response:

In terms of training sites, we plan to use two sites at opposite ends of the region: Neal Hot Springs in eastern Oregon, and Raft River in SE Idaho. Many of our potential sites have similarities to one or both of these sites, and our plans for Q4 will involve comparing these training sites to our prospects in the SRP. These issues will be delved into more deeply in Phase 2.

The effects of the aquifer are well known, as is the regional extent and thickness. These areas would be avoided in future work. Any thermal gradient wells would be sited to avoid the aquifer. There are a large number of drill holes that penetrate the aquifer -- primarily on or near the Idaho National Laboratory, but including one of the Project Hotspot wells -- so there is little need for new deep holes through the aquifer.

Reviewer 29848

Score: Not scored

Comment: There are no training sets (producing geothermal facilities) in the area for calibration and comparison of the models with "geologic reality".

The groundwater temperature is cooler to the northeast because of the presence of an aquifer there. This may make it more difficult to find an economic geothermal resource in this area.

The range of measured temperatures in the study area is generally low (50 deg to 60 deg C).

PI Response:

In terms of training sites, the response above pertains: we will use Neal Hot Springs and Raft River as training sites. The cool groundwater temperatures in the NE point away from that area for potential prospects, but again it depends on aquifer thickness: if thin, the temperature of the overlying groundwater is not a factor. The main point of the increase in groundwater temperatures from NE to SW is that it documents significant heat input from below, which progressively heats the groundwater as it moves away from high elevations in the Yellowstone plateau region toward the Snake River and outlets in the Thousand Springs areas. Calculations by Blackwell and his students have shown that subaquifer heat flows of ≥110 mW/m2 are needed to provide the heat input that will raise the temperature of the groundwater this much (from <9ºC in NE to 17ºC at the Kimama well).

The range in natural hot spring temperatures is not indicative of temperatures at depth. Our multicomponent temperature data (provided by our cooperating project at INL) show reservoir temperatures that range from 75ºC to 168ºC. In addition, the Hotspot Mtn Home well documented fluids at ≥150C, and fluid inclusions in calcite there indicate temperatures as high as 350ºC.

Reviewer 29849

Score: Not scored

Comment: They do not have training sites for their model in their area.

PI Response:

See responses above: we will use Neal Hot Springs and Raft River as training sites

IMPROVEMENTS

Reviewer 23406

Comment: I have no recommendations for improving this project at this time.

PI Response:

Reviewer 29848

Comment: The group needs to look for industry partners and publicize their work in both the local and scientific communities.

Key data gaps need to be identified and addressed.

The construction of common risk segment maps, composite common risk segment (CCRS) maps, and the initial development of a conceptual reservoir model that are expected to be completed in Q3 will have a significant positive impact on the group's overall progress and success.

PI Response:

Our plans for Phase 2 call for an industry-based advisory board to consult with us on our Phase 2 work. We have chosen the advisory board approach because geothermal companies are reluctant at this time to become formally involved in projects that may require divulging privileged information, or expending resources on sites for which they do not have a prior lease agreement. At this point we have invited Roy Mink, consulting geothermal geologist, and Ian Warren, of US Geothermal, to participate on this board and both have tentatively agreed at this time. We are actively seeking additional members. We will follow up with formal invitations and will include written acceptances in our Phase 2 proposal.

We have publicized our work for the scientific community through a Stanford workshop paper (Nielson et al 2015) and a GRC 2015 paper (Shervais et al, 2015). We plan to use the existing Project Hotspot Facebook page with its existing base of followers.

We are in the process of identifying key data gaps (and in fact, completed most of that list at our June Team meeting). These data gaps will form the basis of our Phase 2 proposal, which will focus on three potential prospects with the play area. Our Phase 2 proposal will seek to obtain the additional data needed to identify the best prospect for Phase 3 work.

Reviewer 29849

Comment: They may be able to find appropriate training sites for their model in other areas with similar geology.

PI Response:

See responses above regarding training sites.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006725
Project: Geothermal Potential of the Cascade and Aleutian Arcs, with Ranking of Individual Volcanic Centers for their Potential to Host Electricity-Grade Reservoirs
Principal Investigator: Shevenell, Lisa
Organization: Atlas Geosciences Inc.
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 6.0

Comment: This project is unique among the play fairway group of projects in that it is not intending to discover prospect sized areas for future work. Instead it is identifying volcanic centers which are semi regional locations.

Parts of the work performed as of the time of the Peer Review are truly worldwide in scale. In that sense it appears that it can break significant new ground in understanding which volcanic arcs or parts of volcanic arcs are most likely to host viable geothermal resources. It should result in papers that will be widely read and noted by the world-wide geothermal industry and generate considerable discussion and probably spawn further large scale research so it is expected to have a high impact.

Unfortunately, due to the location choice of the project it appears that this project is also unlikely to result in new exploration or recognize new site specific plays. That is the reason for the score that seems to be erroneously low relative to the previous comments.

This is the only play fairway project that could have significant impacts on another two play fairway projects.

The project is reported to be progressing on schedule.

PI Response:

We appreciate your comments regarding the research aspect of this project. In regards to paragraph 3, this project is highlighting specific portions of the Aleutian and Cascade arcs that justify further exploration, and the play fairway methodology being developed will lend itself to identifying a specific volcanic center or cluster of volcanic centers that warrant exploration in phase 2. Stage 3 could ultimately drill-test specific sites identified during phase 2 exploration. This assessment is conducted in the context of purely scientific considerations first, followed by elimination of prospective sites based on society issues (e.g., withdrawn areas).

Reviewer 29848

Score: 4.0

Comment: Need to do a better job of aligning their project with the GTO goals. May need to use a modified approach that is applicable to play fairway analysis in general so their methodology is transferable from one geologic setting to another.

The awardees have developed preliminary fairway models and preliminary favorability models for both the Aleutians and the Cascades, but if the same models cannot even be used for the two areas of interest in this specific study, how can they be applied to geothermal play fairway analysis in general?

Along these same lines, the majority of the slides refer to arc systems and volcanic centers with only a few slides mentioning "generic" geothermal systems and "different play types". How are the awardees going to take a study that focuses primarily on arc systems and volcanic centers and then apply these data and analyses to play fairway analysis for different types of geothermal systems?

The results being shown in this presentation may be too narrow to be generally applicable to geothermal play fairway analyses in other tectonic settings. It seems that, at this point, the awardees should be directing their efforts toward results that have broader applications.

Slide 25 states, "Parameters of the power distribution curve can be modified for different play types." This statement seems to indicate that the awardees may have broader applications in mind, but how were the data in this slide obtained and analyzed, what are the uncertainties in the data, and exactly how can the parameters in this slide be modified and applied to different play types?

They do not appear to have identified the most promising prospects for development.

What have they done to attract investors, potential users, and/or to publicize their work?

The awardees seem to be knowledgeable and have done a significant amount of data analysis at this point, but I'm not sure that their approach and the work they have done have broad applicability. I'm not sure that the money spent on this project has been money well spent given the GTO goals.

PI Response:

Paragraph 1: Our ranking system builds directly on the play fairway concept, and the favorability rankings are directly applicable to all the volcanic centers in the Cascade and Aleutian Arcs, which is a huge area, much larger than the other project study areas, so we don't think our approach or methodology is too limiting. The method can clearly be applied to other settings as data from around the globe are used to formulate play fairways that define conditions (e.g., structure, tectonics, strain, etc.) most favorable to geothermal development in volcanic arc environments.

Paragraph 2: The reviewer is confused about what we are doing, perhaps because we did not explain it clearly during the time available in the presentation. In fact, the fairway modeling approach we are using for the Cascade and Aleutian arcs is the same for each arc. The model consists of several stages, the first two of which were presented during the peer review. The first stage, which we term the 'Fairway', represents geothermal favorability based on intrinsic evidence (tectonics, structure, strain) before direct evidence such as hot springs and drill data are included. The second stage, which we term the 'Favorability Model', is a modified version of the 'Fairway Model' after direct evidence and degree-of-exploration have been factored in.

Paragraph 3: Our methodology incorporates all types of geothermal plays expected to be encountered in volcanic arcs, by employing appropriate indices based on geologic characteristics that could signal any particular recognized geothermal play. Our study area is much broader than most, if not all, of the study areas of the other research projects, so we feel the results are broadly applicable. In addition, our use of four key types of geologic tiers or hierarchies in the fairway modeling (permeability, heat, fluid composition, and cap rock), facilitates the modification of our approach so that it could be used for exploration of any geothermal play type, even those outside of active arcs. However, our focus is indeed in arc volcanic settings as proposed, and different criteria and ranges of values would be applicable to other settings such as extensional Basin and Range systems, although a similar model may be employed.

Paragraph 4: See comments to paragraph 3 above.

Paragraph 5: Each geothermal play type could have a different size-frequency distribution. Because the peer review only reports on preliminary results, we have not yet calculated size-frequency distributions for different play types, but only showed the size-frequency distribution for all producing arc systems. We intend, to the extent allowable by the data, to calculate size-frequency distributions for each play type of the volcanic arcs during the second half of the project.

Paragraph 6: We clearly did identify volcanic centers much more promising for geothermal development than others, as indicated by the color-coded rankings shown in slides 18-21. These indices can be used to select specific volcanic centers for more detailed exploration. Some of these sites were labeled with text on these maps such as Makushin, Akutan, etc.

Paragraph 7: At the time of the peer review, we had presented one poster and abstract (GSA, Canada), one poster at GRC 2014, and had submitted two papers (GRC, 2015). Since the peer review, we have submitted a third paper (GRC, 2015).

Paragraph 8: Again, we feel that these results are applicable to large regions (see above) as they are applied to all of the Cascades and Aleutians, and can be applied even to larger regions than those of the other Play Fairway projects, which tend to have more spatially focused efforts.

<u>Reviewer 29849</u>

Score: 6.0

Comment: Their study area is scarcely populated and has no geothermal power generation facilities.

They are seriously data limited and while they are building a fairway concept, the PI's admit that it may be "too general to be of much value."

Fairly similarly systematically evaluating the geothermal potential of their area, but don't have any unique approaches.

On the plus side they have collected data from all arc systems worldwide.

They have submitted 3 abstracts and have one publication.

Given the scarcity of data, the team's biggest contributions may be in new data correlations such as the one that resulted from their volunteer collaboration with Nevada Geodetic Laboratory and Max Wilmarth. The team has demonstrated a positive relationship between crustal deformation style (extension and shear) and power density and size of geothermal resources. Even if the team does not develop a complete play fairway concept, advances such as this could impact the research of others.

PI Response:

Paragraph 1: While our study area includes some sparsely populated areas, such as the Aleutian Islands, it also includes volcanic centers close to heavily populated areas, including Seattle, WA, Portland, OR, and Anchorage, AK. Additionally, this limitation was not viewed as a disqualifier of the project during its selection because these areas are underdeveloped relative to geothermal energy. Our study area is unchanged from what was proposed.

Paragraph 2: There may have been a misunderstanding during the presentation. We believe our work to hold significant value, not only in predicting geothermal potential in the Cascades and Aleutians, but also because we are learning more about what types of tectonic and structural conditions are most important for the formation of viable geothermal systems. We do have some challenges in regard to data availability, but we are focusing our study to use types of data that have sufficient availability to be valuable, and are building estimates of reliability of the data into the model, as well as estimates of the degree of past exploration to quantify uncertainties.

Paragraph 3: We believe that many of our approaches have not been used previously and thus we are braking some new ground. For the first time, we are using world models of strain rate, plate motion, and crustal thickness. We are also developing detailed assessments of structural and tectonic settings for each volcanic center with the help of structural specialists who are leaders in their field for making such assessments for geothermal systems in a variety of settings. So on the contrary, we argue that we are using new data in a unique way to assess geothermal potential better than previously possible.

Paragraph 6: Yes, thank-you. We believe our research will have an impact on geothermal research and models elsewhere.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 10.0

Comment: The overall approach to this project is breaking new ground on a regional or continental scale utilizing new data that have become available since Muffler et al. 2000 first compared the Cascades with the Japanese Arc.

PI Response:

Yes, thanks. A number of years have passed since the Muffler work, and much more data are available now than before. So we think this is a overdue research project that can leverage better data sets to refine our knowledge of the factors that control the development of viable geothermal systems.

Reviewer 29848

Score: 4.0

Comment: Seem to be assessing data in arc settings and volcanic centers around the world. However, on a number of slides displaying these global data, data from the Cascades and Aleutian arcs are not shown for comparison.

Slide #18 in the presentation shows the differences in the Aleutian arc preliminary fairway model and states that the "Higher indices driven by more complex/favorable structural settings". Could the awardees be more specific about what these more complex/favorable structural settings are? In the SOPO, the awardees state that estimated productivity will be drawn from volumetric-based Monte Carlo simulations. Is this what is being shown in slide #18? Why aren't the Cascades shown in slide #18? Why are the indices lower to the east? Is the technology used to create this map easily transferable to other areas and projects?

In the next slide, the awardees state, "Relative weighting changes (updates) when direct evidence (geothermometry, well data, and surface features) are considered", but the indices still generally get lower to the east. Why?

What are the differences between slide #18 ("Aleutian Arc Preliminary Fairway Model") and slide #19 ("Aleutian Arc Preliminary Favorability Model")? Why are Atka, Akutan, and Makushin pointed out on slides 18 and 19?

Slide #20 is "Cascade Arc Preliminary Fairway Model" and slide #21 is "Cascade Arc Preliminary Favorability Model". Why are different models being used for the Aleutians versus the Cascades? If the same models cannot even be used for the two areas of interest in this study, how can they be applied to geothermal play fairway analysis in general?

Why are Mt. Meager, Mt. Hood, Medicine Lake, and Mt. Lassen pointed out on slides 20 and 21?

PI Response:

Paragraph 1: Okay, given the scale of a world map, it is sometimes challenging to display all features from volcanic arcs around the world simultaneously. We will try to do better in the future.

Paragraph 2: Yes, to be more specific, the more complex/favorable structural settings in this region are composed of transtensional tectonics with multiple fault intersections. Given the regional scale of our project, we now believe that volumetric Monte Carlo simulations may not be practical (so we are not showing a Monte Carlo ranking in slide 18, instead the rankings are based on the methodologies documented in slides 14, 15, and 16). However, we will use some type of error estimation to characterize the perceived accuracy and reliability of our index rankings. The Cascades are not shown in slides 18 and 19 because they are shown in slides 20 and 21. The indices are lower in the east on slide 18 in significant part because of a more transpressional setting. The technology used to create the map are immediately transferable to all other volcanic arcs in the world, including the Cascades (see slides 20 and 21), and the approach can be readily modified to assess other types of geothermal plays.

Paragraph 3: The indices are lower in the east largely because the tectonic setting appears to be more transpressional in nature.

Paragraph 4: Sorry for not making this clear. Slide 18 represents our "Fairway Model" (see slide 14) based on the presence of geologic characteristics, and slide 19 represents an updated estimate based on direct evidence of geothermal activity, such as hot springs, geothermal wells, etc., and modified by the degree of exploration (again, see slide 14 to see how these models are related to each other). The Fairway Model represents the favorable terrain based on geological characteristics (the "Fairway"), while slide 19 (the 'Favorability Model') represents an updated prediction based on direct evidence. Atka, Akutan, and Makushin were pointed out on the slides because they are known sites of geothermal activity, so they serve as points of reference so that the viewer can see how these systems rank compared to nearby areas.

