Innovative Exploration Technologies

TECHNOLOGY NEEDS ASSESSMENT

DRAFT

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EXECUTIVE SUMMARY

On October 28, 2010, the Innovative Exploration Technologies (IET) Subprogram, within the Department of Energy's (DOE) Geothermal Technologies Program (GTP), sponsored a technology planning workshop in Sacramento, California. The workshop brought together a diverse group of experts from industry, academia, and government. IET solicited input from participants to identify the technology needs and potential advances for the subprogram to pursue over the coming years, specifically with regards to technologies that have the greatest potential to contribute to the IET goal of increasing capacity from new regions and resources.

The *Innovative Exploration Technologies Needs Assessment* is a critical component of ongoing technology roadmapping efforts that will be used to guide the IET Subprogram research and development. Specifically, the needs assessment will help provide the IET public- and private-sector stakeholders with the direction to focus resources in the IET technology space. The assessment will be used as input for an IET technology roadmap that will present a pathway to develop and deploy economically viable, innovative, and scalable exploration technologies. By 2020, the United States geothermal industry could expand to new regions, discover new resources, reduce exploration costs, and achieve a fourfold gain of capacity from 2010. Figure ES-1 presents a graphical representation of the structure and logical flow of the technology needs assessment.

MISSION AND VISION

The IET Subprogram and community envision widespread deployment of innovative technologies that will help developers more efficiently locate viable geothermal resources. The subprogram aims to spur the U.S. geothermal industry to seek green field resources by lowering exploration risks and costs through research, development and demonstration. The subprogram is designed to support GTP's following mission and vision:

GTP Mission:

Help establish geothermal energy as a significant contributor to future U.S. electricity generation by partnering with industry, academia, and the national laboratories to:

- *Discover new geothermal resources,*
- *Develop innovative methods, and*
- *Demonstrate high-impact technologies.*

GTP Vision:

By 2020:

- *Geothermal capacity in the United States reaches 12 Gigawatts (GW) of clean, baseload domestic power, a fourfold gain from 2010.*

IET Subprogram goal:

- *One GW of undiscovered hydrothermal resources are confirmed and brought online in the U.S. by 2020.*

KEY CHALLENGES

This needs assessment identifies key technical and non-technical challenges to achieving the subprogram goal described above. The technical challenges, for which this assessment proposes nine technology advancement needs, fall into five exploration technology areas: geology, geophysics, geochemistry, remote sensing, and cross-cutting. These are described in detail in this report. The non-technical challenges fall into five major themes: policy, permitting, externalities, money/funding, and knowledge sharing/data. While these challenges are critical to the success of IET and GTP goals, this assessment does not address these non-technology-related issues.

TECHNOLOGY ADVANCEMENT NEEDS

This roadmap identifies nine technology needs that are deemed to have the greatest potential impact on increasing geothermal capacity. For each of these needs, this document outlines the advancement required, key benefits, stakeholders, risks, and timeframes for achieving success. The identified needs, organized by the five exploration technology areas (i.e., geology, geophysics, geochemistry, remote sensing, or cross-cutting) will be used to guide the IET Subprogram's efforts to lower exploration risks and costs.

IET Technology Needs Assessment Structure

Mission, Vision and Goals

GTP Program Mission:
Establish geothermal energy as a significant contributor to future U.S. electricity generation by partnering with industry, academia, and national laboratories

GTP Program Vision:
By 2020 geothermal capacity will reach 12 gigawatts (GW) of clean, baseload domestic power, a fourfold gain from 2010.

IET Subprogram Goal:
One GW of undiscovered hydrothermal resource are confirmed and brought online in the U.S. by 2020

Challenges to Achieving IET Goals

Technology Challenge Areas

Geophysics
Geochemistry
Cross-Cutting
Remote Sensing
Geology

Technology Needs

Geophysics

- Better Multi-physics Models to Extend Use of Geophysics for Permeability
- Improve Next-generation Geophysical Air Borne Data

Remote Sensing

- High Resolution Remote Sensing Data and Reliable Automated Processing Methods

Cross-Cutting

- Multi-disciplinary Conceptual Models
- 3-D Modeling Techniques (software)
- Create Case Study Examples of Geothermal Systems in Different Settings

Geochemistry

- Improved Thermodynamic Data for Next-generation Geothermometers
- Development of Geothermometers that Accurately Reflect Lithologic and Tectonic Settings, and Identification of New Thermometers

Geology

- Stress/Strain Data Mapping

Figure ES-1. Innovative Exploration Technologies Needs Assessment overview

PATH FORWARD

The results from this technology needs assessment will be used as critical inputs to ongoing exploration technologies roadmapping. In 2011 a second workshop will be conducted where experts from industry, academia, national laboratories and government will develop pathways to advance the identified technology need areas.

As the IET Subprogram addresses the high-priority potential technology needs described in this assessment, it will evaluate and measure its own effectiveness, as well as the impact of its activities on industry. IET will focus on whether and how much the technology solutions are contributing toward mitigating the key barriers and increasing geothermal energy capacity.

It is important to note that as performance is measured and evaluated, action items may be revised and resources reallocated. Evolving industry trends may cause IET Subprogram priorities to shift, resulting in new priorities and activities. Information from performance evaluations and changes in the industry landscape are likely to feed back into specific technology pathway plans and the overall roadmap.

I. INTRODUCTION

The potential for geothermal energy as a constant, renewable, and domestic energy source is massive. The United States Geological Survey (USGS) estimated in 2008 that the 13 western most U.S. states hold an average of 30,000 megawatts (MW) of undiscovered geothermal resources (see Figure I-1). However, unlike other renewable energy sources—such as wind and solar—a geothermal resource is not confirmed until a well is drilled into the reservoir, costing millions of dollars. Currently, the hit rate for successfully identifying hydrothermal wells is only around 35%[2], leaving upfront costs for early development and associated risk prohibitively high.

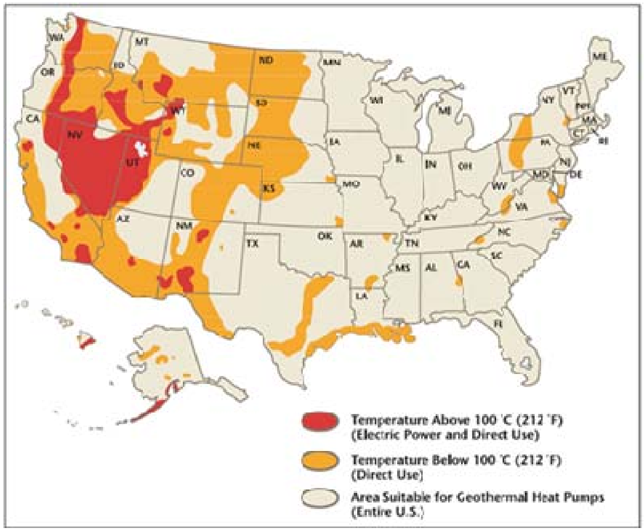

Figure I-1. National Geothermal Data System's map of potential geothermal locations across the U.S.[1]

DOE's Energy Efficiency and Renewable Energy (EERE), GTP assists in developing innovative technologies to find, access, and harness the nation's geothermal resources as a usable baseload source of renewable energy. The current low success rate of discovering geothermal resources is a major barrier to expanding the utilization, efficiency, and understanding of geothermal systems. This challenge increases upfront risk and cost and deters investors and developers from exploring unknown areas, which hinders the industry's already limited knowledge of geothermal systems and why they occur. The consequences of this are immense as the ability to accurately identify potential geothermal resources and increase utilization depends on exploration of currently uninvestigated locations.

INNOVATIVE EXPLORATION TECHNOLOGIES SUBPROGRAM

The IET Subprogram plays a central role within GTP by focusing on advancing exploration technologies to decrease upfront risk for geothermal developers. The United States Geological Survey (USGS) estimated in 2008 the Western United States holds 30,000 MW (mean) of undiscovered geothermal resources.[3] The sub program intends to spur the U.S. geothermal industry to seek green field resources by investing in research, development and demonstration of geothermal exploration technologies. A more accurate understanding of the subsurface before drilling an exploration well will reduce upfront investment costs and risks faced by geothermal developers, and is expected to result in a greater number of geothermal energy projects and installed geothermal capacity. In this way IET is a critical component of GTP's strategy to achieve its goal of developing geothermal as a major source of renewable, domestic, and baseload energy supply for the United States.

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[1] A. Richter, United States - Geothermal Energy Market Report, (Glitnir, 2007).

