4.0 Technical Plan

The technical approach addresses the barriers to deployment of Enhanced Geothermal Systems. The technical plan describes two strategic areas of focus which will be implemented concurrently improve geothermal technology and accelerate EGS commercialization:

1. Research and Development; and
2. Enhanced Geothermal Systems Validation.

Section 4.0 Table of Contents

4.1 Enhanced Geothermal Systems Research, Development, and Demonstration

Commercialization of EGS will require technical and economic improvements in a variety of technologies. The principal barriers to EGS commercialization are creating, sustaining, and reducing the cost of reservoirs. Program R&D will focus on these named barriers as well as heat extraction from the reservoir at economically viable and sustained rates.

The Research and Development portion of the technical plan is divided into eight research areas as shown in Figure 4.1. These areas correspond roughly to the phases in the EGS power plant construction scenario as shown below. The R&D in all phases is conducted in parallel; the R&D Outline serves as an aid in identifying opportunities for the incorporation of newly developed technologies into the Systems Deployment and Validation projects, as well as areas for further development.

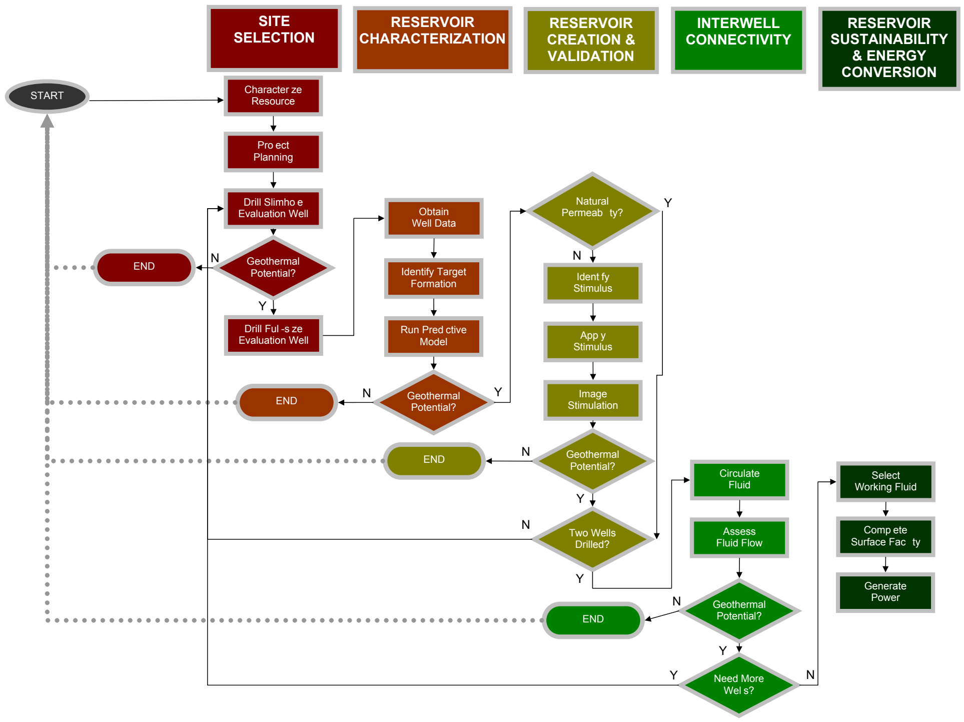


Figure 4.1. Systems Engineering Diagram of GTP Technical Plan Research Areas

Technical Plan Research, Development, and Demonstration Areas:

1. **Site Selection**- addresses tools for the selection of a potential EGS site, both from surface analysis and well bores, logs and well construction.

2. **Reservoir Characterization**- addresses principally downhole instrumentation and the use of this data in modeling the underground environment.

3. **Reservoir Creation- the single** most critical research area establishes permeability and creates and maintains rock fractures. EGS lithology is expected to be primarily igneous, crystalline and generally low porosity, and presents significant technical challenges.

4. **Reservoir Validation**- concerns tools for ensuring that the desired fracturing of the reservoir has been accomplished successfully.

5. **Interwell Connectivity**- deals primarily with tools such as tracers that can be used to ensure that there is a suitable flow path that connects the various injection and production wells in an EGS field.

6. **Reservoir Scale Up**- addresses the development of tools for the determination of the best location of additional injection and production wells as the EGS resource is developed.