Paragraph 5: The models for the Aleutians and Cascades are exactly the same. They are the same models. The only reason they are being shown on different slides is because of the scale. If we showed them on the same slides, everything would be much smaller and more difficult to see.

Paragraph 6: Mt. Meager, Mt. Hood, Medicine Lake, and Mt. Lassen were pointed out on the slides because they are well-known sites of geothermal activity, so they serve as points of reference so that the viewer can see how these systems rank compared to nearby areas.

Reviewer 29849

Score: 5.0

Comment: Given the scarcity of data in their study region, they have collected data from arcs globally.

They are using a GIS system putting multiple datasets in using a tiered modeling approach. Key hierarchical tiers have weighting factors for different types of data.

Worldwide, they have found 84 systems in arc systems and acquired data on those powerplants. 733 volcanic centers are available, but only 74 have a productive power system.

They have collected 160 data fields and are working to determine what is most important.

They have identified their key factors: structure, strain, clay caps, volcanism, permeability/lithology, geochemistry, surface manifestations. Surface features including fumaroles and deposits will be included. Issues of social concern, land use, etc. will be incorporated into their evaluation.

Cascades and Aleutians seem less prospective. No evidence for huge systems. One modeling approach may apply is some kind of direct analog. Looked at regional data to find an analog. Will develop an index and see how existing systems score.

Looking at many subduction related parameters. Best thus far is the magnitude of arc parallel subduction. "It is challenging" to define regional parameters in arc settings. "Gets down to what's happening in each individual center."

Empirical approach. Established cut-offs to include things and lumped things.

Possible approach is defining play sub-types with different size type distributions.

PI Response:

Yes, we are considering some of these possibilities.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: This is a very strong project from an academic perspective. It has the potential to be perhaps the most interesting of all the play fairway projects.

In the Cascades this project appears to be leading to an understanding of why the southern portion of the arc has higher quality resources. It also provides an explanation as to why all of the drilling at Meager Mountain has been unsuccessful in locating commercial permeability. Unfortunately, this apparent understanding has come too late for the funders of that project.

PI Response:

Thanks.

Reviewer 29848

Score: Not scored

Comment: The experience and knowledge of the individuals making up this team.

PI Response:

Okay.

Reviewer 29849

Score: Not scored

Comment: Since they have limited data on their region, the project is leveraging data on island arcs worldwide.

Leveraging networking to secure new data sets ("Nevada Geodetic Laboratory and Max Wilmarth have joined the collaboration team on a volunteer basis: Kreemer has contributed a new global strain rate and plate tectonic model and Wilmarth has contributed world data on geothermal system power densities.")

PI Response:

Yes.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The primary weakness of this project is that it is unlikely to lead to new geothermal developments in the Aleutians or Cascades in the next decade. The Aleutians are just too remote and under populated to support a significant geothermal industry in the foreseeable future and the most obvious Aleutian resources have already been identified. This project is unlikely to lead to drilling in the Aleutians.

It is unclear as to whether this project will lead to a revival of exploration in the southern part of the Cascade Range as it is hampered by environmental issues and land use restrictions in the most promising areas.

It is difficult to see how this project could lead to siting of temperature-gradient holes in the overall time frame of the program.

PI Response:

Paragraphs 1 and 2: The Cascades and Aleutians have been problematic with their lack of established geothermal energy production. We believe that if we can better explain why this is the case from a geological perspective, and at the same time illustrate which portions of these arcs have the best potential for geothermal energy development, it could serve to help reinvigorate exploration in the most appropriate areas. If we can reduce the risk of exploration, through a better understanding of which portions of the arcs warrant exploration and development, a new stage of exploration could begin. There are certainly challenges in terms of accessibility and land use restrictions in some portions of these arcs, but other areas are more accessible.

Paragraph 3: We foresee the selection of one or more volcanic centers for exploration work in phase 2, which could easily lead to the selection of temperature gradient sites for drilling in phase 3.

Reviewer 29848

Score: Not scored

Comment: Although the PI presenting the talk has considerable experience in geothermal resources, she seemed not to have practiced her talk. At one point, when she was about 2/3 through the 20 minutes allocated for the talk but only about 40% through the slides, she made a comment about how she, " ... guessed she better get moving." From that point on, she appeared to rush through the remaining slides. In addition, although the instructions to presenters clearly stated that, excluding the title page, the presentation could be a maximum of 15 slides, at the time the PI finished the presentation, she was on slide #19, and the total number of slides in the presentation was 30.

Much regional exploration data used in this study has relatively high uncertainties.

Among the greatest challenges in this project are the large amount of data search and compilation that are required and the incomplete and uneven nature of the data.

Given the variability of the data, how reliable are the various cut offs being applied to determine what will and what won't be productive?

There are no power generation facilities in either of these arcs, so how are the awardees going to determine sites that are appropriate for testing their models? Have they found any good existing analogs for either the Aleutians or Cascades?

PI Response:

Paragraph 1: Sorry, we will try to do better next time. Please note that these are only preliminary results and that the slides were required to be finalized well before the half-way point in the project timeline. This has been especially challenging for us because of the huge amount of data-collection activities necessary because of the world-wide scope of our investigation. We still managed to generate some preliminary model results prior to the deadline for submitting the powerpoint presentation.

Paragraph 2: We will be characterizing uncertainties as part of this project.

Paragraph 4: We are not using cut offs.

Paragraph 5: This is why we are looking at volcanic arcs elsewhere in the world. You could think of this as a worldwide analogy. We are identifying the key geologic features for a productive system elsewhere in the world, and then looking for those same characteristics in the Aleutians and Cascades.

Reviewer 29849

Score: Not scored

Comment: Limited data within their geographic region. Inconsistency in the data that is available.

PI Response:

We are designing the project to use the data that are the most available and reliable, and we are monitoring the degree of data availability for each area. It is true that data availability is frustrating in some places, but yet, there is a huge amount of data and information available overall, and data quality is improving from year to year.

IMPROVEMENTS

Reviewer 23406

Comment: I have no recommended improvements for this project.

PI Response:

Okay.

Reviewer 29848

Comment: The project needs to change its emphasis to develop applications that are more broadly applicable and transferable to play fairway analysis in general.

During her presentation, the PI stated that "This is basically permeability" model, but none of the slides address this statement. If their work is indeed basically a permeability model, it might have broader applications than what were indicated in the presentation.

In addition, how does their model, which is basically a "permeability" model contrast and compare with geothermal models that consider permeability, heat, and fluids in their play fairway analysis?

PI Response:

Paragraphs 1 and 2: We believe our results are broadly applicable to geothermal play fairway analysis in other areas. Yes, permeability is the key factor in our model, and as you indicate, since permeability is a key factor in other geothermal play types outside of volcanic arcs, the approaches we have developed could be valuable for better assessing geothermal potential in much broader regions.

Paragraph 3: To enhance the applicability of our model throughout the world for all geothermal areas, we have carefully considered four geologic factors in our model (permeability, heat, fluids, and cap rock). In the specific case of volcanic arcs, heat is usually present (because of active or recent volcanism), adequate fluids are usually available (near-neutral pH), and cap rock is usually present (due to the ability of volcanic rocks in high levels of these systems to form clay). For these reasons, the remaining factor, permeability, is especially imporant in volcanic arcs, and has therefore received the greatest attention in our model. So to answer the question, we are considering all factors in our model, and weighting them accordingly. Even though our model relies most heavily on permeability, we are considering all of the factors.

Reviewer 29849

Comment: The PI's note that volunteer collaboration with Nevada Geodetic Laboratory and Max Wilmarth have resulted in contribution of a new global strain rate and plate tectonic model and new data on geothermal system power densities that enabled the team to demonstrate a positive relationship between crustal deformation style (extension and shear) and power density and size of geothermal resources. Even if the team does not develop a complete play fairway concept, advances such as this one could be important. The team should continue to leverage their network and develop new data correlations.

PI Response:

Thanks. We would like to do this.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002828
Project: Recovery Act: Use Remote Sensing Data (selected visible and infrared spectrums) to locate high temp ground anomalies in Colorado.
Principal Investigator: Smith, Jerry
Organization: Pagosa Verde LLC
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 3.0

Comment: The bottom line on this project is that it has succeeded in only one way: It did create a template for obtaining community, county, state, and federal involvement in and support for a routine exploration project. The techniques used by PV were successful and can be replicated in other geothermally prospective communities in the US. Other than this, the project made no real contributions to the achievement of GTO missions and goals. The project will have few impacts on the state of geothermal development; however several project objectives were accomplished. The work accomplished on this project can best be described as "routine" in the geothermal industry (if not previously in Colorado). The review of the results and conclusions of all previously undertaken investigations is standard procedure in the industry. The identification of legal, environmental, logistical, and regulatory requirements and barriers is also routinely conducted by geothermal industry exploration veterans. Accordingly, their completion should not be considered to be contributions to advancement of geothermal development techniques. It is not so much the fact that the drilling to date has not successfully identified potentially developable resources, it is just that all the techniques used were "by the book" (except maybe the MMS soil studies and the use of a 2 meter temperature measuring survey).

PI Response:

Reviewer 29850

Score: 4.0

Comment: Objective was to;
1) Demonstrate community support for geothermal development,
2) develop a sequential model for development,
3) validate remote sensing,
4) demonstrate community and development techniques.

If successful, project could lower cost to assess blind geothermal systems through community engagement.

1. Quality – The quality of the project is hard to assess due to the qualitative nature of the objectives. Although necessary for development, I am not convinced that these are good objective for the GTO office.

2. Productivity – The project compiled existing data, drill 3 thermal gradient wells. Results of the thermal gradient wells suggest the target is not where expected.

PI Response:

Reviewer 23532

Score: 4.0

Comment: If the project had found satisfactory temperatures the project might have provided incentive for the development of other similar low- to moderate-temperature resources in Colorado.
As it stands the project will have little impact on DOE's mission and goals.

PI Response:

Reviewer 23554

Score: 2.0

Comment: The project has accomplished the initial planned phase of temperature gradient drilling. The impact is limited to that.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 7.0

Comment: The scientific/technical approach was reasonably good. PV did make use of abundant pre-existing data and analyzed it well with the help of qualified consultants. I do have a problem in the inclusion of Flint Geothermal, LLC data. This group showed conclusively, several years ago, that its uses of remote sensing to identify geothermal sites in Colorado were not productive. All they did was to confirm known areas ..... no more. The geophysical studies conducted by the Colorado School of Mines were useful and probably accurate, and the geologic interpretations were valid. Unfortunately, the field techniques use by PV to validate the geophysics were not particularly sound. Specifically, the soil gas survey (still being evaluated for some unstated reason) and the 2 meter temperature survey are both techniques of questionable reliability in my opinion. The selection of sites for thermal gradient drilling was both good and bad. TG-1 was drilled near an old Galloway TG hole, but not on or near the Mill Creek Fault for some reason. TGs 3 and 5 locations are somewhat strange, especially TG-5 which was drilled on the footwall of the Victoire fault??? Finally, there were no details given of the downhole geophysics or the geothermal model used to identify drilling sites. This would have been useful in evaluating the validity of the work done to date. The challenges cited by PV were nothing that is not encountered in any drilling program. Little, if anything, new has been contributed in a technical sense by this project unless one considers negative results to be of importance.

PI Response:

Reviewer 29850

Score: 3.0

Comment: The scientific approach was to use existing publically available data and cheaply obtained other data (geologic mapping, CSM geophysical surveys, soil gas sampling, and geochemisty from springs/wells to identify potential resources. All great things to do but not much innovation for the standard methodologies used in any assessment (I would question the utility of the soil gas sampling). Results of the project suggest that the initial assessment failed and that the heat anomaly is to the west.

PI Response:

Reviewer 23532

Score: 6.0

Comment: The project applied a reasonably good suite of exploration technologies in a difficult to understand area. More funding and time may have provided a better outcome. The project demonstrates, in this reviewer’s opinion, the difficulty of applying exploration methods that are not well suited for relatively low-temperature environments. Unfortunately there a few methods other than geologic mapping, seismic surveys and shallow temperature gradient studies that are truly useful. Some initial shallow temperature gradient work to the west may also have been beneficial.

PI Response:

Reviewer 23554

Score: 3.0

Comment: The project purports to achieve the "....unifying objective ... to perfect a geothermal development model whereby geothermal resources can be developed using low cost techniques." It is difficult to see how this approach has perfected much of anything. The project presentation and review documents included little of the remote sensing evaluation, little new in terms of remote sensing techniques, nothing of the advertised catalog of geophysical data. All these data elements represent an established technical approach; however, it is difficult to evaluate how rigorously they were applied without some account of the complete exploration process.
The MMR data were poorly explained and poorly communicated. In essence, the survey results were little more than anomaly searching with high values immediately adjacent to very low values with little rational explanation as to why. The conceptual model of the system is lacking or at least seriously flawed. Selected locations for gradient drilling apparently relied heavily on an existing local series of academic geophysical surveys. The project summary and

presentation never discussed the background for the survey sites, the geologic/hydrologic constraints on interpretation or the much broader regional context that might suggest expanding he investigation area extensive surveys. Interpreting geophysics out of context is a perilous process as the results of this project illustrate.

PI Response:

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: This project proved that prolonged, persistent campaign to obtain the support and involvement of the community, the county, the state and the federal government can be successful. The project did identify all environmental, legal, regulatory, and property-owner related problems and they successfully mitigated all but the Sky Rocket endangered species matter. By the way, if the geothermal is so small that a well has to be drilled in one specific location, the resource is too small to bother developing. Accordingly, the Sky Rocket problem, as it does not cover an extensive area, should not really affect the over-all exploration plan.

If the proposed further exploration via three new thermal gradient holes does not find hot fluids, or high gradients, then there is a good chance that beneficial use can be made of the copious 85F artesian waters that were encountered in the first thermal gradient hole. There is interest in building a large greenhouse complex and the waters might also be used, in a cascading fashion, together with a heat pump, for space conditioning.

PI Response:

Reviewer 29850

Score: Not scored

Comment: Project was able to piece together funding from several sources to attempt to characterize a potential geothermal reservoir in Pagosa Springs.

PI Response:

Reviewer 23532

Score: Not scored

Comment: Overall there were few strengths to this project. However the public outreach and collaboration was very good.

PI Response:

Reviewer 23554

Score: Not scored

Comment: Application of a well-established, well-worn exploration progression.

PI Response:

WEAKNESSES

Reviewer 23478

Score: Not scored

Comment: The main weakness of this project is that it minimally achieves any of the GTO objectives and will have little or no impact on the geothermal industry learning curve. The processes followed were all "routine" for the industry and the problems encountered were typical of a thermal gradient drilling project. There is really nothing new in this project!

PI Response:

Reviewer 29850

Score: Not scored

Comment: Assessment of existing data did not locate target.

PI Response:

Reviewer 23532

Score: Not scored

Comment: One weakness was limiting the study to the area of available geophysical data rather than utilizing shallow temperature gradient studies to explore the westward closure of the Galloway thermal anomaly.