[2] Katherine Young, Chad Augustine, and Arlene Anderson, *Report on the U.S. DOE Geothermal Technologies Program's 2009 Risk Analysis* (Oak Ridge, TN: U.S. Department of Energy, 2010), http://www.nrel.gov/docs/fy10osti/47388.pdf.

[3] *Assessment of Moderate- and High-Temperature Geothermal Resources of the United States* (USGS, 2009), http://pubs.usgs.gov/fs/2008/3082/pdf/fs2008-3082.pdf.

Through the American Recovery and Reinvestment Act, $97.3 million is funding IET projects focused on advancing geothermal exploration technology in an effort to identify undiscovered hydrothermal resources. Research and development (R&D) priorities are focused on overcoming technology barriers that are the greatest hindrance to the development of viable enhanced geothermal systems at acceptable cost, risk, and timeframes. To date, 24 projects funded by the Recovery Act are under way in 9 states (Arkansas, California, Colorado, Hawaii, Idaho, Nevada, New Mexico, Oregon, and Texas).

IET Technology Needs Assessment Scope

The IET technologies addressed in this assessment span the four major technology tool areas—geophysics, geochemistry, geology, and remote sensing as well as cross-cutting tools—that are used in the first two phases of the exploration process (i.e., assessing hydrothermal potential, and confirming temperature/ identifying permeability). IET tools used to confirm the geothermal resource, such as those used for drilling, are not included within the scope of this document. Below are brief overviews of the five IET technology areas for which potential technology needs are proposed in Chapter 4.

- ***Geophysics*** is the physics of the Earth and its environment. Its subjects include the dynamics of the Earth as a whole and its component parts and internal structure, including composition and tectonics, the generation of magmas, volcanism and rock formation, and the hydrological cycle including snow and ice. Geophysics exploration technologies are used to discover mineral and energy resources by analyzing potential petroleum reservoirs, mineral deposits, and geothermal sites.

- ***Geochemistry*** is the study of the chemical composition of the Earth; the chemical processes and reactions that govern the composition of rocks, water, and soils; and the cycles of matter and energy that transport the Earth's chemical components in time and space, and their interaction with the hydrosphere and the atmosphere. In geothermal exploration, geochemistry focuses on the spatial variation in the chemical composition of materials at the surface of the Earth.

- ***Geology*** is the science and study of the solid Earth and the processes by which it is shaped and changed. Today, geology is commercially important for identifying resources, especially in the energy industry, and is publicly important for predicting and understanding natural hazards. Surveying and mapping are two of the most common geological methods for discovering new geothermal sites.

- ***Remote sensing*** is the small- or large-scale acquisition of information of a phenomena in a given area by using either wireless (not in physical contact with the object) recording or real-time sensing devices. There are two main types of remote sensing, passive and active. Passive sensors detect natural radiation, such as heat, from a geothermal reservoir that is emitted by the area being observed. Active collection emits energy over an area and a sensor detects and measures the radiation that is reflected, or backscattered, from the target.

- ***Cross-cutting*** exploration technologies are those that involve some combination of science and exploration techniques of the areas described above.

Purpose of this Document

This document presents a technology needs assessment for the IET Subprogram and identifies areas of potential technology needs to increase exploratory success and reduce up-front developer costs and risks. This document will help the IET Subprogram prioritize and allocate its resources in each of the technology areas (geology, geophysics, geochemistry, remote sensing, and cross-cutting) and provides the groundwork for ongoing IET roadmapping efforts.

Structure and Content

The remainder of this document is organized as follows:

- **Chapter II** presents the ***strategic framework*** from which the roadmap has evolved.
- **Chapter III** discusses the ***technical (and non-technical) challenges*** faced by the IET .
- **Chapter IV** presents the high-priority ***technology needs.***
- **Chapter V** discusses next steps and how the assessment will guide ***further roadmapping efforts***.

II. IET Strategic Framework

This chapt*er provides a framework for the IET Subprogram's investment strategy. Specifically,* it outlines how the specific technology needs identified in this assessment align with the IET Subprogram's goals, and ultimately support GTP's mission and vision and national policies.

IET Technology Needs

The nine, high-priority technology needs identified and discussed in detail in this assessment (described further in Chapter 4) serve as a basis for the IET Subprogram's investment strategy for allocating funds across the five IET technology areas in an effort to achieve the subprogram's goal of finding 1 GW of green field resources by 2020. These technology areas and the associated technology advancement needs are shown in Figure II-1 below.

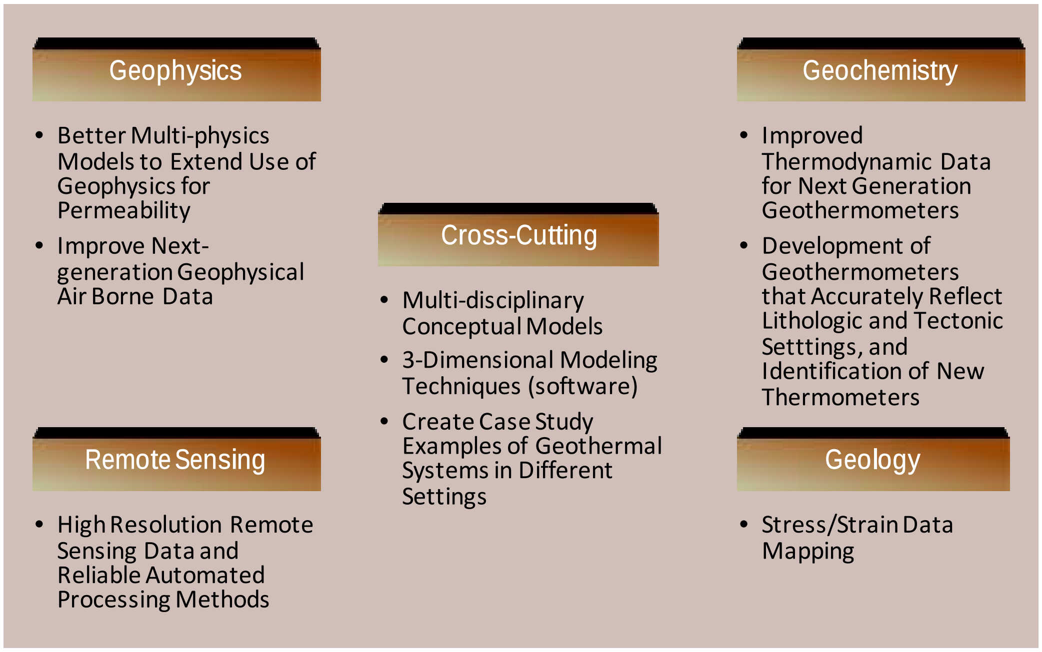


Figure II-1. Innovative exploration technology areas and needs

IET Priorities

Each of the technology advancement needs can be viewed as an investment area for which the IET should allocate funds. The nine technology needs that are discussed in this assessment are deemed by the IET community to have the greatest potential for overcoming the major challenges to achieving increased exploratory success. The advancements are aligned with the IET Subprogram's major goals and rank high in the following IET goal areas:

- Reduce the high level of risk during the early stages of development
- Increase the economic viability of innovative exploration technologies
- Improve the potential for technology to confirm new geothermal capacity
- Foster useful data for the National Geothermal Data System (NGDS)

IET Goal Alignment with GTP Mission and Vision and National Policies

A sound investment strategy will enable the IET Subprogram to achieve its goal of putting 1 GW online of undiscovered resources by 2020 by development of the appropriate technologies needed to locate viable geothermal resources more efficiently and with less cost. Improved, affordable, and widely available exploration technologies ultimately reduce the investment hurdle faced by developers in the form of resource risk. As the risk is mitigated, financing costs will decrease and more projects will be initiated by private industry. Ultimately, this will contribute towards achieving GTP's higher-level goal of establishing geothermal energy as an economically competitive and more widely used energy source. Geothermal energy is also part of the nation's strategy to bring more renewable energy sources online to supply baseload electricity and heat. A larger renewable energy portfolio will ultimately help address climate change and other environmental issues, and increase the availability of domestic energy sources.