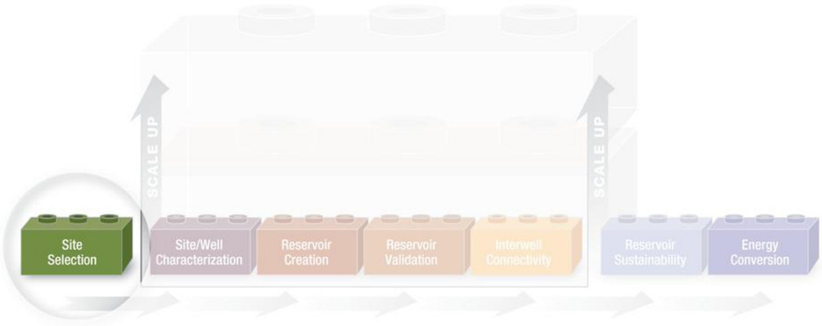
7. **Reservoir Sustainability**- seeks to develop tools for the long-term operation and maintenance of an economic EGS installation.

8. **Energy Conversion**- concerns the development of energy conversion (EC) systems that are suitable for EGS applications.

Because of the process-oriented structure of the RD&D program, it is important to note that in every case, relevant technologies are discussed when first initiated in the process of siting, constructing and operating an EGS facility.

Each of these areas is discussed in more detail in the following sections.

4.1.1 Site Selection



The selection of an appropriate site is the initial step in the construction of an economic EGS field. It should be noted that since well drilling is done as part of the exploration process, the discussion of well drilling technology and advancements is included under the "Well Construction" subsections within this section of the plan. Two goals are associated with this research area, and two sets of barriers, objectives, and tasks are discussed with respect to each goal.

4.1.1.1 Site Selection Goals

In the process of selecting a location for an EGS, issues arise in both the large-scale siting of the system and the small-scale location and drilling of the wells within the site. The goals targeting these separate issues are described below.

Site Characterization

Goal 1: Develop low-risk EGS site selection and characterization technology.

The subsurface environment must be characterized in preparation for creation of the EGS reservoir. Many reservoir characterization technologies already exist and are being used by the geothermal industry or the oil and gas industry; now technical capabilities must be extended for EGS application.

Well Construction

Goal 2: Develop low-cost, high-efficiency well construction (drilling and completion) technology.

Although well-drilling capability is highly advanced in the oil and gas industries, , drilling technology must be improved to enable access to hotter rock suitable for EGS. Conditions that are common in geothermal formations increase the risk that wells will be lost during drilling operations or production may be impaired due to twist-offs, lost tools, lost circulation, casing failures, bad cement jobs, loss of wellbore mechanical integrity, formation damage, and other mishaps from which recovery is not possible. Given the sensitivity of EGS to investment costs, these risks must be minimized through technology and field experience.

4.1.1.2 Site Selection Barriers

Site Characterization

Barrier A: **Site Selection & Resource Assessment** – The ability has not been sufficiently demonstrated to assess potential EGS resources, prioritize potential sites for EGS, and achieve acceptable levels of site selection risk ahead of expensive drilling investments.

Barrier B: **Site Characterization** – Inadequate measuring techniques and knowledge preclude low-risk options to effectively select sites and characterize their physical parameters as potential EGS reservoirs before stimulation. Better data is required to enable successful and replicable EGS development.

Well Construction

Barrier C: **EGS Well Construction Capability** – The inability to drill and complete wells meeting EGS requirements (high temperature, high flow rate, low cost) results in a greater risk of impairing production or even losing wells when drilling.

4.1.1.3 Site Selection Background

Site Characterization

Existing wells do not provide the required density of coverage across the entire country. There are large geographic areas where data is missing, and in other areas data sets have not yet been analyzed due to their cost.

Remote (pre-drilling) Assessment Techniques: The best EGS targets have high temperatures (> 200°C) at shallow depth (< 3 km) and a tectonic stress regime that keep fractures open. Current technology cannot identify such sites with a high degree of certainty without drilling. New and improved remote geological, geochemical, and geophysical techniques are needed to find shallow hot rock and favorable crustal stress conditions where there is no surface manifestation.

For further background information on site characterization, please refer to the resource characterization and site selection procedure in Section 5.

Well Construction

Suitable Drill Bits and Alternative Drilling Methods: Existing drilling methods from the petroleum industry can be adapted to EGS well field requirements, but these technologies are not ideal for geothermal subsurface conditions and formations, which are often hard crystalline rocks. Rotary bits designed specifically for these conditions will be required to enable low-cost and low-risk drilling. Drilling techniques from the mining industry are well suited to hard crystalline rocks, but are generally not designed for holes with large diameters. Revolutionary non-mechanical drilling techniques, such as flame jet drilling, hold promise but have not been tested in well field conditions.