PI Response:

Reviewer 23554

Score: Not scored

Comment: Application of a well-established, well-worn exploration progression.
The techniques applied in this project are part of decades-old practices that prove little new for geothermal exploration and, in the end, little new or encouraging for this prospect. There is little in the project summary or presentation materials that provides much substantiation for the "unifying objective" of "...perfect(ing) a geothermal development model (using) "....dependable predictive data." It is equally difficult to see how this project developed "...dependable predictive data." since the Phase I drilling failed to achieve the minimum goals temperature parameters. If anything, the initial gradient results are disappointing for drilling locations supposedly picked based on that "...dependable predictive data."

It is commendable that these data allow a community to evaluate its geothermal potential. It is difficult to see how community involvement contributes to the GTO mission and technical goals.
Exploration for anomalies is ineffective. Explaining why something occurs and how it fits into a representative testable model of a potential resource is a critical step that moves time-worn methods out of the past and into relevance.

PI Response:

IMPROVEMENTS

Reviewer 23478

Comment: The funds for this project should have been used to undertake a regional and local geologic mapping program, a hydrologic study above and beyond that conducted by Galloway in the 1980s and less use of and reliance on unproven field techniques like the MMS soil survey and the 2 meter temperature study. Usually, one gets what one pays for and that is true in this case. Cheaper is not better.... I would suggest further use of electrical geophysical studies (resistivity, AMT, and/or MT) although the cost may be prohibitive. If PV really wants to generate power in Pagosa Springs, they will have to be financially prepared to drill deep into the Pre-Cambrian basement (3,000 feet or more) and to fund at least 3 wells. For the small amount of power anticipated, I am afraid that this will not be economically feasible.

PI Response:

Reviewer 29850

Comment: The project still seems to be a drill with your fingers crossed with an expectation that the target is now west of Pagosa Springs rather than south of the town. I am not convinced that “following a path of least to most expensive techniques” is the most fruitful. I would be willing to pay for more for data that provides more confidence of success.

PI Response:

Reviewer 23532

Comment: Expanding the study are to the west much sooner and perhaps utilizing shallow temperate gradient studies over a broader area before drilling deep temperature gradient wells.

PI Response:

Reviewer 23554

Comment: At least document the purported remote sensing and geophysical techniques alluded to in the original proposal. It is important to learn from failure.

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0002836
Project: Recovery Act: Merging high resolution geophysical and geochemical surveys to reduce exploration risk at Glass Buttes, Oregon
Principal Investigator: Walsh, Patrick
Organization: ORMAT Nevada, Inc.
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23478

Score: 8.0

Comment: This is a very good project, from conception, through organization, implementation, and to its conclusion due to rigorous Sage Grouse constraints and the end of DOE funding. The idea of conducting multiple types of geoscientific surveys, overlaying the results, and synthesizing the data is not new, but it is rarely done as well as it was for this project. Sub-contractors with significant skills in each exploration style were employed in order to maximize the chances of obtaining valid, reliable results. Accordingly, the geologic mapping was done in great detail; the LIDAR was flown well enough to be able to distinguish topographically related fracture patterns. The hyperspectral survey undertaken over the faulted areas successfully showed lithologies and altered areas, and the MT delineated both areal and subsurface low-resistivity zones. The creation of a 3D model is not unique, but rarely has it been done to facilitate exploration of a blind geothermal prospect. All of the work undertaken by Ormat on this project can serve as a template for comprehensive (if not inexpensive) exploration elsewhere in the world. All of the technical objectives were achieved and the level of productivity was exceptional. It is unfortunate that in the end, the thermal gradient in a deep core hole was not extraordinary, that time was "wasted" due to Sage Grouse-related restrictions, and that DOE funding was not continued. The fact that Ormat now plans to use this model for their future exploration efforts confirms that it may now be considered to be an industry standard.

PI Response:

Reviewer 29850

Score: 3.0

Comment: Objective was to merge LiDAR, hyperspectral, gravity, aeromagnetic and megnetotellurics data set into a single model to reduce risk in assessing blind geothermal systems.

If successful, project could develop a system to assess blind geothermal systems.

1. Quality – The quality of the project came across as rather poor. The different characterization methods were used on two sites but were poorly integrated into a single comprehensive package, more of a couple of characterization methods than coupled characterization methods. It is unclear how the product of this project can be used elsewhere.

2. Productivity – The project is completed and had a total project funding of $8.7M, it is unclear on the funding distribution. The project used the characterization to drill a well that did not show encouraging temperature gradients.

PI Response:

Reviewer 23532

Score: 7.0

Comment: It is difficult to assess some of the technical aspects of this program most likely because of the restrictive time for presentation and length of the peer review submissions. As a result it is difficult to quantify the impact of the exploration techniques was appropriate however their impact on future exploration might be limited. The selection of techniques was appropriate but how well each of them and their combination was poorly presented in the peer review materials. Due to the low temperature in the gradient hole the project was abandoned. As a result the impact of the project is relatively low since there is little evidence of lessons learned. Apparently the technology was not successful in this instance. Perhaps the papers and presentations that resulted from this project provide a more robust evaluation of the technology. The project shows the difficulties faced in geothermal exploration.

PI Response:

Reviewer 23479

Score: 3.0

Comment: Impact to date must be rated as minimal / low, because any information or knowledge that may have been gained has not been widely shared. Publications and presentations are limited to three abstracts at the AGU, GRC, and GSA meetings in the early stages of the project (2010-2011). These abstracts appear to predate much of the actual work done on this project. Further, abstracts in general are ephemera and convey limited information, and any value that is added by an associated presentation can only be obtained by the immediate attendees. This is (was) a very expensive project and its impact to date has not been commensurate with the cost to the taxpayer.

PI Response:

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23478

Score: 8.0

Comment: Ormat employs a great many geothermal geoscientific experts and so the selection of technologies to be used on this project was well conceived and targeted towards the acquisition of as much geothermally-relevant data as possible given time, money, environmental, and permitting constraints. The use of expert sub-contractors to conduct the planned program assured the use of state-of-the-art instrumentation, procedures, data recording, and interpretation. The various

surveys were conducted both in parallel and sequentially so as to optimize the use of one technique to advise a follow-on study.
The activities undertaken in the first phase were augmented by the later work results and between the two phases, many thermal gradients were measured and one deep (3,000 ft.) core hole was drilled to record stratigraphy, permeability, alteration, and temperatures. All of the planned work was completed until the project was prematurely halted due to Sage Grouse-related constraints and the end of DOE funding. A great deal was learned about evaluating blind geothermal prospects and the procedures used can certainly be replicated by future geothermal explorers and would-be developers anywhere in the world.

PI Response:

Reviewer 29850

Score: 3.0

Comment: Work has focused on fairly standard characterization techniques with little work structure on how to combine the techniques into a better understanding of the subsurface system. The project basically failed at predicting a location to drill a test well to confirm characterization results.

PI Response:

Reviewer 23532

Score: 7.0

Comment: The approach of this project was strong. The methods used provide a strong package of methods useful for geothermal exploration. What the [project may show is that some methods have limited value in lower grade resources. MST studies may not delineate targets where lower-temperature resources do not have thermally altered zones associated with the system. Hyperspectral imaging, as pointed out in the presentation, must be dated to determine the age of alteration.

PI Response:

Reviewer 23479

Score: 5.0

Comment: Citing the prohibitive cost of large-scale exploratory drilling, the PIs proposed to collect high-resolution LIDAR, gravity, aeromagnetic, and hyperspectral surveys; merge these datasets; field-check and verify the results; and use the information to site 1-2 slim holes.

PI Response:

STRENGTHS

Reviewer 23478

Score: Not scored

Comment: The strength of this project lies in the selection of the right geoscientific techniques to obtain optimum geothermally-relevant data. The geologic mapping combined with the LIDAR, the aeromagnetic, and the gravity studies allowed detailed mapping of the fracture patterns of the two target areas. The MT revealed the resistivity configuration in the subsurface, and the hyperspectral survey showed the location of alteration as well as providing lithologic information. These surveys, when combined with the lithologic information gained earlier via the drilling of 16 thermal gradient holes provided a great deal of information needed to create a 3D model of the prospects. Accordingly, the sites identified for future drilling could be based on multiple types of data.

PI Response:

Reviewer 29850

Score: Not scored

Comment: N/A

PI Response:

Reviewer 23532

Score: Not scored

Comment: A well thought out and executed exploration program.
The methodology could provide a template for exploration is similar settings.

PI Response:

<u>Reviewer 23479</u>

Score: Not scored

Comment: The innovative elements of the proposal have to do with merger and conjunctive use of the 4 datasets (LIDAR, gravity, aeromagnetic, and hyperspectral). As the PIs indicated, these datasets have the potential to link the surficial expression of faulting and hydrothermal discharge (LIDAR, hyperspectral) with its deeper expression (gravity, magnetic).

PI Response:

WEAKNESSES

<u>Reviewer 23478</u>

Score: Not scored

Comment: The only weakness in this project was that it was constrained by Sage Grouse matters and permitting delays. Possibly (but maybe not) Ormat could have investigated pre-project to learn about the Grouse situation and about the length of time it would take to get permits. Sometimes this is a chicken-and-egg matter where you have to know where you want to drill before you can do the research that would have minimized the bird and permit problems. Otherwise, I cannot currently come up with any other glaring weaknesses to this project.

By the way, the presenter showed two slides that were not in the "Presentation" given to this reviewer. (This is really not important with regard to the project comments).

PI Response:

<u>Reviewer 29850</u>

Score: Not scored

Comment: Independent analysis of standard characterization techniques. See technical approach

PI Response:

<u>Reviewer 23532</u>

Score: Not scored

Comment: No weaknesses other than environmental issues were perhaps under estimated

PI Response:

Reviewer 23479

Score: Not scored

Comment: (1) Lack of sharing of results. As indicated under “Impact…”, publication / presentation of the results have been extremely limited.

(2) More specifically, even the GTO 2015 peer-review presentation provides little indication of how the datasets were merged and used conjunctively, and

(3) There is lack of detail regarding the siting and results of the 1st slim hole.

PI Response:

IMPROVEMENTS

Reviewer 23478

Comment: Sorry, I have no suggestions for improvements. This project was well conceived, well executed, and should have a positive impact on GTO objectives as well as geothermal industry exploration styles for the future, especially with regard to blind prospects.

PI Response:

Reviewer 29850

Comment: The project has ended. All data from the project should be put into the NGDS for future analyses.

PI Response:

Reviewer 23532

Comment: None

PI Response:

Reviewer 23479

Comment: This was a very expensive project with very limited archival output (3 abstracts). Value can be returned only through effective communication of results to date. Returning to the original goals of the proposed work, it is key to explain (1) how the datasets were “merged”; (2) what value was obtained from each dataset, vs. their conjunctive interpretation; and (3) what were the results of the 1st slim hole, and what might cause the “not encouraging” gradient?

PI Response:

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006727
Project: Structurally Controlled Geothermal Systems in the Central Cascadia Arc-BackArc Regime, Oregon
Principal Investigator: Wannamaker, Phil
Organization: University of Utah/EGI
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 6.0

Comment: The anticipated impact of this research in leading to geothermal developments in the central Cascade Range of Oregon is likely to be rather minimal. Temperatures encountered in slim holes and wells in the central Oregon Cascades to date have been discouraging, something not mentioned in the project documents to date. The chemistry of the thermal fluids have been known for decades and there is no reason to expect that additional study will provide encouragement for industry to revisit the area. Right now there is no particular reason to expect that any new reservoir locations that might result from this study will have more encouraging temperatures.

The primary impacts are more likely to be to the research and academic communities, which may still be significant.

The project appears to be on schedule and will meet its objectives.

PI Response:

We are either going to understand whether the Cascades region (Central in particular) carries significant geothermal potential, or we are going to walk away from it. We view the Central segment as being the most promising of the Cascades because Great Basin-style extensional tectonism has migrated from the southeast and landed upon pre-existing arc magmatism. Thus there are two possible modes of creating heat sources, and extensional deformation is the most direct way of creating space for fluids.

It is agreed that prior data have not been encouraging and that is why we have not dwelled on them. There needs to be a novel approach instead of plowing the same tired ground (figuratively). This is why we are emphasizing MT data in a new application as a direct means to see into the third dimension. Recent experience with MT in the extensional Great Basin proper is exciting in that it shows low-resistivity upwellings coming from depth into the producing systems (e.g. Dixie Valley, McGinness Hills, western Utah PFA). This is seen clearly in the Taupo NZ fields as well. Structural setting and isotope geochemistry support the presence of large-scale permeability at those systems. In particular, new structural analysis has focused the existence of prominence cross-arc trends intersecting the N-S graben faulting grain.Thus it makes sense to use MT data to look for such upwellings in the Central Cascades to possibly signify nearby blind geothermal resources. This would seek systems that don't merely represent shallow outflow and that currently could be masked by a rain curtain or vegetation canopy.

Stated another way, we believe the prior MT geophysical concept has been sufficiently proved elsewhere and so should be considered here. We examine the admittedly sparse MT data in this PFA to see what shows. However, a primary goal of the PFA is to define data needs in a possible future effort. The OSU structural analysis certainly shows there is plenty of potential for large-scale dilatency. Isotope geochemistry, especially 3He, shows that magmatic input is lurking nearby.

Almost undoubtedly, a primary recommendation of ours at the end of Phase I will be collection of new data in Phase II intended to address the potential of hidden systems.

Thus we hope very much that the ramifications of this approach will be more than academic.

Reviewer 29848

Score: 4.0

Comment: Goals are to develop a PFA model for the Central Cascades, but this will be difficult given the sparseness of their data for the area.

Integration of MT resistivity, structural analysis and fluid geochemistry constitutes methodology for prioritizing exploration and play ranking.

Have been given a lot of money ($537,482) for an area that seems to have such low potential.

PI Response:

Given the possibly unrealized potential of the Central Cascades region as discussed above for Rev 23406, the current sparsity of data should not prevent an attempt at forward progress. We doubted since the original proposal that drilling targets could result merely from Phase I effort. The reviewer does touch upon the three principal components of our approach. Given that existing temperature data are uninspiring, plus the characteristics of the region that have masked previous exploration, we need a new paradigm. A newly capable geophysical (MT) approach may be able to see into the third dimension to detect blind heat sources and permeability. Placement of new data would be guided by new regional structural constraints and geochemistry.

The project supports the salary and travel of four professionals, three postdoctoral researchers and a graduate student. Thus such a project budget is not out of line. None of the principals but one has state or institutional support and so they depend upon projects such as this to cover all costs including livelyhoods.

Reviewer 29849

Score: 6.0

Comment: The PI has already had considerable impact through his the advances he has made in the modeling, interpretation and use of MT. In this project the PI's are integrating MT resistivity, structural analysis and fluid geochemistry constitutes to prioritize exploration and rank plays. Low resistivity up-welling resolved using new MT inversion capability. New LiDAR and high res DEM data allow ID of hidden recent faulting, NW cross-arc trends and structural settings for dilatency assessment. The greatest contributions of this project may be continued demonstration of the value of MT in geothermal exploration and the use of LiDAR.