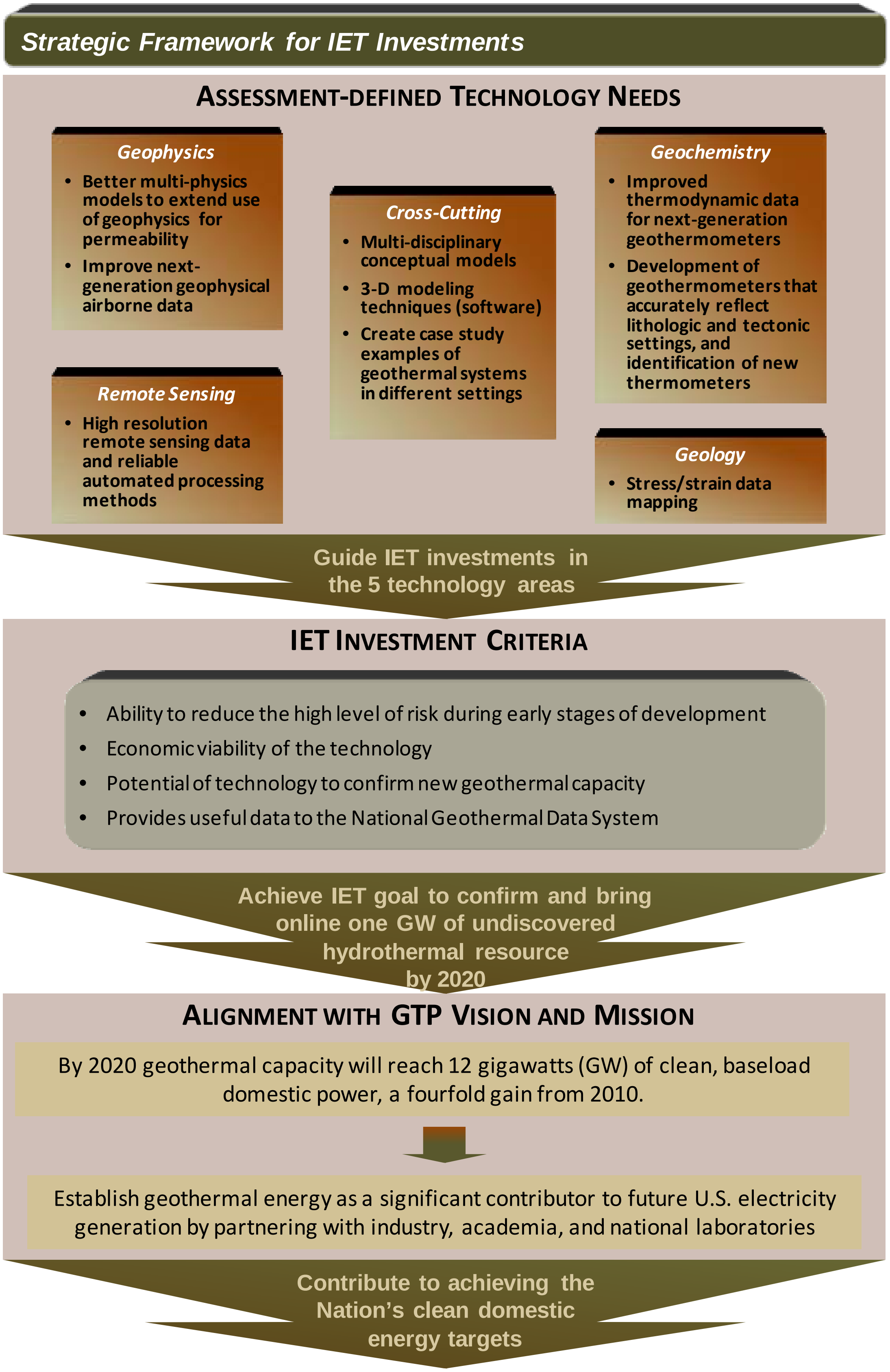


Figure II-2. Strategic framework for innovative exploration technology investments

III. Key Challenges

Although geothermal energy has not attracted significant investment or attention in the United States until recently, it has immense potential as a renewable, zero-emission energy source providing stable, cost-competitive, and reliable base-load-capable power that is valued by the public and well-integrated with other resources and infrastructure. It is the goal of the U.S. geothermal community to increase capacity from new regions and resources, and overcome the current barriers preventing geothermal energy's advancement. Decreasing exploration risks and costs through IET will play a major role in achieving the nation's potential for geothermal energy. The following sections describe the technical and non- technical challenges faced by the IET community in its efforts to contribute towards a successful geothermal energy future in the United States.

Technical Challenges

The key technical challenges that currently restrict the effective, large-scale deployment of innovative exploration technologies or prevent these technologies from being used effectively to detect geothermal resources can be grouped into the following five technology areas.

Geophysics

The most important geophysical barriers to the successful use of IET are the inherent challenges of determining permeability at depth without drilling.. The ability to find sufficient permeability for economic production is essential for geothermal resource developers. Geophysical tools are needed to determine permeable zones from surface measurements. In addition to permeability, the technical community currently lacks the ability to sufficiently image fluids and flows. There are few physics-based anomalies that can be targeted in the reservoir by geophysics.

In addition to permeability and fluid flows, it is now significantly challenging to remotely predict temperature at depth. There is a need for more detailed heat flow maps, for the ability to predict open fracture locations, and for rapid airborne reconnaissance of resistivity to find new prospects. It would be extremely useful to be able to see deeply enough with rapid reconnaissance methods to pick up subsurface evidence of hydrothermal activity, such as by a resistivity anomaly. Although it would be valuable to couple magnetotelluric resistivity with another technology (such as an isotope) to get a reliable indicator of a geological resource from the surface or the air, the ability to do so is currently insufficient. Presently it is challenging to determine both system size and whether a resistivity anomaly is related to current geothermal activity. Furthermore, there is an unmet need to address the "non-uniqueness" of geothermal inversions.

Geochemistry

In the geochemistry arena, geothermometer technology needs to be further tested and refined. The information provided by geothermometers on gases, liquids, isotopes, and trace elements is inadequate, and is unable to explain and/or leads to inconsistent lab results. In addition, there is a need for better tools that are smaller for slim holes and perform in higher temperatures at lower costs. There is a particular lack of inexpensive wide-area reconnaissance tools for areas where data is sparse.

Geology

Many geologic features of a potential geothermal exploration site are currently challenging to understand. These include the site's tectonic context, structure setting and detail, strain-stress inversion, and permeability at depth at fracture scale. Regional active structures, such as the structural settings of hydrothermally active systems, tend to be insufficiently understood. It is challenging to age-date hot spring deposits, and no good methods currently exist for determining if a hot feed lies below thermal anomalies. In addition, the limited availability of sufficient geologic maps for exploration hinders the ability of using these technologies for effectively detecting geothermal resources.

Remote Sensing

To date, remote sensing's feasibility has yet to be demonstrated at a large scale. Challenges remain in utilizing regional light detection and ranging (LIDAR), hyperspectral, forward-looking infrared, and thermal imaging data, and there is an ongoing need for high-resolution, low-cost strain maps to enable remote sensing. The area to be surveyed is often vast and the data sets can be large, hence current automated regional reconnaissance data analysis and processing are inadequate. For data-sparse areas in particular, there is insufficient experience in the use of wide-area reconnaissance tools.

Cross-Cutting

Beyond the specific needs in the geochemistry, geology, geophysics, and remote sensing domains, various cross-cutting challenges currently affect all geothermal exploration technologies. It is both important and challenging to evaluate combinations of technologies in addition to each technology individually.

- ***Certain crucial modeling tools are absent.*** There is a lack of occurrence models and a lack of affordable tools to integrate multiple, three-dimensional (3-D) data sets to create improved subsurface 3-D models. Regarding the occurrence models, there is a lack of understanding what geologic environment is sufficient and necessary for hydrothermal systems. If there was more insight into why high-temperature systems exist, this knowledge could be applied toward finding hidden systems and new sites.

- ***Beyond modeling, other needed information may not be available.*** No world atlas of geothermal occurrences exists. Case studies, information on the habitats and meso-scale tectonic settings of geothermal systems, and occurrence trends are insufficiently described. There is a need to explore new areas and to delineate anomalous areas (including via surveys). There is also a need to link characteristics of the subsurface reservoir to measurements made at the surface. In particular, there is limited ability to identify or characterize a potential resource without drilling and identifying hidden resources except by accident. Overall, there is a need to better evaluate prospect risk and uncertainty with sparse data.

- ***Even where data and tools exist, availability may low.*** The extensive body of oil, gas, and mining industry knowledge could be more actively leveraged by geothermal developers. Beyond data, other groups' tools could be more effectively used, especially federal agency tools such as the National Science Foundations' Earth Scope, NASA's airborne science surveys (e.g., InSar, Hyperspec, and LIDAR), and USGS surveys and maps. Cross-cutting barriers exist in data synthesis, the cost of 3-D integrative data software, and the need for geothermal-specific software.

Non-technical Challenges

The geothermal industry faces various non-technical challenges in successfully deploying IET. The challenges lie in five main areas. The first four challenges relate to economics and policy issues, and are recurring themes faced by the entire geothermal community. The fifth challenge, knowledge sharing/data, pertains more specifically to IET.