High Temperature Logging Tools: Due to insufficient market demand and the limited availability of high temperature components, service companies do not currently provide all the high-temperature logging and drilling tools required to drill EGS wells. Existing logging tools for measuring temperature, pressure, flow, and other formation characteristics, as well as fracture imagining, require heat shielding and can only be used for brief periods. While the drilling industry works within these limitations, tools capable of operating in environments greater than 200°C are needed for EGS. Other reservoir monitoring sensors such as seismometers capable of operating in severe geothermal conditions will be required. Logging tools and sensors will require advances in components, battery technology, materials, and fabrication methods.

Ability to Satisfy the Large Well Diameter Requirement of EGS: Large diameter wells are required for economic EGS production rates. Large initial surface well diameters are costly, and geologic issues, unanticipated borehole stability problems, cold water influx, and other unforeseen events requiring additional casings can reduce the diameter from the original design and reduce the ultimate flow capacity of the well.

Underreamers, which are commonly used in the oil and gas industry to enlarge the wellbore below casing, are not suitable for use in geothermal lithologies and temperatures. In addition, completion and later intervention through production tubing unacceptably small diameter and flow capacity for EGS.

Unsuitability of Existing Casing Designs and Materials for EGS: Casing and cementing costs make up roughly 30 percent of the cost of constructing a geothermal well. Casing designs and casing material properties required for EGS are not available at low cost or are unsuitable in severe geothermal conditions. “Lean” casing designs such as expandable tubulars, casing-while-drilling, and low-clearance casing systems (i.e., with a minimal annulus between casing strings) now emerging in the oil and gas industry offer cost and performance advantages, but have not yet been applied to geothermal wells.

Corrosion and Scaling: High temperatures and fluid chemistry and pH make corrosion and scaling a major challenge. Improved anti-corrosion and anti-scaling materials are difficult to develop at reasonable costs.

4.1.1.4 Site Selection Objectives

The EGS concept is to engineer a geothermal energy system in the absence of preexisting permeability, fluids, or a natural convective system. As a result, the assessment and selection of EGS sites will differ from traditional hydrothermal exploration. EGS site selection does require estimation of many of the same geologic variables as hydrothermal exploration, such as heat flow and geothermal gradient, past and current stress state, rock type, depth of overburden, and fracture patterns, among other parameters. Among these variables, the principal criterion for EGS will be to identify areas of high temperature gradient where a reservoir can be created at economically drillable depths. EGS resource assessment and site selection will be aided by the U.S. Geological Survey's (USGS) ongoing update of the U.S. hydrothermal resource assessment.

Site Characterization

The most pressing R&D needs related to regional-scale exploration concern remote data acquisition, such as developing satellite or other remote-based (e.g., aeromagnetic) technologies to measure heat flow and regional deformation or to "see" through the shallow sub-surface. The primary objectives of research are to improve signal quality and reduce noise.

Table 4.1. Site Characterization Objectives

Number	Description	Barrier
1	By 2012, provide EGS feasibility information to the public based on data available.	A
2	By 2015, analyze the ultimate potential for EGS. The analysis will address necessary resources, transmission, reservoir sustainability, water needs, and interactions between an EGS economic sector and other sectors.	A
3	By 2009, specify needs for characterization of the physical parameters of potential EGS reservoirs before drilling.	B
4	By 2009, set technical objectives for improvement of geophysical methods for the characterization of the physical parameters of potential EGS reservoirs before drilling.	B

Well Construction

The objectives for well construction technology are based on incremental extension of wells into the hostile environment associated with EGS reservoirs. This environment is typified by high temperatures and its concomitant rise in chemical activity as well as the great depth and complex lithology of the setting.

Table 4.2. Well Construction Objectives

Number	Description	Barrier
1	By 2009, define baseline EGS wells (e.g. what kind of diameters will be run, vertical or directional, two small wells vs. one large well, downhole completion schemes, etc.)	C
2	By 2015, demonstrate well construction technologies that reduce the cost of drilling and completion by 10 percent.	C
3	By 2015, demonstrate the use of native drilling electronics and tools capable of operating at 250oC.	C

4.1.1.5 Site Selection Technical Approach

Site Characterization

As a result of the Geothermal Technologies Program research, a range of new geologic, geophysical and geochemical methods has been developed. Although many of these methods were originally borrowed from the mineral and petroleum industries, the uniqueness of geothermal systems requires significant innovation. Improvements in the geophysical methods are the most significant because of their ability to image the subsurface. As the emphasis of the Geothermal Technologies Program shifts toward EGS, and geothermal energy becomes an increasingly important energy source, all three geoscience disciplines will be increasingly tested.