The PI would have more impact if he looked for more opportunities to assist others in using MT and other remote sensing technologies in their regions. It is difficult in a competitive environment to collaborate with possible competitors, but in the end open and supportive collaboration creates the best results. When the PI obtained new MT data that covered not only his project area, but also that of the Washington State team, he should have acted as a true "elder statesman" and leader by reaching out to the Washington State team to make them aware of the existence of the data and explore ways in which they could collaborate to strengthen both of their projects.

PI Response:

Reviewer 29849 has a relatively good grasp of what we are attempting. We would fine-tune the description in the following way. As discussed for Reviewer 23406, the role of the MT component in any of the structurally controlled PFAs is to seek low-resistivity upwellings signifying shallowing heat sources and permeability. The sparseness of the MT data in the Central Cascades has limited the possible imaging of such upwellings to areas around Mt Jefferson (incl Breitenbush) and at Kahneeta. This is a tiny fraction of the total PF area and reflects the sparse MT coverage. This fact, taken together with the relevance of MT data to detecting blind systems as demonstrated in other areas, is going to lead to a call at the end of Phase I for more MT data coverage over the Central Cascades PF area in Phase II. Several dilatent structural areas being and to be revealed by the LiDAR, high-res DEM, new analysis, plus local volcanic/geochemical setting, will provide general target areas for such surveying.

However, there is a serious misconception about the Mt St Helens MT data included in our oral presentation. These data were not acquired for us in this project; new data collection was not allowed anyway. They were taken by Dr. Graham Hill in 2009 as part of his Ph.D thesis at Monash Univ, Australia. No U.S. funds were used in that survey and the data are owned by Hill, not us, and they are not ours to give away. Inversion of those data with our new finite element algorithm was shown as code validation only because it is the best data set of which we are aware that includes substantial topography. That is why it was presented in the Approach section, and not the Results section. The example is part of the paper in review lead by Wannamaker's post-doc Michal Kordy on which Hill is a coauthor. That ms was written before the PFA projects started and it is still in journal review. So it is not part of our PFA. Corina Forson and the WA team were aware of these data independently of us; an earlier interpretation of the data was published by Hill (without us) in 2010 in Nature Geoscience.

The competitive nature of the PFA project program cannot be brushed aside. Approximately 40 proposals were originally submitted, and 11 chosen. There will be a downselect by the end of this year to ~4. There was no provision or encouragement in the FOA about cooperation across groups. DOE personnel have stated that the program intends to stick close to the letter of the FOA. Most of the personnel on this PFA depend on putting together a series of projects such as this for their professional existence in geothermal research. If there was more stability, cooperation would be straightforward. Otherwise there is no basis for calls that we undercut our competitive advantage.

Having said that, we note that the PI Wannamaker started discussing the Mt St Helens data set with Forson at the Peer Review and in weeks following. Preprints of the paper containing the inversion were shared including new graphics of plan views at various levels. The reviewer is evidently unaware of all this. The Utah group is hoping that the Mt St Helens data might be used as leverage for early release of the iMUSH MT data currently being collected under NSF support.

SCIENTIFIC/TECHNICAL APPROACH

<u>Reviewer 23406</u>

Score: 5.0

Comment: The technical approach to this project so far comes across as being more of a regional geochemical, geological, and geophysical study than a project truly focused on either understanding the existing known geothermal systems or finding additional blind systems. That said, the technical approach to a regional geochemical, geological, and geophysical study is good.

PI Response:

As the reviewer points out elsewhere, existing systems and manifestations are disappointing. Many have argued that they are dominated by near-surface hydrology. That is why we believe a very different tack is required, one that has a chance of seeing through to depth. Our PFA is a region united by a specific tectonic framework. Paradigms from other regions based upon MT geophysics, structure and isotope geochemistry are appropriate in defining that tack. But the Central Cascades demonstrably will require a significant investment in new data to achieve that. It was a constraint of the FOA that marginal increases in existing prospects was not to be part of the work plan.

Reviewer 29848

Score: 6.0

Comment: Their approach combines MT (new 3D MT inversion method that is potentially proprietary), structure, and geochemistry (but the geochemical modeling methodology may also be proprietary).

They have recently acquired some LIDAR data, and this along with high resolution DEM may help define the structure in the areas as well as overcome the problems of dense vegetation.

PI Response:

The key point to recognize is that recently advanced geophysical methodology can reveal termperature and deep fluid upwellings that may not be manifest in the relatively shallow evidence represented by springs and thermal gradient drilling. Dilatent structures and thermal influences can, to a large degree, define where followup geophysical data are best taken.

Reviewer 29849

Score: 6.0

Comment: The area suffers from data sparseness and the focus seems to be on developing technologies especially enhanced MT modeling and also reaction-based geothermometers, which seem to be superior to older geothermometers. They are leveraging a new Lidar base and new 3D MT inversion system in the most extensional section of the cascades. They are identifying heat, access to fluid, heating pathway for fluid, permeable reservoir and cap rock and inspired by their work in the Great Basin. They have identified a few structures that can feed into hi-T systems and magmatic "underplating structures".

Making good use of MT and LiDAR in an area with sparse data, because of high rain fall and dense forestation. High resolution 10 m DEMs are enabling geologic structure interpretation in the forest canopy. Used LiDAR coverage of Central Oregon showing intersecting faults.

Using spring geochemistry to estimate deep temperatures and magmatic component. Geothermometry approach incorporates information on the mineralogy of the formations through which the water is flowing. Looking for intersection points to avoid dilution -- have Three Sisters area as a training area for geothermometry. High H3 points to deeper magmatic source that is younger (and hasn't been lurking around in the crust).

The strong technical competence and use of new tools is paired with substandard use of statistical methods to recognize the inherent uncertainty and ambiguity in the data. The PI describes himself as using deterministic as compared with statistical approaches. It would be beneficial to incorporate more error and uncertainty analysis and metrics into the strong analytics. Numerical factors were not assigned in detailed weighting. They are not doing a mathematical weighting of the different factors. The PI should enhance his strength in development of individual valuable tools by acknowledging inherent uncertainty.

PI Response:

Generally a good grasp of our approach to date. We have recognized the data sparseness, especially the MT geophysical data, from the beginning. Nevertheless, its potential to reveal heat upwelling and large-scale permeability is high based on both Great Basin and New Zealand experiences. Given that there are numerous sizeable zones of potential dilatency in the project area based on newly analyzed structural geology, it makes sense to seek such geophysical structures. The sparseness of the MT data, which thus yielded only a few probable upwelling structures, points to one thing mainly: a substantial amount of new data needs to be gathered. At the moment, the priority area is a corridor from north of Mt Jefferson to south of Three Sisters.

At this point it is important to stress the unusually great amount of new analytical work that has been done in this project relative to others. In particular there has been an outstanding increase in knowledge of the structural framework based on new LiDAR analysis and compilations. We also have produced the first 3D inversion of all public domain MT data of quality in the project area. Hard results such as these are required before any statistical estimation or analytic decision making can be done.

We understand the call for error analysis, but this needs to be approached carefully and in ways appropriate to data types. For example, MT tomographic images do not come with error estimates on the individual voxel values (parameters) because the point of tomography is that neighboring parameters are almost completely correlated. The smoothing stabilizers are designed to minimize structure and suppress that not demanded by the MT observations. A means of model assessment we will exemplify is to remove the Kahneeta upwelling structure and display the misfit to the data that results.

We welcome the reviewer recommendation of multi-criteria decision making methods (MCDMs) such as Analytic Hierachy Processing (AHP). These turn out to be quite popular but should not be confused with statistical evaluation because probability distributions are not explicitly considered. However, they have organizational merit and can be employed in sensitivity analyses toward decisions by varying criteria weights. It is not dissimilar from the composite common risk segment analysis (CCRS) we proposed and we will compare them. We have to this point been heavily engaged with other hard analyses as described to create input to decisions. These are necessary because existing data appear dominated by shallow effects and thus have limited further use in resource assessment. Overmanipulation of statistics using outdated results will not yield positive outcomes.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment: The team working on this project is very strong and capable of collecting and interpreting the data.

PI Response:

We appreciate that. We are trying to argue a new approach as described elsewhere.

Reviewer 29848

Score: Not scored

Comment: Advanced MT techniques (but experience with interpreting these data is from an area with different geologic characteristics).

Have done some initial 3D MT Inversion imaging in the Mt. St. Helens area as well as around Mt. Jefferson including Breitenbush and Kahneeta.

Have also initiated some structural work in the western and high Cascades showing the geographic relationship between hot springs and faults.

In this most extensional portion of the Cascades, they are depending on extensional stress for permeability.

PI Response:

The geological characteristics have many similarities with those of the Great Basin, which is why we argued that inferences from the latter were relevant to the current project. Furthermore, the Taupo volcanic zone of New Zealand is a mixed arc-extension regime and similar geophysical structures feeding into the producing fields have been detected. The impact of Great Basin extension on this segment of the arc is confirmed by e.g. Ingebritsen and Mariner (2010, JVGR) where they note it probably is responsible for the huge step decrease in hydrothermal energy release per unit length of arc shortly north of Mt Jefferson (i.e., into Washington state).

Our group has considerable experience with interpreting geothermal exploration data in arc systems elsewhere in the world such as Indonesia and the Philippines, in addition to extensional prospects (e.g., Moore et al., 2008, AJS; Raharjo et al., 2010, GRC). This allows us to construct valid geological models for geothermal resources in the Central Cascades to guide play fairway prioritization.

The Mt St Helens image presented was for algorithm validation, which is why it appeared in the Approach section. We have been developing slip, dilatency and stress models for the project area since the peer review.

Reviewer 29849

Score: Not scored

Comment: Excellent use of MT and remote sensing (LiDAR and DEM). Leveraging these new tools to map beneath the canopy in a densely forested region with sparse data.

Developing and using new geothermometry to better understand fluid flow.

PI Response:

The new recognition that MT is detecting high-T permeable upwellings beneath major systems is a primary thrust. Structure and isotope geochemistry will guide future data siting efforts. It was unfortunate perhaps that our Cascades project was presented before our Great Basin project. The latter with its more extensive data illustrates our approach more clearly.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: There are two most obvious weakness of this project. This first is the selection of the central Cascade Range of Oregon as its focus. The remoteness and steepness of the range, along with a high percentage being within Wilderness Areas virtually assure that most of the area cannot and will not be extensively developed in the foreseeable future.

The second weakness is the lack of emphasis and recognition and understanding of previous exploration efforts in the central Cascade Range of Oregon. Only one reference of 3 pages of references in the original application is even indirectly directed to this. This begs the question as to how this work will build on and improve the geothermal understanding of the central Oregon Cascade Range. As one possible example of this, slide 7 presented at the Peer Review shows Green Ridge-Black Butte structural intersections with the Metolious Springs at the nexus. The problem with this is that the Metolious Springs are perhaps the largest cold spring in the Oregon Cascades.

Nowhere are high temperatures known to exist. The temperature-gradient drilling in the project area to date has shown that any useful holes will need to be relatively deep and costly core holes.

There are no successful deep wells or operating geothermal fields to serve as test cases or calibration points.

PI Response:

The Central Cascades was selected on the grounds of its unique magmatic and extensional tectonics relative to the rest of the chain. The percentage of the project area that is in wilderness is relatively small and concentrates in the highest elevations that would be most difficult to exploit anyway. Sadly for most other reasons, snowpack is predicted to diminish considerably over the next few decades making year round access easier. Timber companies operate extensively in the area so we would not discount interest in a good geothermal resource.

We have tried to be clear that we don't believe there is that much more to be milked from the existing well and spring data. This agrees with the generally pessimistic assessment about them expressed previously by the reviewer. A new approach to detect blind resources is needed. We believe that should be centered on new geophysical data guided by the new structural analyses and geochemistry. As Metolius Springs shows, not all favorable structures contain a geothermal resource; this pre-project example was intended mainly to demonstrate the resolution of new LiDAR. However, all geothermal occurences do appear to occupy favorable structures. We also recognize that Central Cascades development probably will require deeper drilling than done heretofore. In the current economic climate, that is discouraging. Carbon-sensitive externalities may change that.

Reviewer 29848

Score: Not scored

Comment: Sparse data is a major problem for this study.

Need to overcome dense vegetative cover and rain curtain masking.

The gravity data is too sparse, and the magnetic data primarily shows the near surface geology.

The reaction based geothermometery gives higher temperatures than the cation (Na, K) based geothermometers, and this work has apparently primarily been done in the Three Sisters area.

The relative weightings of the different risk factors will be done very simply (3 colors: low, medium, and high).

Much of this part of the Cascades is in wilderness areas.

Need to determine whether the heat source in various parts of the study area is magmatic or metamorphic in origin.

PI Response:

Sparse data was recognized at the outset. Given the active tectonic setting, this region should have potential but requires a new approach. We work through the existing data in large part to demonstrate how keen is the need for new collection. Approach to the weighting of risk factors is evolving, but our intial approach was reviewed favorably in our original submission. Actually, a relatively small volume is in wilderness area which we would not wish to see exploited anyway. The need to determine the heat source is not so much a weakness as a role for new data gathering. As stated elsewhere, this was never meant to be a one-shot project.

Reviewer 29849

Score: Not scored

Comment: 1. Deterministic as opposed to statistical approach: While it is appropriate for experts to have a preferred realization of the data, is beneficial and informative to incorporate uncertainty into play fairway analysis. A promoter of a tool or a methodology often wishes to minimize uncertainty to more readily explain complex analysis and interpretations to less knowledge people, but incorporation of uncertainty is critical. In the petroleum industry exploration and reserves determination, considerable emphasis is placed on recognizing alternative interpretations of datasets.

2. Acting as a leader rather than a competitor: The PI is clearly collaborating with many of the other projects. As a leader, he should continue to enhance his reputation and value by looking for new collaborations and actively supporting younger and less experienced teams. The interaction with the Washington State team could have been much more supportive. It would have been more appropriate to mention the existence of the MT and LiDAR data in the Q&A session for the Washington State Team instead of as part of the presentation of his project. Leaders are strong and do not feel threatened by others. It is a sign of weakness to fail to support less experienced colleagues.

PI Response:

We hope progress won't get sidetracked by semantic differences re deterministic vs statistical. In deterministic, we are simply creating the inputs to the criteria and subcriteria of an MCDM process by novel analyses of the existing data. The exploration paradigm is that systems lie in dilatent structures, the MT inversions could show which structures truly hold upwelling fluids, and the geochemistry may confirm that deep seated fluids are entering a system. This concept directly relates to the criteria of heat source, fluid source and permeability that are essential to an MCDM like CCRS or AHP. Our approach that advocates new types of data to see into the third dimension recognizes wide community acceptance that the shallow hydrological regimes dominates the historical observables in this PF area. Mindlessly applying statistics to an outdated paradigm will only mislead into expensive failures.

On the issue of competition let us once again attempt to correct the record. The statement that the PI is clearly collaborating with many of the other projects is false. He leads one other project in the extensional eastern Great Basin. He is a Co-I with a minor role in the central Great Basin project of PI J. Faulds, and that role was set with the original awarded proposal of Faulds. He collaborates after the fact on no others consistent with how the FOA was laid out. We have already described that an interpretation of the Mt St Helens MT data set had been published long before the PFA program began and the WA team was aware of it. It was for our code validation which is why it was shown in the Approach section.