- ***Policy.*** It is currently challenging to get the supporting government entities on the same page to provide a sustained, focused, and long-term science-based effort for DOE's geothermal programs to develop and deploy IET. Existing policy processes pose challenges for matching existing DOE funding with potential recipients as funding does not always target the high priority technology advancement needs or go to the companies that are the best suited for the work.
- ***Permitting.*** Permitting and leasing agencies often lack knowledge of geothermal energy technologies and procedures. Not only is geothermal poorly understood, but its permitting must conform to different standards than oil and gas permitting. Further, there are conflicts between regulatory constraints from different agencies surrounding the use of public land.
- ***Externalities***. The geothermal industry faces certain challenges regarding the state of the current energy environment. These externalities include the current price of electricity, which is still relatively inexpensively provided by traditional fuels; public perception, which is not always on the side of those developing exploration technologies since drilling funds may be seen as "corporate welfare"; and the dearth of available qualified scientists in IET.
- ***Money/Funding.*** The costs of exploration drilling for geothermal sources are persistently high. There is a lack of capital and cooperative mechanisms to conduct high-risk reconnaissance as the geothermal community does not adequately utilize cost sharing opportunities with the oil and gas industry to conduct, for example, stratigraphic tests used in hydrocarbon exploration. Rather than enrolling in such partnerships, the geothermal industry currently competes with the oil, gas, and mining industries for services. Additionally, the cost of cutting-edge technology is high, limiting the breadth of its utilization. In particular, the companies interested in innovations may be under funded as major geothermal companies do not participate in funding exploration, there is no debt financing available for exploration, and risk-tolerant equity funding for exploration has proven difficult to attract. All these factors impair interested parties in their ability to adopt such technologies.
- ***Knowledge Sharing/Data***. Insufficient documentation exists on past successes and failures in geothermal exploration. Challenges also surround intellectual property and data sharing, such as developers holding data for leasing purposes. Regional data collection is a challenge, especially in areas outside those that have been proven, as is identification of new geothermal provinces or trends in data-sparse areas.

While these challenges are critical to the success of IET and GTP goals, this assessment does not identify potential solutions to these non-technology-related issues.

IV. Technology Needs

This chapter presents an overview of the technology advancement needs associated with each of the five IET technology areas by highlighting the high-priority technology needs in each area. Detailed worksheets for the nine highest-priority technology needs, listed below in Table IV-1, are presented in Appendix A.

• Better Multi-physics Models to Extend Use of Geophysics for Permeability • Improve Next-generation Geophysical Airborne Data	**Geophysics**
• Improved Thermodynamic Data for Next-generation Geothermometers • Development of Geothermometers that Accurately Reflect Lithologic and Tectonic Settings, and Identification of New Thermometers	**Geochemistry**
• Stress/Strain Data Mapping	**Geology**
• High Resolution Remote Sensing Data and Reliable Automated Processing Methods	**Remote Sensing**
• 3-D Modeling Techniques (software) • Multi-disciplinary Conceptual Models • Create Case Study Examples of Geothermal Systems in Different Settings	**Cross-cutting**

Table IV-1. Nine high-priority technology needs in five exploration technology areas

Technology Areas

Geophysics

Both geophysical models and geophysical data are needed to advance geothermal technologies. Research programs should be developed to define geothermal signatures in different tectonic settings and to identify geophysically detectable features in geothermal reservoirs.

There is a need for **advancement of superior multi-physics models**. These models would extend the use of geophysical data to identify subsurface permeability by unifying physical, chemical and hydrological properties. Technology advancement is also needed to provide seismic reflection data in volcanic strata. To develop such a capability, a technical contest could be issued. Beyond multi-physics models and seismic reflection technology, there is a need to **improve the next generation of geophysical airborne data**. This need could be met by testing advanced airborne tools, including magnetotelluric and time-domain electromagnetic tools over known geothermal systems, by leveraging other agencies' satellites and airborne data and combining multiple airborne sensors on a single platform. Lastly, better and potentially new borehole tools are needed, including tools capable of higher temperature operation.

The following two technology needs in geophysics are most needed to support the IET Subprogram vision and carry important benefits to industry as a whole. In Appendix A , each is described in detail on a technology needs map.

- *Better Multi-physics Models to Extend Use of Geophysics for Permeability.* Better models would increase drilling success rates, reduce economic risk of geothermal development, bring more geothermal energy online, and support workforce development. Advancement of this technology benefits geothermal developers and owners, geophysical service companies, and drillers. Challenges to overcome include equivocal results, insufficient research workforce in this discipline and a limited number of case studies. DOE could work with universities, national laboratories, service companies and geothermal developers to advance this technology and achieve success in 5 years.
- *Improve Next-generation Geophysical Airborne Data.* Advancement in this technology area will help identify hidden resources and will benefit the Bureau of Land Management and stakeholder companies. Technical challenges include problems in flying surveys and interception in areas of high relief. Significant advancement in this area can be achieved in 2 years.

GEOCHEMISTRY

One of the most needed advancements in geochemistry is improved thermodynamic and kinetic data for fluids and minerals; this **data will enable development of the next generation of geothermometers**. Specifically, geothermometers that clearly identify geochemical temperature and new geothermometers, if they exist, are needed. Advancements are needed to enable an accurate definition (using lab and field experiments) of **geothermometry as it applies to variable lithologic regimes**. To enable the discovery of new geothermometers, basic research is needed on fluid chemistry from known geothermal systems.

The following two high-priority technology advancements in geochemistry are most needed to support the IET Subprogram mission and vision:

- *Improved Thermodynamic Data for Next-generation Geothermometers.* Better data is inexpensive and will improve the ranking of potential resources, evaluation and management of reservoirs, prediction of temperature at reservoir depth, and understanding of fluid rock structure in reservoirs and during transport/flow. Difficulties in scaling lab determined data to field data can present challenges to advancement in this area. Improvements can be accomplished in 1-2 years but full success with validation of improved reaction transport models will take 5-7 years.
- *Development of Geothermometers that Accurately Reflect Lithologic and Tectonic Settings, and Identification of New Thermometers.* This technology will improve the ability to quickly assess the thermal conditions of a subsurface geothermal system and will benefit developers, researchers, and national labs. No technical risks to success were identified during the workshop for development of improved geothermometers and it was estimated that success could be achieved in 5–10 years.

GEOLOGY

In the geology arena, advancements are needed in **stress and strain data mapping** and in correlating improved tectonic stress and strain data with thermal data. Stress and strain maps would predict fractures and assist in solving the question of permeability. Advancement could be made through acquiring additional data to fill in gaps of regional geodetic, local structural and borehole data, and developing detailed district maps and 3D models of strain and stress. A confirmed model connecting geophysics, hydro-geochemical, and geologic data to map permeable paths in the subsurface would also improve the technical community’s understanding of permeability. Overall, there is a need for an improved conceptual model to understand the subsurface, so as to require fewer slim holes and thereby reduce costs. There is a need to adapt projects to model fluid flow in the fractured crust, and for a reliable “crack finder.” Lastly, a decisional tree or matrix describing the effectiveness of various techniques in various geological settings could help meet explorers’ needs for detailed geological information.

The following technology advancement in geology is most needed to support the IET Subprogram mission and vision:

- *Stress/Strain Data Mapping.* This technology will apply to case studies, reduce risks of drilling, and assist the understanding of induced seismicity. It will benefit regulators and operators. Challenges in this area include abnormal stress regimes and lack of borehole data. Development objectives in stress/strain mapping can be achieved in 1–3 years.

Remote Sensing

Remote sensing advancements are needed to enable the acquisition of **high-resolution remote sensing data sets** via multiple methods over large areas in new regions. Specifically, there is a need to establish **reliable automated processing** tools and techniques and develop affordable software for subsurface data-set model integration.

The following technology advancement in remote sensing is most needed to support the IET Subprogram mission and vision:

- *High-Resolution Remote Sensing Data and Reliable Automated Processing Methods.* Improved data and methods will create multiple modern regional data sets and defray costs of cutting-edge exploration tools and will benefit stakeholder companies, universities, and the NGDS. In order to accomplish this, links between data and resource potential need to be defined. This technology can be achieved in 1–3 years.

Cross-Cutting

Opportunities exist for technical advancements that will provide "cross-cutting" support for all geothermal IETs. Improved, **multi-disciplinary, conceptual models** hold promise for increasing the understanding of the subsurface, thereby requiring fewer slim holes and avoiding the associated costs. Development and confirmation of a model that connects geophysics, hydro-geochemical data, and geologic data, and maps permeable paths in the subsurface would enhance understandings of permeability and reduce drilling, exploration and production risk. Opportunity exists to develop projects to model fluid flow in the fractured crust. **3-D modeling techniques and software** are needed, as are improved and easier to use data integration tools and software for model development. Improvements in data inversion codes, especially of multiple data sets, have promise. The application of stochastic or Monte Carlo inversion to match cross-disciplinary datasets is able to generate a range of possible models.

Case study examples of geothermal systems in different settings could serve to identify key attributes to use in exploration, and also to establish occurrence models. To provide these case studies, DOE could support multi-company, multi-disciplinary projects; these "group shoots" could test combinations of technologies and publish all of the resulting data. District mapping programs show promise for increasing the knowledge base of existing resources. There is a need for combined studies of the correlation between geochemistry and thermal studies at specific locations. Such studies would couple diverse data sets through common physical and chemical overlapping laws, providing combined data. In addition, there may be opportunities for a program to define geothermal signatures in different tectonic settings.

The following three cross-cutting technology advancements were identified as having the most potential to enable achievement of the IET Subprogram mission and vision:

- *Multi-disciplinary Conceptual Models.* Improved conceptual models will lead to increased drilling and exploration success, which benefits operators of participating projects, competitors, and the industry as a whole. The limited availability of non-proprietary data could be a barrier to success for this technology need. Success can be achieved in 1–3 years.

- *3-D Modeling Techniques (software).* Enhanced software will lead to improved understanding of conceptual models which leads to reduced drilling costs, this drives industry to provide more and more functionality and benefits developers by providing better and more affordable tools. Success can be achieved in 1 year.
- *Create Case Study Examples of Geothermal Systems in Different Settings.* Better case studies will streamline explorations by highlighting key attributes and data needed in each setting and will benefit stakeholder companies, NGDS, and researchers. This improvement can be achieved in 3–5 years but a classification scheme for geothermal systems is a critical initial step.

V. PATH FORWARD

The technology needs identified in this assessment provide the groundwork for further technology roadmapping within the IET subprogram. Using the nine identified high-impact research areas, GTP, in collaboration with stakeholders, will develop technology pathways with milestones and metrics to advance geothermal exploration technologies.

MEASURING SUCCESS TOWARDS IET GOALS

The ultimate goal for IET technology advancements is lower exploration costs and risk to support the discovery of the significant unidentified geothermal resource in the U.S. In order to measure progress towards achieving this goal, the IET community needs to define metrics with which to measure the impact of subprogram technology advancement activities. The metrics should also be able to be tied to the overall GTP mission and vision of geothermal energy becoming a major source of clean, renewable, domestic, and baseload electricity. There is both a need for a clear MW goal towards which IET should strive, as well as a need to understand the assumptions behind the USGS projection of a 30 GW future for geothermal energy. Appendix D lists preliminary metrics identified by the Geothermal Technologies Program for assessing its performance towards achieving its overall goals with respect to new geothermal deployment. These metrics can serve as a guide for the IET Subprogram in developing metrics specific to its technology advancement activities.

BEYOND ROADMAPPING

It is important to note that as performance is measured and evaluated, action items may be revised and resources reallocated. Evolving industry trends may cause IET Subprogram priorities to shift, subsequently resulting in new priorities and activities. Figure V-1, below, depicts the overall pathway from the current technology needs assessment and roadmap development through activity implementation, increased deployment of IET technologies, and achievement of the IET Subprogram goal. Figure V-1 also shows that information from performance evaluation and changes in the industry landscape are likely to feed back into specific pathway plans and the overall assessment and strategic roadmap.

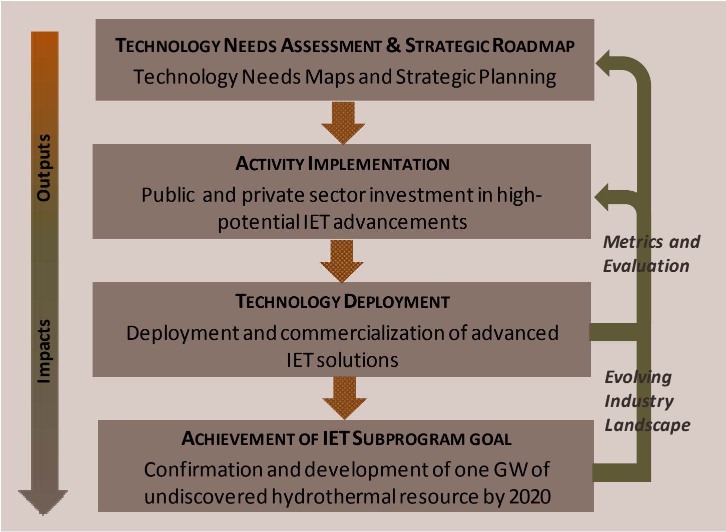


Figure V-1. Technology assessment and roadmap implementation and evaluation

Appendix A: Technology Needs Maps

Each of the nine technology needs described in the following maps represents an area of investment for the IET Subprogram to consider. Each map describes the current state of technology; the desired future state; the benefits of achieving the advancement; and the associated risks, key stakeholders, and projected time frames. The maps also include an approximation of where the technologies currently reside along the technology development pathway—from fundamental R&D to commercial deployment.

Geophysics 1: Better Multi-physics Models to Extend Use of Geophysics for Permeability

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- Various methods are not being combined: seismic (active and MEA), electrical (airborne, surface, downhole), stress-strain (structural geological, geodesy, LIDAR), geology, distributed temperature measurement (fiber optic), borehole breakouts, borehole flow, and geochemical
- Relatively complete data sets can be tested against production to understand the value of the data sets; however, there are few such data sets, including some that are very old, in which case software to process them has become outdated
- Education curriculum does not include integration
- Paucity of publically available data, including failure case histories (data sets that did not work)

To What? – Definition of a Successful Advancement

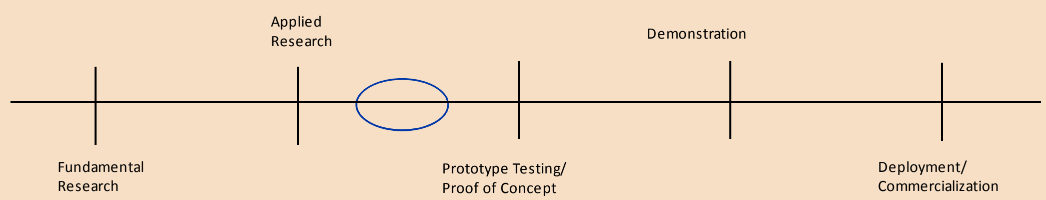
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- A unified model utilizing physical, chemical, and hydrological
- Model and trials with data are published in open literature
- Failure case histories documented thoroughly
- Predictive capability is numerically assessed
- Proven reduction in economic risk of geothermal drilling
- Graduation of experienced multi-physics modelers educated in integration techniques

How Do We Get To Deployment End-state?

What are the benefits? More complete and integrated data sets result in greater resolution of subsurface attributes from geophysical data	*What are the risks to success?* Equivocal results, failure of multi-physics models, insufficient research workforce, and too few case studies
Who benefits? Geothermal developers/owners, geophysical service companies, and drillers	*Who are the participants/partners?* Universities, service companies, geothermal consultancies (Geothermix, SAIC, ROARS, ThermalChem, Thermasource), and developers (NCPA, Terragen, Calpine, ORMAT), note: experts with strong conceptual background are needed to do the integration piece; international expertise
How soon can success be achieved 5–10 years	*Comments?* High priority, 5-year, $3 million–$5 million per year projects would be ideal; more than 5% required match would kill university involvement

Technology Readiness Level/Maturity



Geophysics 2: Improve Next-generation Geophysical Airborne Data

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- Technology currently used a lot in other industries (e.g. mining, oil and gas)
- Penetration of airborne data (e.g. magnetotellurics [MT]/electromagnetics – different wavelengths of energy to probe the earth [EM]) has reached depths of interest to geothermal and is being applied in minerals exploration; MT uses the suns solar field and lightning to map out resistivity variation down to approximately 200 meters
- Mining industry's use of airborne MT still relies on ground-based data to increase reliability of airborne data
- Airborne gravity is well understand in mining but not in geothermal applications
- Aeromagnetics (high resolution) and Airborne MT show alteration destruction of magnetite in young volcanics where there is sulfite
- Few companies use airborne MT inversion for topography as it is expensive, though the data collection is cheap
- Neither successful nor negative case histories (failures) have been published
- Most of the MT/EM work is done overseas