Regarding the advancement of young professionals, the Utah PI has provided 24 financially supported mentorships at M.S., Ph.D and post-doc levels. In this project, DOE support funds three postdocs and a grad student. The PI is steadily approached by more applicants than he can take on in this fragile support climate. Those will be the young professionals to whom he remains most loyal.

Whether projects can be cooperative is a matter that the DOE needs to clarify. For instance, near the beginning of June's DOE PFA newletter, an initial assessment of the peer review meeting states: "The competition for the down-select is heating up!". There also was no recommendation to do this in the reviews of the original proposal. If for Phase II there was e.g. a suggestion from the GTP that the Washington and Oregon project areas might be combined, we could welcome it to the extent that the collaboration makes sense scientifically and the level of possible support is commensurate with an enlarged area.

Given the inconsistency of the reviewer's apparent understanding re the framework of the FOA or our history, the final ad hominem remark of the reviewer is not considered qualifying.

IMPROVEMENTS

Reviewer 23406

Comment: Hopefully the final product from this project will have more of an emphasis on geothermal prospects in the central Cascade Range of Oregon than was shown at the Peer Review.

PI Response:

As noted elsewhere, progress in the Central Cascades toward identifying prospect-scale resources will need to be a staged effort with an appropriate investment in new data. That is a stated goal of the FOA. This was never meant to be a one-time exercise. We are trying a new approach and not dwelling on overfished waters.

Reviewer 29848

Comment: Need to get further along in 3D modeling, acquire more diverse types of data, and integrate the disparate types of data into a single coherent interpretation.

PI Response:

At the time of this review response, the MT data inversion is essentially mature and the new faulting map is quite close. We will incorporate the data set types appropriate to making play recommendations but intend to more fully incorporate heat flow and volcanic age into the presentation.

Reviewer 29849

Comment: 1. As a leader support younger researchers in geothermal even if they are working on competing projects.

2. Recognize the inherent uncertainty in the methodologies and provide error analysis and alternative realizations.

3. The tool used by the Washington State team that incorporates psychology and statistics could be very beneficial in the weighting. The tool was used by that team to reveal when team members were making inconsistent decisions.

PI Response:

We have addressed competition elsewhere regarding the nature of the FOA. Further guidance will need to come from the DOE. Cooperation would be more encouraging if there was less overall fragility. We have experienced situations in that regard when the program does not make awards. Nevertheless, over time we have supported and advanced a large number of young professionals. We are not in this to compete for the sake of competition.

Some model testing of the overall MT structure will be presented to provide a sense for model resolution. An uncertainty measure for the structural data is being developed. An error estimate is available for the Geo-T reaction-based temperature regression, although we expect deterministic factors such as deep hydrologic pathway topology will outweigh that. Kriging statistics will be examined for their potential usefulness in propagating through multi-criteria weights. But we point out again that existing data may be dominated by near-surface effects, and that meaningful resource assessment in the Central Cascades probably requires new data about which currently derivable statistics have limited applicability.

MCDM through AHP can be a useful means of expressing the combination of data sets and models for PFA. Inconsistency can be judged for variation in criteria weights, though by definition there is no inconsistency for uniform weights. The 'psychology' aspect just means that an expert can assign a criterion weight based on no more than 'gut-feeling'. The WADGER team approach and a model was laid out in a WA state report published in July 2014 already just as the PFA awards were being announced (Boschmann et al, 2014, OFR 2014-02). It is suggested that the reviewer look into that report to see the extent to which their current PFA effort has been able to break new ground since that publication. We are looking into the AHP approach for relevance to our exploration paradigm and will compare the approach with our CCRS.

Review: 2015 Geothermal Technologies Office Peer Review
ID: EE0006732
Project: Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah
Principal Investigator: Wannamaker, Phil
Organization: University of Utah/EGI
Panel: Exploration Validation / Play Fairway Analysis

IMPACT OF RESEARCH, ACCOMPLISHMENTS, RESULTS AND PROGRESS

Reviewer 23406

Score: 9.0

Comment: In some ways this is a smaller-scale variation of the UNR project in western and central Nevada with a different emphasis on the available geological and geophysical data sets. It is probably the second most likely of the projects to result in the identification and development of new geothermal resources.

The overall area is large enough that it should host multiple new targets to be identified. The team has already identified locations based on structural settings that are of interest.

The project appears to be on schedule and meeting its progress goals.

PI Response:

The eastern Great Basin is a unique play fairway area and should not be lumped with others. It contains a pronounced Quaternary magmatic trend including rhyolites with several possible magmatic systems running the length of the state. There are unique controls on systems here through the intersection of the modern N-S rifting with the pre-existing E-W lineaments and plutonic belts. Thus we are hoping this fairway will contain more high-enthalpy resources than is usual. If this bears fruit, the entire western Utah corridor from Idaho to the Grand Canyon may be in play. Although the nominal square mile coverage of the eastern Great Basin PFA appears smaller than that of UNR, the impact of our project area in terms of potential megawatts is at least as high. The UNR project team pointed out that they are concentrating on limited subsets of the large rectangular area drawn, namely the northwestern and northeastern portions.

Reviewer 29848

Score: 7.0

Comment: The goals for this project appear to be consistent with the goals and objectives of the GTO. It seems these awardees intend to open an underdeveloped U.S. geothermal province and identify new plays and play types within this province.

Need to identify and integrate the heat source, access to fluids, pathways to heat up and concentrate fluids, high permeability reservoirs, and caprocks.

PI Response:

We are especially excited by the potential for large, high-enthalpy systems in the PFA given the active volcanic trend running the length of the state, plus large-scale intersection of structural trends creating dilatency.

Reviewer 29849

Score: 6.0

Comment: The PI described the approach as "very deterministic". In petroleum industry exploration the importance of recognizing inherent uncertainty has led to an emphasis on probability and multiple realizations of data. The team makes excellent use of analytical techniques but undercut their influence and impact by focusing on a deterministic interpretation of that data. In exploration it is important to recognize the confidence in certain types of results. Taking a "deterministic" approach is the behavior of a promoter as opposed to a knowledgeable and highly skilled specialist in exploration. There is value in knowledge and intuition, but it should not displace statistical analysis and interpretation, rather it should supplement it.

Since the PI is also PI of a project in the Central Cascades Arc - Backarc Regime in Oregon there is strong flow of ideas and approaches between the two projects. It might be better to combine the Washington State Project and the Central Cascades Project to have that influence proceed in a more collaborative way that also supports and mentors some younger PI's. The younger team could also improve the work of the older, more experience team by coaching them on use of the tool that they are using that combines statistical analysis and psychology.

The PI's have leveraged their exploration approach and exported it to their Cascades project. Different geothermal models are being used in the different areas. Determination of boundary of the clay zones -- geometry and compositions are also different. The PI said that they are, “Playing off in the great basin. Want to see that extended. Method is established, but data needs will be brought out."

PI Response:

We hope progress in this PF area won’t be sidetracked by semantic issues, and the reviewer seems to be paraphrasing the presenter to some extent. When we referred to deterministic, it was in terms of creation of a specific exploration paradigm where certain geophysical data (MT, verified where possible by seismic swarms) have recently become understood to be direct indicators of upwelling heat and fluid, with implied large-scale permeability, connected to deep magmatic activity. These upwellings appear to exploit dilatent structures, identification of which is the second leg of our exploration stool using mapped structures and, where appropriate, gravity. The third leg is the fluid geochemistry which suggests that at least some of these systems pull fluid from much broader volumes than is represented in the rock compositions of the producing reservoirs. This supports using MT images as proxies for large-scale permeability and heat upwelling. This is an exploration approach that sets us apart from other groups.

Regarding statistical approaches, some clarification is needed. On the one hand there are data driven techniques such as kriging and probability kriging, seamlessly integrated into ArcGIS. These are data-based and use local averaging of ground truth to derive summary spatial functions and extrapolate into poorly or unsampled areas. The uncertainty intervals can become very large where coverage is poor. Nevertheless, we are producing and examining these in our project. On the other hand, regarding the Analytic Hierarchy Processing (AHP) technique that WADGER applied referred to by the reviewer, it is interesting to see the comment "There is value in knowledge and intuition, but it should not replace statistical analysis …". Actually, AHP is classified as an expert knowledge based technique as compared with a data-based technique (e.g., Hosseinali and Alesheikh, 2008, AJAS). Its touted strength is its acceptance of gut-feeling resource criteria weighting values, which presumably is what the reviewer is referring to as 'psychology'.

The latter two paragraphs are not primarily about our eastern Great Basin PFA project but seem to have been pasted from the Central Cascades review for some reason. Perhaps the reviewer was going to edit these for Great Basin relevance. It would be unfair if the reviewer means to conflate what she/he objects to in the Cascades project with our Great Basin project as a means to cast the latter in a bad light. We will comment further in this reply regarding use of the Analytic Heirarchy Process tool mentioned, and the issue of competition/collaboration.

It appears that the reviewer sometimes is reaching for criticisms here. Some of the language verges on being, well, a bit snarky. For example, bringing up terms like "promoter" or (later) "artful impositions" is inappropriate and those are not our words.

SCIENTIFIC/TECHNICAL APPROACH

Reviewer 23406

Score: 9.0

Comment: The approach is solid with a large and geologically interesting area that has three operating fields to serve as training or test locations.

The project team is already highly experienced in the project area and over past years has built up a substantial data base to build on.

There are three quite variable operating fields within the project area to use as calibration points.

PI Response:

We would just like to emphasize that our approach has detection of blind systems very much in mind. Historically recognized surface manfestations should not necessarily be the limiting factor for the overall potential of a region.

Reviewer 29848

Score: 7.0

Comment: In the future, this project will develop conceptual models of geothermal systems that integrate geophysics, geology and geochemistry.

They claim to apply rigorous 3D analysis of diverse data sets, but this is not shown in their presentation.

Also in the future, geochemical models of deep fluid flow pathways and sources will need to be correlated with geophysical and geological structures in order to identify potential buried plays within the fairways.

In addition, areas of permeability and deep fluid sources will need to be identified in the future.

Elements of Extension: Most geothermal systems in the Great Basin have one of the following: high strain, dilation, shear, and/or total fault offset. Data representing these elements of extension were classified and fused into a "layer of evidence", that is to be used as part of the structural composite risk segment. No high risk areas lacking all indicators are found within the study area.

PI Response:

First, the project started with a conceptual model of an extensional geothermal system as expressed in MT geophysics, 3D structural geology, and geochemistry from experience in the central Great Basin. This model is being verified in the more magmatic eastern Great Basin now, to constitute a predictor of geothermal favorability. The exploraton paradigm builds upon recent observations that high-T systems exhibit MT low-resistivity structures projecting from mid-crustal depths that connect some proportion of magmatic sources into the systems. The systems possess permeable volumes created by favorably dilatent geological structures. Isotope and major element geochemistry generally confirm that the geophysical and geological structures are characteristic of potentially productive systems. We seek areas of such confluence, or at least a subset of the three indicators, as a measure of resource possibility in our PFA.

State-of-the-art rigorous 3D analysis certainly has been applied to the large MT data set and 3D location of seismic swarm clusters has been in progress. Fault intersections creating dilatency are 3D structures and we are expanding our inventory of these in this PFA. Areas of hidden heat and permeability perhaps are most directly identified by MT upwellings corroborated by structural intersections.

<u>Reviewer 29849</u>

Score: 6.0

Comment: This area had the benefit of a large amount of data. The PI's combined an unusually large MT dataset with a seismicity data set. A new MT data inversion system was used. Use MT to identify high-T fluidized upwellings, test possible deep fluid zones with seismic swarms, mapping and high resolution geomorphology. The value of this work was diminished however by taking a "very deterministic approach."

The seismic analysis is still in progress. The interim seismicity analysis has looked at swarms. They are currently trying to lower detection limits.

Geochemical modeling has indicated that there can be much larger flows than are obvious from current production.

Temperature wells are primarily clustered in individual prospects, but not shown in the data. Phillips had a lot of widely space temperature data. The PI noted that more data is being found in private hands, "that kind of data is gradually emerging from closets."

The focus on a deterministic interpretation is a key concern. The PI spoke of "artful impositions" and that the most simple ways to fit the data in an earth is undoubtedly more complicated. There are many old jokes about all of the different ways multiple geologists will contour the same data and that if you have 4 geologists in a room you will have at least 5 opinions on the subject. That is why it is very important to include statistical analysis and recognize the probability of different realizations. Not only will a group of geologists have different opinions, but different disciplines will tend to take different approaches and have different realizations. The weighting system used by Washington State that incorporates both statistics and psychology sounds like a good tool to tease out the uncertainty in the deterministic models proposed by experienced experts.

This project is being given a lower Scientific/Technical grade than the Cascades project, because it appeared that most of the new tool development was focused on the Cascades project, while both are being negatively impacted by the failure to incorporate a probabilistic approach to model development.

PI Response:

We have discussed elsewhere the reviewer's perception of "deterministic" and hope there will not be inordinate fixation. We simply meant that we are developing specific data sets and new-concept geomodels to localize high priority areas based as much as possible on hard data. We are not merely extrapolating through e.g. probability kriging from clustered known data. This tends to restrict high priority areas to already known geothermal occurences. We argue for the importance of utilizing data which can see into the third dimension especially for glimpsing blind system potential that may have no other manifestation. After we have performed such quantitative analysis, the heat and permeability implications can be used to construct layers for multi-criteria decision making methods.

Agreed the temperature data are clustered close to recognized projects. This just reflects the reality that geothermal systems are discrete occurences controlled by structural intersections. This is why statistical extrapolation to identify other possible play areas is so hazardous in geothermal as compared to oil&gas. The water chemistry spring locations were shown on slide 9 of the presentation, with the water chem temperatures vs real temperatures on slide 17.

The reviewer misheard the PI. Keeping models as simple as possible while still explaining the data is the standard for geoscience interpretation. In other words, one wishes to avoid artifacts not demanded by the data. Folksy anecdotes about geologists in this regard are not constructive; are all opinions equally informed? We do appreciate the reviewer stimulating a closer look at the AHP approach used by the WADGER group. It has similarities to the composite common risk segment (CCRS) approach we started with. AHP showcases criteria weighting and we will certainly be comparing it as we perform CCRS. However, it is not probability-based as we have noted.

We recommend that the reviewer look at the WADGER OFR 2014-02 which is clearly the template for their current PFA. It is suggested that the reviewer look into that report to see the extent to which their current PFA effort has been able to break new ground since that publication. While many of the AHP weightings are qualitatively reasonable and consistent with the exploration elements we have adopted, a rationale for specific weight values was not presented in that report other than a decision not to overweight fault density.

It really is unfortunate that the reviewer decided to downgrade the score of this section because of a serious reviewer misconception. Both the MT geophysical inversion and geochemical geothermometry capability were developed under support of independent DOE contracts, and not specifically for the central Cascades project. That is why these were introduced in the Approach section, not the Results section. The new technology is applicable to a great many other geothermal prospect possibilities. Perhaps it would have been better if the eastern Great Basin PFA project was presented before the Central Cascade one, because the former probably would have set up our approach more clearly given its higher data content. Of course, the program organizers could not have known that a priori. But the reviewer should not be basing scores on false notions.