To What? – Definition of a Successful Advancement

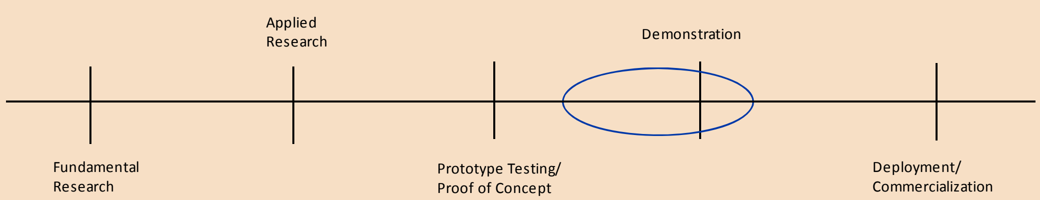
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Development of processing methods to adapt the airborne MT/EM tools to geothermal applications particularly with respect to handling topography:
  - Improved scalability of EM/MT data
  - Reduction of time and cost of performing Airborne MT three dimensional (3-D) inversions
- Detailed records of failed cases in addition to successes and access to these records
- Potential to combine with other airborne sensors, such as chemistry or remote sensing, on the same platform to establish useful sensor combinations (e.g., spectral gamma, radiometry, hyperspectral imaging, and LIDAR)

How Do We Get To Deployment End-state?

What are the benefits? Greater resolution of MT and EM data and reduced time and cost for data processing—performing multiple tests from a single airborne platform reduces permitting costs and ensures consistency of results across time and space.	*What are the risks to success?* Problems in flying and interception in areas of high relief; for platform combining airborne sensors there is a risk of interference by different instruments in such close proximity.
Who benefits? Bureau of Land Management (revenues from new prospects), companies (profits), and mankind (expand capacity)	*Who are the participants/partners?* Geotech, U.S. Geological Survey, other industries like coal mining, Chevron, international collaborations (New Zealand, Australia, Canada)
How soon can success be achieved 2 years	*Comments?* The International Partnership for Geothermal Technology could facilitate collaboration so DOE could study Australian data from mineral deposits; the technology needs to be proved for geothermal applications

Technology Readiness Level/Maturity



Geochemistry 1: Improved Thermodynamic Data for Next-generation Geothermometers

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- Most chemical geothermal work in practice is based on empirical or theoretical relationships—the range of uncertainty is too large
- Transport to reservoir, re-equilibration overprints deep-water rock equilibration temperature
- Determination of thermodynamics and kinetic-rate parameters relies primarily on applied technologies and feeds off of ongoing fundamental research funded by DOE. Reaction transport models are presently being applied, but need better constraints

To What? – Definition of a Successful Advancement

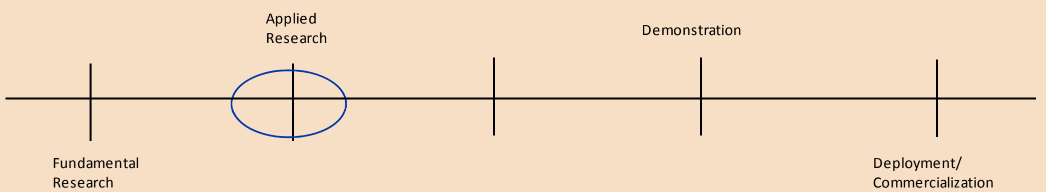
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Determination of improved thermodynamic and kinetic data for fluid-mineral systems that are needed to develop the next generation of geothermometers—done in context, targeting correct species of rock
- Incorporation of improved thermodynamics and kinetic rate data into robust reaction transport models
- Greater empirical validation for low-temperature and low-permeability systems, enabling determination of longer history of water

How Do We Get To Deployment End-state?

What are the benefits? Cheap technology, improved prediction of temperature at reservoir depth, better understanding of fluid rock structure in reservoir and during transport/flow, improved ranking of potential resources, improved evaluation of geothermal reservoir, and improved reservoir management	*What are the risks to success?* Difficult to scale lab determined kinetic data to field data
Who benefits? Geothermal developers/owners, geophysical service companies, and drillers	*Who are the participants/partners?* National labs, academia, and industry
How soon can success be achieved 5 years	*Comments?* Improvements can be accomplished in the near term (1–2 years), full success will take validation and improved reaction transport models (5–7 years)

Technology Readiness Level/Maturity



Geochemistry 2: Development of Geothermometers that Accurately Reflect Lithologic and Tectonic Settings, and Identification of New Thermometers

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- Geothermometers largely reflect empirical correlations developed in the 1980–1990 period and are not specifically related to the range of lithologic and tectonic regimes and electrolyte compositions in which geothermal systems are found
- Geothermometers are not specifically adapted to the conceptual targets (e.g., the NAKMG geoindicator plot)—limitations in detecting the level of permeability
- Need new plots that are more effective in differentiating permeability. Characterize permeability from associated water sample.
- Looking for less dramatic permeability through much more diffusive rock

To What? – Definition of a Successful Advancement

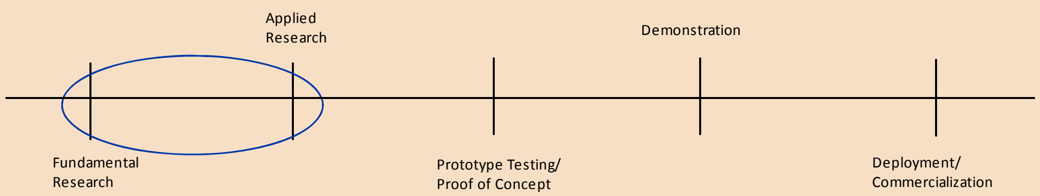
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Next-generation geothermometers will:
  - Work with lower TDS fluids, have longer memory and greater sensitivity to whether water is static or a moving aquifer
  - Work with lower temperature, more dilute water that is less connected to the deep systems
  - Resist contamination by drilling fluids
- Examination (laboratory) of the behavior of liquid and gaseous chemical component in variable lithologic, hydrologic flow, and temperature conditions
- Development of predictable and reliable correlations of the geothermometers with data from real geothermal metamorphic terrains/systems
- Success can be measured by comparison of drilling/sampling results to geothermometer predictions

How Do We Get To Deployment End-state?

What are the benefits? Ability to quickly assess the thermal conditions of a subsurface geothermal system	*What are the risks to success?* Discontinuous funding and low priority of the activity within the organizations involved (including industry, academia, and national labs)
Who benefits? Geothermal developers, academic researchers, and national labs	*Who are the participants/partners?* Academic
How soon can success be achieved 5–10 years	*Comments?*

Technology Readiness Level/Maturity



GEOLOGY 1: STRESS/STRAIN DATA MAPPING

FROM WHAT? - Current State

What is the state of knowledge or technology that needs to advance?

- Data is sparse in most areas
- Some areas lack well-exposed strain indicators
- Detailed geologic mapping
- Borehole data
- Comparison of borehole data and local fault kinematics data
- Quaternary fault studies

TO WHAT? – Definition of a Successful Advancement

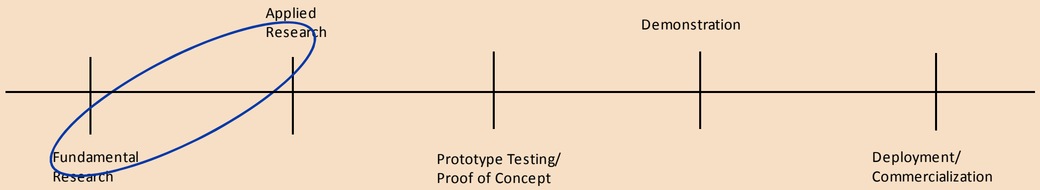
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Additional data to fill in gaps
  - Identification of places in the United States that have data sets/logs large enough where subsurface stress regime can be determined
  - Determination of the predictive value of the data for each location—what geological environments does surface data best predict subsurface attributes?
  - Integration of regional geodetic, local structural, and any borehole data
  - Determination of changes in stress with depth
- Detailed district maps
  - Stress inversions and modeling
  - Slip tendency analyses
  - Induced seismicity estimates
- Achievement of 3-D models of strain and stress will be considered a success
  - Publicized district maps
  - Slip tendency maps

HOW DO WE GET TO DEPLOYMENT END-STATE?

What are the benefits? Application to case studies, improved targeting of permeability (statistically) and understanding of induced seismicity	*What are the risks to success?* Abnormal stress regimes and lack of borehole data
Who benefits? Regulators and operators	*Who are the participants/partners?* Academia, need expert for surface work (e.g., UNR—surface stress and remote sensing); U.S. Geological Survey, DOE, Industry—Chapel Hill, Terragen (for large imaging data sets), LUDITE, Cal Energy
How soon can success be achieved 1–3 years	*Comments?*

TECHNOLOGY READINESS LEVEL/MATURITY



REMOTE SENSING 1: HIGH RESOLUTION REMOTE SENSING DATA AND RELIABLE AUTOMATED PROCESSING METHODS

FROM WHAT? - Current State

What is the state of knowledge or technology that needs to advance?

- Free satellite data is already available, which helps to narrow down zones for collecting airborne data
- Airborne systems are in place and being used by other industries (e.g., hyperspectral used for mineral exploration), but they are not fully exploited or used as routine parts of geothermal exploration
- Commercial off-the-shelf tools exist for processing data, but remote sensing data and tools have not been fully exploited for geothermal exploration
- Low-resolution magnetic, resistivity, and gravity data are available for large parts of United States. There is a paucity of high-resolution data over geothermal targets
- Processing of airborne remote sensing data (especially automating the process of data georectification and mosaicing) is still a challenge. A lot of manual time is invested in making data usable.
- Published literature in geothermal remote sensing is still limited compared to other application areas.

TO WHAT? – Definition of a Successful Advancement

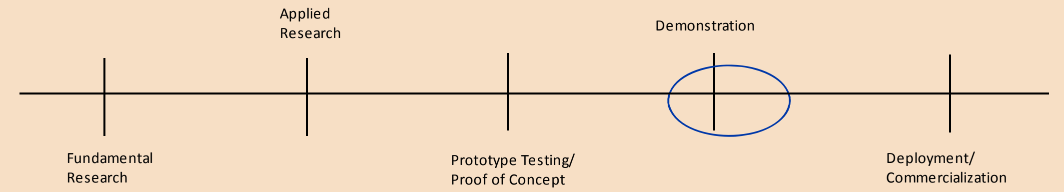
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Acquire airborne gravity magnetics, hyperspectral, light detection and ranging, resistivity, thermal infrared data, and similar data over target areas
- Links between data and resource potential need to be defined
- Make data publically available as a baseline for geothermal prospects, including documentation of:
  - The accuracy and reliability of results through systematic sensitivity analysis
  - How data is converted to quantitative information (temperature, heat capacity) and translated into production capacity
- Prove automated data processing for large area surveys
- Resource assessment should be based on analysis of multiple datasets
- Monitoring an area with remote sensing (temporal) after the area is developed to collect multi-temporal data

HOW DO WE GET TO DEPLOYMENT END-STATE?

What are the benefits? Multiple modern regional data sets over a data location; reduction of time to process data; greater usage of airborne data; defray costs of cutting edge exploration tools	*What are the risks to success?* Low risk—could spend money acquiring airborne data over area that is not a potential site; however, the information would still be useful
Who benefits? Companies, universities, and the National Geothermal Data System (NGDS)	*Who are the participants/partners?* Service providers, universities, and non-governmental organizations
How soon can success be achieved 1–3 years	*Comments?* The technology is developed, the challenges are implementing technology to geothermal exploration, automating the data processing, and bringing the technique from regional to local scale.

TECHNOLOGY READINESS LEVEL/MATURITY



Cross-Cutting 1: Multi-disciplinary Conceptual Models

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- Variable knowledge base across disciplines and explored locations
- Lack of case studies and lack of synthesis, existing studies are of varying quality
- Most old data is not up to current professional standards
- Some newer developments have little or limited public knowledge
- Knowledge needs to advance in all disciplines

To What? – Definition of a Successful Advancement

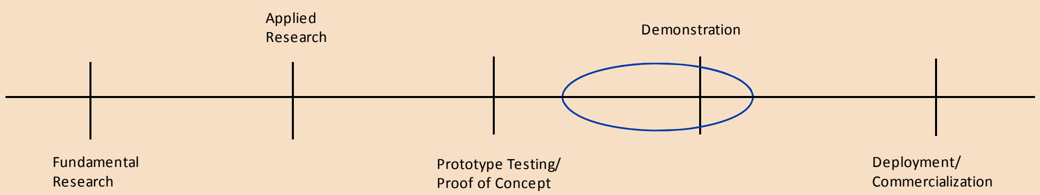
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Development of more complete and comprehensive data sets across multiple disciplines and locations
- Better integration of multiple datasets, including surface geophysical data acquired for 3-D subsurface imaging (e.g., seismic reflection, MT), as well as geochemical and geological data (e.g., isotope geochemistry, surface geology, borehole temperature gradients, and well-logs)
- Better characterization of known systems and extrapolation to undeveloped areas to identify favorable settings with more certainty
- Better definition of geothermal fingerprints (using case studies)
- Publication of case studies, including greenfields

How Do We Get To Deployment End-state?

What are the benefits? Improved conceptual models leading to better exploration strategies, increased drilling, and exploration success	*What are the risks to success?* Uncooperative producers and a need to collect some additional data
Who benefits? Operators of participating projects, competitors, and industry	*Who are the participants/partners?* Geothermal developers and exploration companies with possible assistance from other researchers such as reservoir geologists
How soon can success be achieved 1–3 years	*Comments?* We need to develop new understandings, not new techniques or tools

Technology Readiness Level/Maturity



Cross-Cutting 2: 3-D Modeling Techniques (software)

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- 3-D software exists for imaging/mapping MT and seismic microearthquake data
- Multiple programs from a variety of vendors—each software has its pros and cons
- No commercial or academic software platforms (Geotech is trying to develop this)
- Typically vendors offer the 3-D surveys, modeling, and interpretation as a combined service. Customized software for in-house use by developers is done mostly for the oil and gas industry where there is more funding
- A handful of companies have the ability to do 3-D inversions— Sluberger can only do commercial 3-D; Chevron is the only one that can do in-house and has four researchers (LDL) that have proprietary model
- Ranging in cost from $3,000–$50,000
    - High cost reduces use of "proven" technology
    - Complex or "buggy" software limits easy adoption

To What? – Definition of a Successful Advancement

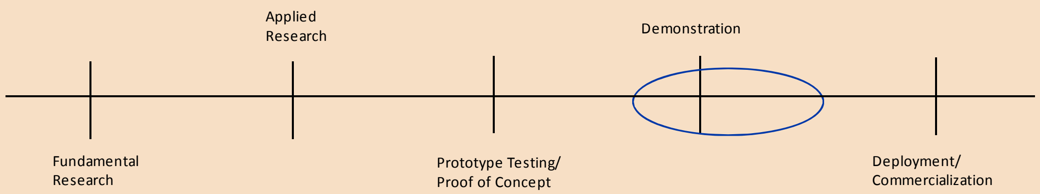
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Open source 3-D MT code: advancement and increased availability of programs that can better integrate complete data sets (e.g., Worldwind by NASA), possibly through funding of a public sector modeling suite
    - Software using complete data sets that has improved resolution
    - Software that has a common platform, allowing for greater interoperability and easier exchange of information sharing
    - Simplification of data input with built-in quality checks
    - Improved graphics
- A successful project will have reduced software costs and increased availability (to gain wider use and competition)

How Do We Get To Deployment End-state?

What are the benefits? Software that interprets integrated data sets leads to increased 3-D mapping resolution and an improved understanding of conceptual models (ultimately resulting in reduced drilling costs)	*What are the risks to success?* Few, including a lack of widespread adoption
Who benefits? Drives industry to provide more functionality, and developers and explorations have better and more affordable tools	*Who are the participants/partners?* Software development/sales working with industry to develop geothermal-specific 3-D modeling packages
How soon can success be achieved In one year the technology will exist, but it will be expensive for individual companies	*Comments?* Could work with Google Earth and SketchUp to expand to geological/geophysical display

Technology Readiness Level/Maturity



Cross-Cutting 3: Create Case Study Examples of Geothermal Systems in Different Settings

From What? - Current State

What is the state of knowledge or technology that needs to advance?