STRENGTHS

Reviewer 23406

Score: Not scored

Comment:
The project area consists of lands that are close to 100% developable.

This project dovetails nicely with ongoing work by the State of Utah to make the case that there may be extensive deep reservoirs waiting to be discovered beneath the basins in the project area.

The project area is amenable to low cost temperature-gradient hole drilling if it is selected for additional funding.

PI Response:

We agree. Under our exploration paradigm, virtually the entire N-S extent of western Utah may have potential.

Reviewer 29848

Score: Not scored

Comment: Advanced MT technology.

Potentially have some powerful techniques, but these techniques need to be explained and integrated to come up with a coherent and substantiated interpretation.

PI Response:

We believe the exploration paradigm was stated succinctly in the Project Summary document. It builds upon recent observations that high-T systems exhibit MT low-resistivity structures projecting from mid-crustal depths that connect some proportion of magmatic sources into the systems. The systems possess permeable volumes created by favorably dilatent geological structures. Isotope and major element geochemistry generally confirm that the geophysical and geological structures are characteristic of potentially productive systems.

Reviewer 29849

Score: Not scored

Comment: The team has great experience and are leaders in the development and use of MT and geothermometers. The team is collaborating with several other play fairway projects.

PI Response:

The team has advanced a unique exploration paradigm both in terms of combination of techniques and the geographic/geologic area. The matter of collaboration needs to be clarified. To the extent that any team members collaborate currently on other projects, that is as formal PIs or Co-Is as was set from the beginning of the proposal process. Following that, the structure of the FOA is one of competition for best ideas and outcomes, and a downselect on that basis is forthcoming. For instance, near the beginning of June's DOE PFA newletter, an initial assessment of the peer review meeting states: "The competition for the down-select is heating up!". The DOE will need to provide clarification as to whether there should be cross project collaboration beyond that, and how it is to be considered in the downselect.

WEAKNESSES

Reviewer 23406

Score: Not scored

Comment: The biggest weaknesses to this project that may be the relatively small number of hydrothermal systems that discharge to the surface within the project area, relative to say western or central Nevada. This may be indicating that the project area is somewhat less blessed with geothermal activity and probably is reflected by the expectation to identify 2-3 new locations..

PI Response:

Given the wide acceptance that a large proportion of potential geothermal resources are probably blind, and given the active extensional-volcanic setting of the project area, a persistent exploration effort should eventually yield high-enthalpy payoff. If in Phase II we can extend MT coverage past the southern end of the Mineral Range and cover the intersection with the E-W Blue Ribbon lineament, of order a half dozen new potential systems may be visible. In addition, this play fairway concept probably can be extended the entire N-S extent of western Utah.

Reviewer 29848

Score: Not scored

Comment: The different types of data are not tied together either geographically or in terms of an integrated interpretation.

There are alternative models that could fit these same data.

The presenter stated that this area has high temperature geothermal potential, but temperatures from wells, hot springs, or geothermal producing areas are not shown on geographic maps in the presentation.

Locations of the MT data and MT inversions shown in the various slides are often hard to determine in this presentation. The locations and overlap of the MT data and MT inversions with other different kinds of data are also often difficult to determine and need to be clearly shown.

The awardees depend quite a bit on 3D MT modeling and imaging in this presentation. Although the awardees for this project claim to have other types of data, they need to include and integrate these other types of data with the MT data. They need to make sure to use and integrate a wide variety of data instead of relying too much on just a few types of data.

Although other types of data are mentioned in the presentation, most of the data shown in the presentation is MT data, and the existing MT data appear to be limited to three areas.

The methods for processing the MT data to create the inversions appear to be proprietary.

Seismic swarm clusters from Arabasz et al., (2007) were subcontracted using propriety software with unclear selection parameters. The results from Arabasz et al., (2007) need to be re-examined.

MT coverage is to the west of the good seismicity coverage; there is very little area of overlap for these two critical types of data. Seismic data is needed over the producing geothermal systems.

It is apparently a work in progress to compare seismicity clusters with MT and geological structure.

Where are the areas of structural interest compared to the greater study area?

Comparison and integration of the MT data with other types of data appears to be largely a future development for this project.

PI Response:

Please see our response to this reviewer 29848 just above defining our exploration paradigm. It is true that MT data constitute a large proportion of the thrust. That is because they are recognized as providing the most direct view to depth of heat and fluid upwelling, and deep permeability.

The main structural areas of interest could be more clearly plotted. They include intersection of the N-S rift faults with E-W lineaments. The former are on slide 3. The latter are a bit more interpretive following Rowley and will be presented in more detail in future.

Not sure why the fact that we have developed a new method to invert MT data is considered a weakness. As the FOA and subsequent DOE newsletters make clear, this is a competitive process with downselects based on quality of ideas and results. The development is new and the PI's Ph.D student (now postdoc in this project) deserves to see his work in print before we consider the future of the algorithm. Universities have become quite strict about intellectual property and the federal government supports that.

As for data coverage overlap, a goal of Phase I is to point out data needs that could be addressed in a Phase II.

It also is true that much of the project as presented at the peer review is in progress, as the review materials needed to be submitted approximately one-half way through the project period. For instance, we are continuously working to improve the seismic swarm detections.

Reviewer 29849

Score: Not scored

Comment: The "over confidence" of acknowledged experts is a weakness. In a Shakespearean way, our greatest strength is often also the seed of our weakness. In Shakespeare, when weak players make mistakes it is a comedy, but when strong players make critical errors it is a tragedy. The team needs to admit that while experience and the intuition that accompanies it are important, the interpretations of their data are not unique so that each realization has a probability (far less than 100%) of being reality. Therefore statistical weighting and multiple realizations of the individual datasets and combinations of the individual datasets add tremendous value. Modern exploration is a game of statistically-informed probability.

PI Response:

Perhaps more kafkaesque than shakespearean, after slighting our approach the reviewer puts forward another that does not operate as the reviewer perceives and yet is actually not much dissimilar to what we plan ultimately. AHP is defined as an expert knowledge based decision process, not probabilistic or statistical. The criteria weighting values can be relatively 'hard' numbers based on quantitative information such as we are developing with our techniques, or it will accept gut-feeling, 'intuitive' (not our word) values which accommodate the 'psychological'. The team is not "over-confident" and its capabilities and experience are not weaknesses. The team advances a promising and unique new exploration concept that is increasingly well founded. Mindlessly applying statistics to an outdated paradigm will only mislead into expensive failures.

IMPROVEMENTS

Reviewer 23406

Comment: I strongly encourage the research team to make a good effort to acquire and use as much as possible all temperature-gradient data that might become available.

PI Response:

Indeed we will. However, because a directive of the FOA was to not work toward expanding existing systems but instead seek new ones, to some extent the existing data represent plowing old ground. They also tend to represent shallow depths except perhaps in already recognized fields. This is why we are emphasizing methodology that can "see" into the third dimension to seek new heat and fluid sources and large scale permeability.

Reviewer 29848

Comment: They seem to have a lot of data. They need to determine the critical data and focus on these critical data, especially in the areas where the important data overlap geographically.

There are producing geothermal systems in the study area that they need to use in order to better understand and calibrate their data in the study area.

New waveform correlation techniques for seismic swarms may improve event detectability by 1-2 orders of magnitude. Need to test new seismic clustering and detection techniques to verify existing swarms and increase event identification within the existing swarms.

They need to have a map that shows where the existing hot springs and producing geothermal systems are in the study area (where they supposedly obtained geochemical and temperature data) as well as where the MT data, seismic swarm, and structural data are. It would also not hurt to have maps showing where the gravity, magnetic, heat flow, DEM, and other data are as well.

The various types of data need to be weighted and integrated into a series of possible interpretations (including the uncertainty in the various types of data and interpretations).

PI Response:

Slide 9 in the presentation showed the springs and the producing areas of our PF. Slide 3 showed the MT site distribution and the N-S Q faults and the Q volcanism. The latter also shows the gravity contours. Slide 7 showed the locations of the seismic swarms as known at the start of our analysis. We continue to work on data fusion and presentation as the project proceeds.

Reviewer 29849

Comment: The team should incorporate probabilistic analysis in all stages of its work and interpretation. The existence of multiple realizations should be acknowledged and leveraged to create a more robust play fairway analysis. The team should consider using the tool that the Washington State team is using that incorporates psychology and statistics into the weighting of different datasets.

PI Response:

We should not confuse probabilistic with analytic decision making processes. The WA state approach is the latter and has similarities with the CCRS method we began with, perhaps with somewhat different conceptualization of weighting.

Appendix II: Recommendations for Improving the Peer Review Process and Summarized Survey Results

Recommendations for Improving the Peer Review Process

Positive Feedback:

- The format and topics this year were the best compared to any of the last five years.
- GTO DOE directors, managers, and officers do a great job of coordinating the funded projects.
- For the most part, sessions ended on time and moderators kept the review on schedule.

Improvement Opportunities:

- Proppants is a topic that has not been extensively looked at and, although not as important in sharing, is key for hydraulic fracturing to maintain the permeability after fluid pressure is reduced.
- Innovative stimulation is very important for construction and this session had a great portfolio. Would be good to see advanced zonal isolation coupled to advanced hydro stimulation added to the project deck for "baseline" comparison.
- The review criteria need to be more focused on the science and technology aspect of the results. Many projects skimmed over results and that is the most important aspect of the review not, for example, the milestones.
- Some PIs withheld critical information, claiming to be proprietary data. For a proper review the proprietary data should also be made available to reviewers under a non-disclosure agreement.
- Weaknesses and Improvements are largely redundant, weaknesses could be removed. Q&A was usually too short.
- Some projects with multiple phases/years of input - difficult to fit into presentation template or 20 minute time limit. Other projects, e.g. if only 1 year, fit well into the presentation template.
- Having a limited number of slides is useful, but the timing is better. If the presenters need an additional slide to show a figure but can finish in 20 minutes, then they should be allowed to do so.
- Presentations were too short. More systems schematic diagrams, energy and mass balances would be useful.
- Presentation submission improved, but there is more room for improvement – plenary and lunch presentations would benefit from more urgency – maybe a deadline of the Wednesday before would be appropriate.
- GTO moderators should introduce themselves and reviewers at beginning of session. Perhaps the entire award team could stand and be recognized.
- Send the reviewer assignments to each moderator ahead of the peer review (and have it printed out in each room). Update the guidance to ask the moderators to make sure their assigned reviewers are present.
- GTO could have a mandatory internal meeting at the beginning of the day (~15min max) to gather, get marching orders, talk about needs or concerns, address issues, etc. The other option would be a de-brief gathering at the end of the day.
- Would be helpful to use a conference app (e.g. Guidebook, Bizzabo).
- Technology wrap-up sessions – Program Managers and their moderating staff need more training to facilitate these sessions. Develop templates for the Program Managers to use to facilitate the technology wrap-up sessions.

Summarized Survey Results

Presentation Templates:

- The general theme from the reviewers is that they would like to see more content focused on the science of the work. One suggestion would be to allow the Principal Investigators (PIs) to post links to published material within their project summary. Perhaps this can help reviewers to feel that they have better background on the project.

- In the presentation template, urge PIs to breeze over the background, and focus on the science. Remind them that they don't need to spend equal amounts of time on every slide.
- Consider writing up "A Tips for Success" document for PIs. This document would focus on ways that they can optimize their time at" the front of the room during the presentation and Q&A. For instance, encourage the PIs to respond to the questions asked and to not go off on tangents.

Moderator Guidance:

- Should have GTO and Staff meeting prior to the peer review meeting, the night or week before. At least a moderator session. WebEx is an option.
- Consider delegating the time keeping task to someone other than the moderator so they can focus on the presentations.
- Tech Wrap-ups really need to be discussed in more detail prior to the review. Encourage the moderators to work with their teams. Tech wrap ups tend to work better with projects that are somewhat related. Provide a slide to guide the tech wrap up discussion that helps orient them to the tech area and tie it to the GTO Roadmap.

P2RMIS:

- Consider a communication portal between PIs and reviewers.
- Consider combining weaknesses and suggestions for improvement in to one category. As an alternative, perhaps we just need more robust reviewer training. We could suggest that they write 'see above' as opposed to repeating comments that apply to both 'weaknesses' and 'suggestions for improvement'.
- In regards to reviewers that feel they don't have the expertise, they should note their lack of expertise in the comments, then comment on what they feel they can, and finally score that project a zero so that the score sticks out and DOE can remove it if desired.

Other:

- In the opening plenary session, consider having a brief discussion to go over the review criteria, what the judges were "grading" on, and when the results should be available.
- If there are fewer project next year, consider doing the audience Q&A after each project.
    - Plenary- In developing content, consider sending a questionnaire to industry in order to seek suggestions for plenary/lunch speakers. Consider having more programmatic presentations as the attendees wanted to hear more about what DOE was up to.