- In each setting, identify key attributes related to geothermal systems
- For settings, use the U.S. Geological Survey classification system (not yet published) or other appropriate methods (volcanic or extensional mixed)
- Geophysical and other data
- Better data and imaging paradigms for geothermal fluids

To What? – Definition of a Successful Advancement

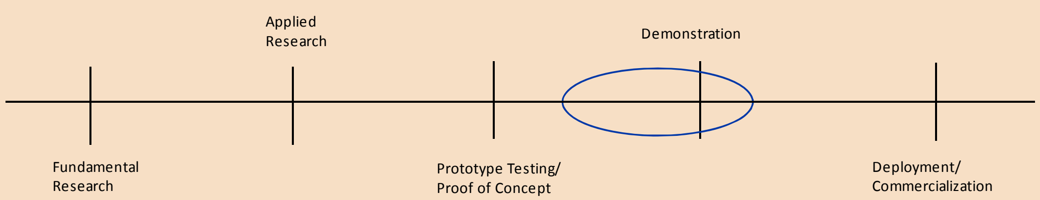
Where does knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

- Identification and documentation of well-characterized geothermal systems for each setting that can be used as case studies
- Use of multidisciplinary data sets leads to "group shoot," testing/verification of conceptual models of case studies.
- Development of conceptual models (using integrated data) for case studies
- Identification of key attributes/parameters required for a productive (commercial) geothermal system at a given setting
- Development of a conceptual model for each setting

How Do We Get To Deployment End-state?

What are the benefits? Streamlines explorations by highlighting key attributes and data needed in each setting	*What are the risks to success?* Insufficient data; systems not readily classified by an existing work-flow process do not characterize into geothermal reservoir systems well enough to be exploiting commercially
Who benefits? Companies, data to/from the NGDS, researchers (university and national labs)	*Who are the participants/partners?* NGDS, companies, universities, labs, service providers, and international partners
How soon can success be achieved 3–5 years	*Comments?* The classification scheme is a critical initial step

Technology Readiness Level/Maturity



Appendix B: Workshop Participants

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Appendix C: Workshop Results

Key Technical Challenges

Geochemistry	Remote Sensing	Geology
• Refine and test geothermometers, gases, liquids, isotopes, trace elements, and inconsistent lab results ●●●●● (5) • Better tools–lower cost, higher temperature, smaller for slim holes (0)	• Demonstrate the feasibility at large scale ●●● (3) • High, low-cost resolution strain maps ● (1) • Area to be surveyed is vast and data sets can be large—need new tools for automated regional reconnaissance data analysis and processing, lack of experience in wide-area reconnaissance tools for sparse-data areas ● (1)	• Tectonic context, structure setting and detail, strain, stress inversion, define permeability at depth at fracture scale ●●●●●(5) • Availability of sufficient geologic maps for exploration ●●● (3) • Lack of understanding of regional active structures ● (1) • Age dating hot spring deposits (0) • No way to tell if hot feed is below thermal anomalies (0)

Geophysics	Cross-cutting
• Permeability at depth without drilling with geophysics and geochemistry and geology ●●●●●●●●●●● (11) • Lack of ability to image fluids and flows ●●● (3) • Non-uniqueness of geophysical inversions ●● (2) • Lack physics-based anomalies that can be targeted by geophysics (in the reservoir) ●● (2) • Remotely predicting temperature at depth ● (1) • "Detailed" (to be defined) heat flow map (0) • Couple magnetotelluric/resistivity anomaly with other technology (isotope to get reliable indicator of geological resource from surface to air (0)	• Big picture—evaluating combos of technologies in addition to each individually ●●●●●●● (7) • Lack of occurrence models ●●●●● (5) • Lack of affordable tools to integrate 3-D and multiple data sets ●●●● (4) • Need to link subsurface reservoir to surface measurements ●●● (3) • Need to explore new locations ●● (2) • Availability of existing data ●● (2) • Use other federal agency tools—collaborative partner, NSF Earth scope, NASA airborne science surveys (InSar, Hyperspec, LIDAR, etc.), USGS survey and map (0)

● each orange dot represents one vote as a high priority/critical technical barrier

Non-Technical Barriers

<table>
<tr><th>Permitting</th><th>Externalities</th></tr>
<tr><td>• Lack of geothermal knowledge on permitting/leasing side
• Double standards for oil and gas versus geothermal permitting</td><td>• Electricity rates
• Public perception of drilling funds as potential "corporate welfare"
• Growing the scientist base
• Sufficient quantity of quality investigators available in a reasonable time frame</td></tr>
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<table>
<tr><th>Money/Funding</th><th>Knowledge Sharing/Data</th><th>Policy</th></tr>
<tr><td>• Under-funded companies interested in innovations
• Costs of cutting edge technology is high—limits broad utilization
• Exploration drilling costs
• Lack of capital and mechanisms to conduct high-risk reconnaissance (e.g., cooperative strategraphic test costs)
• Competition with oil, gas, and mining for services (more industry partnerships—we need a champion)</td><td>• Lack of documentation of success and failure
• Shared database of resources
• Lack of a comprehensive database available to all companies
• Intellectual property/data sharing issues (i.e., balancing between data sharing and developers potentially wanting to hold data for leasing purposes)
• No participation from major geothermal companies—need to attract risk-tolerant equity funded
• Context conceptual models
• Identifying new geothermal provinces or trends in sparse data areas
• Data integration (affordable tools are needed)
• Regional data collection, especially in areas outside those proven</td><td>• ARRA funds (the strings attached are so onerous it may not be worthwhile for National Environmental Policy Act, Davis Bacon Act and permitting)
• Need a long-term phased program, science-based effort
• Sustained effort from DOE
• Get the supporting government entities on same page
• Lack of focus in DOE program
• Lack of geothermal experience in DOE
• Unrealistic time frames in TSX
• DOE money supporting the small companies
• Federal lands regulatory constraints, conflicting interests on public land use</td></tr>
</table>

Technology Needs

Geophysics

- Better multi-physics models to improve/extend use of geophysical data to identify subsurface permeability ●●●●●●●●●●●●●● (14) *
  - Program—define geothermal signatures in different tectonic settings
  - Develop research program to identify geophysical detectable features in geothermal reservoirs
  - Subsurface imaging—look outside of geothermal to physics arena, issue technical challenge/contest
- Improve next generation geophysical airborne data ● (1) *
- Technology advancement, seismic reflection data in volcanic strata ● (1)
- Higher temperature and/or [new] bore-hole tools (0)

Geochemistry

- Improved thermodynamic and kinetic data for fluids and minerals needed to develop the next generation of geothermometers ●●●●●● (6) *
- Accurately defining geothermometery as it applies to variable lithologic regimes using lab and field experiments ●● (2) *
  - Geothermometers that clearly identified geochemical temperature and new geothermometers if they exist
- Basic research on fluid chemistry from known geothermal systems, using modeling packages, to find new geothermometers (0)

Remote Sensing

- Acquire high-resolution remote sensing data sets (multiple methods) in new regions over large areas ●●● (3) *
  - Establish reliable automated processing ● (1)
  - Affordable software for subsurface data set model integration (0)

Geology

- Stress/strain data mapping—improve tectonic stress, strain data then correlate to thermal data ●●● (3) *
  - Stress/strain maps to predict fractures (solve permeability)
- Develop a reliable "crack finder" (0)
- "Geothermal Wikipedia," tree based on effectiveness of various techniques in various geological settings (0)

Cross-cutting

- Create case study examples of geothermal systems in different settings to identify key attributes that can be used in exploration ●●●●●●●●●●●●●● (14) *
  - DOE supports a few "group shoots"—multi-company, multi-disciplinary, all data published → combinations of technologies
  - Case studies to establish occurrence models
- Multi-disciplinary conceptual models—improved conceptual model to understand the subsurface so fewer slim holes are needed, reducing cost ●●●●●●●●●●● (11) *
  - Projects—model fluid flow in fractured crust
  - Permeability—continuous model that connects geophysical hydro-geological and geological data that maps permeable paths to subsurface
- 3-D modeling techniques—software ●● (2) *
  - Improve/easier to use data integration tools/software for model development
- Combined studies of the correlation between geochemistry and thermal studies at specific locations ●● (2)
  - Coupled data—coupling diverse data sets through common physical and chemical overlapping laws
- Lack of adequate workforce ●● (2)
- District mapping programs ● (1)
- Improved data inversion codes especially of multiple data sets ● (1)
  - Apply stochastic/Monte Carlo inversion to match cross-disciplinary data sets—range of possible models
- Develop regional geothermal centers ● (1)
- Projects—publish syntheses of results from previous DOE USGS programs, regional vs. small scale (0)
  - Aggregated database of proprietary data
- Program define geothermal signatures in different tectonic settings (0)

● each orange dot represents one vote as a high priority technology solution

* green star means that the advancement was developed into a worksheet

Appendix D: Geothermal Technologies Program Performance Metrics

Preliminary Targets for Program Performance Metrics

Metric	Unit of Measurement	2011 Status	2020 Target	2030 Target
Exploration cost per site	Dollars ($)	Developing baseline	TBD	TBD
Undiscovered resource confirmed	Megawatt (MW)	Analysis underway	1 GW	TBD