Appendix III: 2015 Peer Review Meeting Detailed Agenda

2015 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

GEOTHERMAL TECHNOLOGIES OFFICE
May 11-14 2015 Peer Review Agenda

Monday May 11

The Westin Westminster 303-410-5000
10600 Westminster Blvd, Westminster CO 80020

print date 05/06/2015

Track 1-Systems Analysis & LowTemp - Room Standley I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Wendy Harrison, Colorado School of Mines Plenary - GEOTHERMAL ENERGY: Global Reach, Local Impact room: Westminster III & IV
9:00a-9:30a 30 min	Systems Analysis: Systems Analysis, Resources Assessment, Data System Development & Population, Education	**Tom Lowry, SNL** GT-Mod
9:30a-10:00a 30 min		**Greg Mines, INL** GETEM
10:00a-10:30a 30 min		**Thomas Edmunds, LLNL** The Value of Geothermal Power for Integration of Intermittent Generation
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		**Jordan Macknick, NREL** Projected Deployment of Geothermal Technologies Subject to Water Availability Constraints
11:30a-12:00p 30 min		**Kate Young, NREL** Regulatory Roadmap
12:00p-12:30p 30 min		**Dan Getman, NREL** Geothermal Prospector
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Tim Reinhardt, DOE Vision Study room: Westminster III & IV
2:00p-2:30p 30 min		**Chad Augustine, NREL** Geothermal Resource Potential and Supply Curve Improvement
2:30p-3:00p 30 min		**Chad Augustine, NREL** Strategic Analysis
3:00p-3:30p 30 min		**Colin Williams, U.S. Geological Survey** National Geothermal Resource Assessment and Classification
3:30p-3:40p 10 min		Audience Q&A
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		**Wrap up: Systems Analysis Session**
4:30p-5:00p 30 min		
5:00p-5:30p 30 min		
5:30p-5:40p 10 min		

Track 2 Hydrothermal - Room Westminster II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Wendy Harrison, Colorado School of Mines Plenary - GEOTHERMAL ENERGY: Global Reach, Local Impact room: Westminster III & IV
9:00a-9:30a 30 min	Hydrothermal: Reservoir Fracture Characterization & Fluid Imaging	**Rob Mellors, LLNL** Stochastic Joint Inversion for Integrated Data Interpretation in Geothermal Exploration
9:30a-10:00a 30 min		**Dr. Andre Revil, Colorado School of Mines** Time-lapse joint inversion of GEOphysical Data and its application to gEothermal prospecting - GEODE
10:00a-10:30a 30 min		**Rob Mellors, LLNL** Identifying High Potential Well Targets with 3D Seismic, and Mineralogy
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		**Chad Augustine, NREL** SURGE: Sedimentary Geothermal Feasibility Study
11:30a-12:00p 30 min		**Lianjie Huang, LANL** Imaging Fault Zones Using a Novel Elastic Reverse-Time Migration Imaging Technique
12:00p-12:30p 30 min		**Chad Augustine, NREL** SURGE: Completing Horizontal Geothermal Wells
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Tim Reinhardt, DOE Vision Study room: Westminster III & IV
2:00p-2:30p 30 min		**Wrap up: Reservoir Fracture Characterization & Fluid Imaging**
2:30p-3:00p 30 min	Hydrothermal: Exploration Validation / Play Fairway Analysis	**James Faulds, Nevada Bureau of Mines and Geology, University of Nevada-Reno** Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways
3:00p-3:30p 30 min		**Nicole Lautze, University of Hawaii** Comprehensive analysis of Hawaii's geothermal potential through Play Fairway integration of geophysical, geochemical, and geological data
3:30p-3:40p 10 min		Audience Q&A
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		**Richard Stephen Middleton, LANL** Hydrogeologic windows: Regional Signature Detection for Blind and Traditional Geothermal Play Fairways
4:30p-5:00p 30 min		**Lisa Shevenell, Atlas Geosciences Inc.** Geothermal Potential of the Cascade and Aleutian Arcs, with Ranking of Individual Volcanic Centers for their Potential to Host Electricity-Grade Reservoirs
5:00p-5:10p 10 min		Audience Q&A
5:10p-5:40p 30 min		

Track 3 EGS1 - Room Westminster I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Wendy Harrison, Colorado School of Mines Plenary - GEOTHERMAL ENERGY: Global Reach, Local Impact room: Westminster III & IV
9:00a-9:30a 30 min	Enhanced Geothermal Systems: Tracers / Zonal Isolation / Geochemistry	**Lyle Burns, Clean Tech Innovations, LLC** SPI Conformance Gel Applications in Geothermal Zonal Isolation
9:30a-10:00a 30 min		**Jefferson Tester, Cornell University** A Reactive Tracer Method for Predicting EGS Reservoir Geometry and Thermal Lifetime: Development and Field Validation
10:00a-10:30a 30 min		**John Christensen, LBNL** Radioisotope Tracers and Fracture Attributes for Enhanced Geothermal Systems
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		**Richard A. Kemp, SNL** Tagged Nanoparticles for Fluid Flow Monitoring
11:30a-12:00p 30 min		**Toshi Sugama, BNL** Temporary Sealer Materials
12:00p-12:30p 30 min		**Kevin Knauss, LBNL** Fluid Chemistry and Fracture Growth: What's the Connection?
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Tim Reinhardt, DOE Vision Study room: Westminster III & IV
2:00p-2:30p 30 min		**Wrap Up: Tracers / Zonal Isolation / Geochemistry Session**
2:30p-3:00p 30 min	Enhanced Geothermal Systems: High Temp Tools, Drilling Systems	**Kamalesh Chatterjee, Baker Hughes Oilfield Operations Incorporated** Recovery Act: High Temperature 300C Directional Drilling System, including drill bit, steerable motor, and drilling fluid, for Enhanced Geothermal Systems
3:00p-3:30p 30 min		**Kamalesh Chatterjee, Baker Hughes Oilfield Operations Incorporated** Directional Measurement-While-Drilling System for Geothermal Applications
3:30p-3:40p 10 min		Audience Q&A
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		**David Raymond, SNL** High Temperature Downhole Motor
4:30p-4:40p 10 min		Audience Q&A
4:40p-5:10p 30 min		
5:10p-5:40p 30 min		

Track 4 EGS2 - Room Standley II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Wendy Harrison, Colorado School of Mines Plenary - GEOTHERMAL ENERGY: Global Reach, Local Impact room: Westminster III & IV
9:00a-9:30a 30 min	Enhanced Geothermal Systems: Innovative Stimulation Techniques	**Carlos Fernandez, PNNL** Reservoir Stimulation Optimization with Operational Monitoring for Creation of EGS
9:30a-10:00a 30 min		**Mark Grubelich, SNL** Gas Generator Development and Testing for Controlled Rapid Pressurization Using Liquid Propellants for EGS Well Stimulation
10:00a-10:30a 30 min		**Charles Carrigan, LLNL** Validation of EGS Feasibility and Explosive Fracturing Techniques
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		**Wrap Up: Innovative Stimulation Techniques Session**
11:30a-12:00p 30 min	Enhanced Geothermal Systems: Supercritical Carbon Dioxide/Working Fluids	**Curt Oldenburg, LBNL** Push-pull well testing using CO2 with active source geophysical monitoring
12:00p-12:30p 30 min		**Tom Buscheck , LLNL** Active Management of Integrated Geothermal CO2 Storage Reservoirs in Sedimentary Formations
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Tim Reinhardt, DOE Vision Study room: Westminster III & IV
2:00p-2:30p 30 min		**Barry Freifeld, LBNL** Geothermal Energy Production Coupled with CCS: Heat Recovery Using an Innovative High Efficiency Supercritical CO2 Turboexpansion Cycle
2:30p-2:40p 10 min		Audience Q&A
2:40p-3:10p 30 min		**Wrap Up: Supercritical Carbon Dioxide / Working Fluids Session**
3:10p-3:40p 30 min		
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min	Enhanced Geothermal Systems: Enhanced Geothermal System Demonstrations	**Joseph Moore, University of Utah** Concept Testing and Development at the Raft River Geothermal Field, Idaho
4:30p-5:00p 30 min		**Mitch Plummer, INL** EGS Reservoir Stimulations and Long-Term Performance Modeling
5:00p-5:30p 30 min		**Lianjie Huang, LANL** Joint Active and Passive Seismic Imaging of EGS Reservoirs
5:30p-5:40p 10 min		Audience Q&A

2015 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

GEOTHERMAL TECHNOLOGIES OFFICE

May 11-14 2015 Peer Review Agenda

Tuesday May 12

The Westin Westminster 303-410-5000
10600 Westminster Blvd, Westminster CO 80020

print date 05/06/2015

Track 1-Systems Analysis & LowTemp - Room Standley I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Mike Pacheco, NREL Geothermal's Role in an "All of the Above" Energy Strategy room: Westminster III & IV
9:00a-9:30a 30 min	Low Temp: Hybrid/Value Added Systems	Craig Turchi, NREL Low-Enthalpy Geothermal Desalination
9:30a-10:00a 30 min		David. J. Heldebrant, PNNL Geothermal Power Generation and CO2 Capture Co-Production
10:00a-10:30a 30 min		Pete McGrail, PNNL Integrating Compressed Air Energy Storage and Geothermal for Grid-Scale Renewables Integration
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		Dan Wendt, INL & Craig Turchi, NREL Geothermal risk reduction via geothermal/solar hybrid power plants
11:30a-12:00p 30 min		Dan Wendt, INL Forward Osmosis Purification of Co-Produced Water
12:00p-12:30p 30 min		Pete McGrail, PNNL Development of New Biphasic Metal Organic Working Fluids for Geothermal Systems
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Holly Thomas, DOE Play Fairway RFI Session room: Westminster III & IV
2:00p-2:30p 30 min		Adrian Sabau, ORNL Freeform Heat Exchangers for Binary Geothermal Power Plants
2:30p-2:40p 10 min		Audience Q&A
2:40p-3:10p 30 min		Wrap up: Hybrid/Value Added Systems Session
3:10p-3:40p 30 min	Low Temp: Mineral Recovery	Jay Renew & Ryan Melsert, Southern Research Institute Geothermal Thermoelectric Generation (G-TEG) with Integrated Temperature Driven Membrane Distillation and Novel Manganese Oxide for Lithium Extraction
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		Susanna Ventura, SRI International Selective Recovery of Metals From Geothermal Brines
4:30p-5:00p 30 min		Athanasios Karamalidis, Carnegie Mellon University Chelating Resins for Selective Separation and Recovery of Rare Earth Elements from Low Temperature Geothermal Water
5:00p-5:10p 10 min		Audience Q&A
5:10p-7:00p 1hr 50min		Poster Session Networking Event in Westminster Foyer

Track 2 Hydrothermal - Room Westminster II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Mike Pacheco, NREL Geothermal's Role in an "All of the Above" Energy Strategy room: Westminster III & IV
9:00a-9:30a 30 min	Hydrothermal: Exploration Validation / Play Fairway Analysis	John Shervais, Utah State University Play Fairway Analysis of the Snake River Plain
9:30a-10:00a 30 min		James McClain, University of California-Davis Geothermal Play Fairway Analysis of Potential Geothermal Resources in NE California, NW Nevada, and Southern Oregon
10:00a-10:30a 30 min		Corina Forson, Washington Division of Geology and Earth Resources Geothermal Play-Fairway Analysis of Washington State Prospects
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		Phil Wannamaker, University of Utah/EGI Structurally Controlled Geothermal Systems in the Central Cascadia Arc-BackArc Regime, Oregon
11:30a-12:00p 30 min		Teresa Jordan, Cornell University Low Temperature Geothermal Play Fairway Analysis for the Appalachian Basin
12:00p-12:30p 30 min		Phil Wannamaker, University of Utah/EGI Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Holly Thomas, DOE Play Fairway RFI Session room: Westminster III & IV
2:00p-2:30p 30 min		Dr. Greg Nash (PI) & Carlon Bennett, Ruby Mountain Inc. The Convergence of Heat, Groundwater, & Fracture Permeability: Innovative Play Fairway Modelling Applied to the Tularosa Basin
2:30p-3:00p 30 min		Jerry Smith, Pagosa Verde LLC Recovery Act: Use Remote Sensing Data (selected visible and infrared spectrums) to locate high temp ground anomalies in Colorado.Confirm heat flow potential w/ on-site temp surveys to drill deep resource wells
3:00p-3:30p 30 min		Patrick Walsh, ORMAT Nevada, Inc. Recovery Act: Merging high resolution geophysical and geochemical surveys to reduce exploration risk at Glass Buttes, Oregon
3:30p-3:40p 10 min		Audience Q&A
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		Gregory Newman, LBNL Iceland Geophysics: Advanced 3D Geophysical Imaging Technologies for Geothermal Resource Characterization
4:30p-4:40p 10 min		Audience Q&A
4:40p-5:10p 30 min		Wrap up: Exploration Validation / Play Fairway Analysis Session
5:10p-5:40p 30 min		Eric Hass, DOE Play Fairway Focus Discussion with PFA Award Recipients
5:40p-7:00p 1hr 20min		Poster Session Networking Event in Westminster Foyer

Track 3 EGS1 - Room Westminster I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Mike Pacheco, NREL Geothermal's Role in an "All of the Above" Energy Strategy room: Westminster III & IV
9:00a-9:30a 30 min	cont'd -- Enhanced Geothermal Systems: High Temp Tools, Drilling Systems	Randy Norman, Perma Works Well Monitoring Systems for EGS
9:30a-10:00a 30 min		Grzegorz Cieslewski, SNL High Temperature Chemical Sensing Tool for Distributed Mapping of Fracture Flow in EGS
10:00a-10:30a 30 min		Dr. Bjorn Paulsson, Paulsson, Inc. Development of a 300°C, 200 level, 3C Fiber Optic Downhole Seismic Receiver Array for Surveying and Monitoring of Geothermal Reservoirs
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		Grzegorz Cieslewski, SNL Enhanced High Temperature/High Speed Data Link for Logging Cables
11:30a-12:00p 30 min		Toshi Sugama, BNL & Erica Redline, SNL Elastomeric Material Evaluation and Development
12:00p-12:30p 30 min		Avery Cashion, SNL Evaluation of High Temperature Components for Use in Geothermal Tools
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Holly Thomas, DOE Play Fairway RFI Session room: Westminster III & IV
2:00p-2:30p 30 min		Ernest L. Majer, LBNL Testing and Calibration of HT Wide-bandwidth Seismic Sensors for EGS Applications and Collaboration with IPGT Program
2:30p-3:00p 30 min		Grzegorz Cieslewski, SNL Deployment of Integrated Wide Bandgap Sensor, HT Packaging, and Data Communication System
3:00p-3:10p 10 min		Audience Q&A
3:10p-3:40p 30 min		Wrap Up: High Temp Tools, Drilling Systems Session
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min	Enhanced Geothermal Systems: Reservoir Modeling	Eric Sonnenthal, LBNL ARRA THMC Modeling
4:30p-5:00p 30 min		Dr. Ahmad Ghassemi, The Board of Regents of the University of Oklahoma 1 Recovery Act: Development of a Geomechanical Framework for the Analysis of MEQ in EGS Experiments (GEYSERS) 2 Analysis of Geothermal Reservoir Stimulation using Geomechanics-Based Stochastic Analysis of Injection-Induced Seismicity 3 Three-dimensional Modeling of Fracture Clusters in Geothermal Reservoirs
5:00p-5:10p 10 min		Audience Q&A
5:10p-7:00p 1hr 50min		Poster Session Networking Event in Westminster Foyer

Track 4 EGS2 - Room Standley II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Mike Pacheco, NREL Geothermal's Role in an "All of the Above" Energy Strategy room: Westminster III & IV
9:00a-9:30a 30 min	cont'd -- Enhanced Geothermal Systems: Enhanced Geothermal System Demonstrations	Susan Petty, AltaRock Energy, Inc. Recovery Act: Newberry Volcano EGS Demonstration
9:30a-10:00a 30 min		Eric Sonnenthal, LBNL Evaluation of Stimulation at Newberry Volcano EGS Demo Site Through Natural Isotopic Reactive Tracers and Geochemical Investigation
10:00a-10:30a 30 min		Peter Drakos, Ormat Nevada, Inc. Feasibility of EGS Development at Bradys Hot Springs, Nevada
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		Sharad Kelkar, LANL Bradys and Desert Peak Numerical Modeling
11:30a-12:00p 30 min		Nicholas Davatzes, Temple University Monitoring EGS Stimulation and Reservoir Dynamics with InSAR and MEQ
12:00p-12:30p 30 min		Kurt Feigl, University of Wisconsin-Madison Poroelastic Tomography by Adjoint Inverse Modeling of Data from Seismology, Geodesy, and Hydrology
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Holly Thomas, DOE Play Fairway RFI Session room: Westminster III & IV
2:00p-2:30p 30 min		Mark Walters, Calpine - Geysers Power Company LLC Demonstration of an Enhanced Geothermal System at the Northwest Geysers Geothermal Field, California
2:30p-3:00p 30 min		Jonny Rutqvist, LBNL Geysers Calpine Modeling
3:00p-3:30p 30 min		Sharad Kelkar, LANL Archive of Fenton Hill Data; Creation and Testing of Data Sets for Simulation and Testing
3:30p-3:40p 10 min		Audience Q&A
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		Wrap Up: Enhanced Geothermal System Demonstrations Session
4:30p-5:10p 30 min		Hosted By: Charlie Visser, NREL Geothermal Development in African Nations
5:10p-7:00p 1hr 50min		Poster Session Networking Event in Westminster Foyer

2015 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY GEOTHERMAL TECHNOLOGIES OFFICE

GEOTHERMAL TECHNOLOGIES OFFICE
May 11-14 2015 Peer Review Agenda

Wednesday May 13

The Westin Westminster 303-410-5000
10600 Westminster Blvd, Westminster CO 80020

print date 05/06/2015

Track 1-Systems Analysis & LowTemp - Room Standley I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Lauren Boyd, DOE Frontier Observatory of Research and Geothermal Energy (FORGE) room: Westminster III & IV
9:00a-9:30a 30 min	Low Temp: Mineral Recovery	Raymond Addleman, PNNL Recovery of Rare Earths, Precious Metals and Other Critical Materials from Geothermal Waters with Advanced Sorbent Structures
9:30a-10:00a 30 min		Dean Stull, Tusaar Corp. Environmentally friendly economical sequestration of rare earth metals from geothermal waters
10:00a-10:30a 30 min		Caroline Ajo-Franklin, LBNL Engineering Thermophilic Microorganisms to Selectively Extract Strategic Metals from Low Temperature Geothermal Brines
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		Pete McGrail, PNNL Magnetic Partitioning Nanofluid for Rare Earth Extraction from Geothermal Fluids
11:30a-12:00p 30 min		Robert Zierenberg, University of California - Davis Maximizing REE Recovery in Geothermal Systems
12:00p-12:10p 10 min		Audience Q&A
12:10p-12:40p 30 min		Wrap up: Mineral Recovery Session
12:40p-2:00p 80 min		Lunch - Erick Burns, USGS New Tools for Understanding Heat and Groundwater Flow in the Northwest Volcanic Aquifer Province, USA room: Westminster III & IV
2:00p-2:30p 30 min	Low Temp: Low Temperature Resources	William D. Gosnold, University of North Dakota Recovery Act: Electric Power Generation from Low to Intermediate Temperature Resources
2:30p-3:00p 30 min		Greg Mines, INL & Tom Williams, NREL Low Temperature Project Analysis
3:00p-3:10p 10 min		Audience Q&A
3:10p-3:40p 30 min		Wrap up: Low Temperature Resources Session
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		[redacted]
4:30p-5:00p 30 min		[redacted]
5:00p-5:30p 30 min		[redacted]
5:30p-5:40p 10 min		[redacted]

Track 2 Hydrothermal - Room Westminster II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Lauren Boyd, DOE Frontier Observatory of Research and Geothermal Energy (FORGE) room: Westminster III & IV
9:00a-9:30a 30 min	Hydrothermal: Systems Analysis, Resources Assessment, Data System Development & Population, Education	Patrick Dobson, LBNL & Kate Young, NREL Resource Reporting Methodology Analysis and Development of Geothermal Resource Reporting Metric for GTO's Hydrothermal Program
9:30a-10:00a 30 min		Greg Mines, INL Hydrothermal Reservoir Productivity
10:00a-10:10a 10 min		Audience Q&A
10:10a-10:40a 30 min		Wrap up: Systems Analysis, Resources Assessment, Data System Development & Population, Education Session
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min	Hydrothermal: Drilling Systems	Dale Wolfer, Atlas Copco Secoroc LLC Advanced Percussive Drilling Technology for Geothermal Exploration and Development
11:30a-12:00p 30 min		Charlie Visser, NREL SURGE: Geothermal Drilling and Completions: Petroleum Practices Technology Transfer
12:00p-12:30p 30 min		Toshi Sugama, BNL Multifunctional Corrosion -resistant Foamed Cement Composites
12:30p-12:40p 10 min		Audience Q&A
12:40p-2:00p 80 min		Lunch - Erick Burns, USGS New Tools for Understanding Heat and Groundwater Flow in the Northwest Volcanic Aquifer Province, USA room: Westminster III & IV
2:00p-2:30p 30 min		George Trabits, Trabits Group, LLC Recovery Act: Development Of An Improved Cement For Geothermal Wells
2:30p-3:00p 30 min		Douglas Blankenship, SNL Drilling Technologies Evaluation
3:00p-3:10p 10 min		Audience Q&A
3:10p-3:40p 30 min		Wrap up: Drilling Systems Session
3:40p-4:00p 20 min		Break
4:00p-5:40p 100 min		NREL/LBNL DOE Resource Reporting Methodology Effort-Update/Discussion

Track 3 EGS1 - Room Westminster I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Lauren Boyd, DOE Frontier Observatory of Research and Geothermal Energy (FORGE) room: Westminster III & IV
9:00a-9:30a 30 min	cont'd – Enhanced Geothermal Systems: Reservoir Modeling	Mark White, PNNL Support of the DOE GTO Model Comparison Activity
9:30a-10:00a 30 min		Dr. Derek Elsworth, Pennsylvania State University Recovery Act: THMC Modeling of EGS Reservoirs - Continuum through Discontinuum Representations: Capturing Reservoir Stimulation, Evolution and Induced Seismicity
10:00a-10:10a 10 min		Audience Q&A
10:10a-10:40a 30 min		Wrap Up: Reservoir Modeling Session
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min	Enhanced Geothermal Systems: Reservoir Fracture Characterization & Fluid Imaging	Tim Kneafsey, LBNL Sustainability of Shear-Induced Permeability for EGS Reservoirs
11:30a-12:00p 30 min		Susan Carroll, LLNL Viability of Sustainable, Self-Propping Shear Zones in EGS: Measurement of Reaction Rates at Elevated Temperatures
12:00p-12:10p 10 min		Audience Q&A
12:10p-12:40p 30 min		[redacted]
12:40p-2:00p 80 min		Lunch - Erick Burns, USGS New Tools for Understanding Heat and Groundwater Flow in the Northwest Volcanic Aquifer Province, USA room: Westminster III & IV
2:00p-2:30p 30 min		Dr. Ahmad Ghassemi, The Board of Regents of the University of Oklahoma Laboratory-Scale Characterization of EGS Reservoirs
2:30p-3:00p 30 min		Rick Allis, University of Utah Novel Geothermal Development of Deep Sedimentary systems in the US
3:00p-3:30p 30 min		Dr. Derek Elsworth, The Pennsylvania State University Surface and Subsurface Geodesy Combined with Active Borehole Experimentation for the Advanced Characterization of EGS Reservoirs
3:30p-3:40p 10 min		Audience Q&A
3:40p-4:00p 20 min		Break
4:00p-4:30p 30 min		Dr. Chris Marone, The Pennsylvania State University Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production
4:30p-5:00p 30 min		Dr. Matthew Becker, California State University Long Beach Phase I Project: Fiber Optic Distributed Acoustic Sensing for Periodic Hydraulic Tests
5:00p-5:30p 30 min		Richard Hughes, LA State University Geothermal Resource Development with Zero Mass Withdrawal, Engineered Convection, and Wellbore Energy Conversion
5:30p-5:40p 10 min		Audience Q&A

Track 4 EGS2 - Room Standley II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
		No Meetings Scheduled

2015 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

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May 11-14 2015 Peer Review Agenda

Thursday May 14

The Westin Westminster 303-410-5000
10600 Westminster Blvd, Westminster CO 80020

print date 05/06/2015

Track 1-Systems Analysis & LowTemp - Room Standley I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
		No Meetings Scheduled

Track 2 Hydrothermal - Room Westminster II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Marianne Walck, Sandia National Laboratory Subsurface Engineering R&D Crosscut (SubTER): adaptive control of fractures and fluid flow room: Westminster III & IV
9:00a-9:30a 30 min	Hydrothermal: Geochemistry	**Mark Conrad, LBNL & Earl Mattson, INL** Geothermometry Mapping of Deep Hydrothermal Reservoirs in Southeastern Idaho
9:30a-10:00a 30 min		**Patrick Dobson, LBNL** Use of He isotopes for geothermal resource identification in the Cascades and Snake River Plain
10:00a-10:30a 30 min		**Mack Kennedy, LBNL** Surface estimates of deep permeability
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		**Nicholas Spycher, LBNL** Surprise Valley Geochemistry
11:30a-12:00a 30 min		**Eric Sonnenthal, LBNL** Integration of Nontraditional Isotopic Systems Into Reaction-Transport Models of EGS For Exploration, Evaluation of Water-Rock Interaction, and Impacts of Water Chemistry on Reservoir Sustainability
12:00p-12:10p 10 min		Audience Q&A
12:10p-12:40p 30 min		**Wrap up: Geochemistry Session**
12:40p-2:00p 80 min		Lunch - Jay Nathwani, DOE FY16 Lab AOP Session room: Westminster III & IV

Track 3 EGS1 - Room Westminster I

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
8:00a-9:00a 60 min		Marianne Walck, Sandia National Laboratory Subsurface Engineering R&D Crosscut (SubTER): adaptive control of fractures and fluid flow room: Westminster III & IV
9:00a-9:30a 30 min	cont'd – Enhanced Geothermal Systems: Reservoir Fracture Characterization & Fluid Imaging	**Dr. Roland Gritto, Array Information Technology** Seismic Analysis of Spatio-Temporal Fracture Generation During EGS Resource Development
9:30a-10:00a 30 min		**Ileana Tibuleac, Board of Regents, NSHE, obo University of Nevada, Reno** Quantifying EGS Reservoir Complexity with an Integrated Geophysical Approach - Improved Resolution Ambient Seismic Noise Interferometry
10:00a-10:30a 30 min		**Stephen Bauer, SNL** Laboratory Evaluation of EGS Shear Stimulation
10:30a-10:40a 10 min		Audience Q&A
10:40a-11:00a 20 min		Break
11:00a-11:30a 30 min		**Philip Bingham, ORNL & Yarom Polsky, ORNL** Application of Neutron Imaging and Scattering to Fluid Flow and Fracture in EGS Environments
11:30a-12:00a 30 min		**Kelly Rose, NETL** Novel use of 4D Monitoring Techniques to Improve Reservoir Longevity and Productivity in Enhanced Geothermal Systems
12:00p-12:10p 10 min		Audience Q&A
12:10p-12:40p 30 min		**Wrap Up: Reservoir Fracture Characterization & Fluid Imaging Session**
12:40p-2:00p 80 min		Lunch - Jay Nathwani, DOE FY16 Lab AOP Session room: Westminster III & IV
2:00p-3:40p 100 min		**Lauren Boyd, DOE** Code Comparison Workshop
3:40p-4:00p 20 min		Break
4:00p-5:40p 100 min		**Lauren Boyd, DOE** Geochemistry/Tracers Workshop

Track 4 EGS2 - Room Standley II

Time	Panel	Presenter(s), Awardee (or Organization), Project Title
		No Meetings Scheduled

Appendix IV: Peer Review Attendees

Last Name:	First Name:	Company/Organization:
Addleman	R. Shane	Pacific Northwest National Laboratory
Adomako	Kofi	Albah Manufacturing Technologies Corp
Ajo-Franklin	Caroline	Lawrence Berkeley National Lab
Akar	Sertac	National Renewable Energy Laboratory
Akerley	John	Ormat
Alexander	Scott	University of Minnesota
Ali	Syed	University of Wisconsin-Madison
Allis	Rick	Utah Geological Survey
Alvarado	Vladimir	University of Wyoming
Ampuero	Jean Paul	Caltech Seismolab
Anderson	Arlene	U.S. DOE Geothermal Technologies Office
Arias	Diego	Luminate LLC
Arnold	Elizabeth	DOE – Office of Energy Efficiency and Renewable Energy
Asanuma	Hiroshi	Advanced Industrial Science and Technology
Augustine	Chad	National Renewable Energy Laboratory
Baker	Kate Hadley	(retired)
Baria	Roy	Consultant
Barker	Benjamin	Barker Engineering
Basu	Prodyot	Vanderbilt University
Battocletti	Liz	Consultant
Bauer	Stephen	Sandia National Laboratories
Becker	Matthew	California State University Long Beach
Beers	Gary	Industrial Water Permitting and Recycling
Bennett	Carlon	Ruby Mountain Inc
Benoit	Dick	Sustainable Solutions
Bharathan	Desikan	nGen Condensers LLC
Bielicki	Jeffrey	The Ohio State University
Black	Herb	Office of Natural Resources Revenue
Blankenship	Douglas	Sandia National Laboratories
Bloomfield	Kit	Sigma3
Bonneville	Alain	Pacific Northwest National Laboratory
Bowden	Dave	Sustainable Media
Boyd	Lauren	U.S. DOE Geothermal Technologies Office
Boyd	Ron	Atlas Copco Secoroc LLC
Bradford	Scott	Front Line Ventures
Brady	Pat	Sandia National Labs
Brennan	Ann	National Renewable Energy Laboratory
Bronicki	Lucien	Ormat Technologies Inc
Brophy	Paul	EGS Inc.
Brown	Christopher	Pacific Northwest National Laboratory
Brown	Shaun	Lawrence Berkeley National Lab

Last Name:	First Name:	Company/Organization:
Budd	Anthony	Geoscience Australia
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Appendix VI: Acronym List:

ANL:	Argonne National Laboratory
AOP:	Annual Operating Plan
ARRA:	American Recovery and Reinvestment Act of 2009
CEC:	Chemical Energy Carriers
CO_2:	carbon dioxide
DOE:	United States Department of Energy
EERE:	Office of Energy Efficiency and Renewable Energy
EGS:	Enhanced Geothermal Systems
FOA:	Funding Opportunity Announcement
FY:	Fiscal Year
GAO:	U.S. Government Accountability Office
GDR:	Geothermal Data Repository
GETEM:	Geothermal Electricity Technology Evaluation Model
GTO:	Geothermal Technologies Office
GWe:	Gigawatt(s) electric
H_2O:	water
JEDI:	Jobs and Economic Development Model
kWh:	kilowatt hour(s)
IEA-GIA:	International Energy Agency's Geothermal Implementing Agreement
IET:	Innovative Exploration Technologies
IPGT:	International Partnership for Geothermal Technologies
LANL:	Los Alamos National Laboratory
LBNL:	Lawrence Berkeley National Laboratory
LCOE:	levelized cost of electricity
LLNL:	Lawrence Livermore National Laboratory
MEQ:	microearthquakes
MOHCs:	Metal Organic Heat Carriers
MWD:	Measurement-While-Drilling
MWe:	Megawatt(s) electric
NAS:	National Academy of Sciences
NCG:	non-condensable gas
NEPA:	National Environmental Policy Act
NGDS:	National Geothermal Data System
NREL:	National Renewable Energy Laboratory
OMB:	White House Office of Management and Budget
ORNL:	Oak Ridge National Laboratory
PI:	Principle Investigator
PNNL:	Pacific Northwest National Laboratory
P2RMIS:	Program and Peer Review Management Information System
R&D:	Research and Development
RD&D:	Research, Development and Demonstration
SAM:	System Advisor Model
$scCO_2$:	supercritical carbon dioxide
SiC:	Silicon Carbide
SNL:	Sandia National Laboratories
SWIW:	single-well injection withdrawal
THMC:	Thermal Hydrological Mechanical Chemical (model)

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