A variety of remote sensing techniques are used in the geothermal, oil and gas, and mining industries. In general, these techniques currently have limited resolution and accuracy, and have not been adapted to the EGS resource assessment and site selection problem. Nevertheless, the following list includes remote exploration techniques with potential applicability:

- **Surface Geological Mapping** – (Section 5.0 Program Analysis discusses in more detail) measuring physical rock properties and interpreting the results in terms of geologic features. Measurements can be taken from the ground surface or via remote sensing (i.e. from aircraft or satellites).
- **Geochemical Surveys** – conducting chemical analysis of rock, soil, stream sediment, plant, or water samples.
- **Electrical Resistivity (or Specific Electrical Resistance) Surveys** – introducing electrical current into the ground via two electrodes and measuring differences in electric potential in the current using two or more other electrodes.
- **Self Potential Surveys** – measuring electrical voltage variations in the Earth's surface.
- **Magnetotelluric Surveys** – utilizing telluric currents (both naturally occurring and controlled source electric currents in the earth) to measure natural electric and magnetic fields.
- **Seismic Surveys** – measuring the variation in the rate of propagation of seismic waves in layered media to delineate subsurface geologic structures.
- **Magnetic Surveys** – mapping variations in the magnetic field of the Earth attributable to changes in structure or magnetic susceptibility in certain near-surface rocks.
- **Gravity Surveys** – mapping variations in the Earth's gravitational field due to irregularities or anomalies in gravity caused by differences in the density of rock formations.
- **Interferometric Synthetic Aperture Radar (InSAR)** – remote sensing technique measuring ground deformation such as subsidence, which may help map the boundaries of producing geothermal systems and explore for new resources.
- **Thermal Gradient Well Drilling** – measuring the temperature gradient in water-filled rotary-drilled wells (typically 30 to 600 meters deep).

Well Construction

The focus of the Well Construction program element is the creation and maintenance of EGS wells. Technologies are required for drilling the wells, determining the native characteristics of the wellbores, engineering the wells to enable stimulation, and ensuring the long-term integrity of the wellbore to enable permanent well completion. Many of the essential subsurface and surface technologies exist and are in use by the geothermal and oil and gas industries, but have technical limitations in regards to EGS application. The current limitations of these technologies, whether rooted in fundamental physics or in economics, represent barriers to development of an EGS energy industry.

The Program will focus R&D activities on the most critical well field construction technology gaps and will coordinate the R&D with the Field Projects program element to insure that newly developed technologies are tested in the appropriate settings as field activities progress. The results of field activities will also inform ongoing R&D planning and priorities.

4.1.1.6 Site Selection Programmatic Status

DOE exploration activities historically focused on the western United States. The following table provides a brief look at site selection program activities.

Table 4.3. Fiscal Year 2008 Site Selection Technology/Program Activities

Task	Approach	Organization
Fracture and water flow detection and imaging	Improve geophysical remote assessment techniques	LBNL; TBD through solicitation 08GO98008 and future solicitations
Enhance EGS well drilling capability	Development of drill bits and drilling systems optimized for EGS drilling conditions	SNL and Others
Provide specialized EGS well completion engineering capability	Development of high temperature components e.g. elastomers to extend range and life of well field operation tools	SNL and Others

Demonstrating the utility of slimhole drilling for exploration purposes significantly decreased the cost of initial exploration for geothermal resources. The Sandia National Laboratories (SNL) slimhole drilling program demonstrated that: 1) flow or injection tests on slimholes could accurately predict production characteristics of production-diameter wells in the same reservoir, and 2) slimhole drilling is cheaper than a comparable large-diameter well in the same location. Field experience showed that costs were 45 to 65 percent of conventional drilling cost, and logging and measurement techniques are adequate to characterize a geothermal reservoir. A Slimhole *Handbook* was distributed to industry and is used as a textbook in Iceland's UN Geothermal Training Program. Slimhole exploration is now widely used by industry.

In the late 1970s, the vast majority of oil and gas wells were drilled with roller-cone bits. In 1977, General Electric introduced a synthetic bit material of diamond grains sintered with cobalt, generically called polycrystalline diamond compact, or PDC, bits. Early field results were disappointing. SNL funded field tests and studies of rock/cutter interaction, diffusion bonding of the compact to the bit, and frictional heating of the cutters. As a result, PDC bits dominate the oil and gas drilling industry at an estimated $1.9 billion in sales in 2007, compared to $1.2 billion for roller-cone bits. The bits reduce drilling costs from $500/foot to $300/foot. Hard rock performance is still insufficient for the geothermal industry, although ongoing research is encouraging.

SNL pursued use of continuous-transmission, high-bandwidth downhole data to reduce the cost of geothermal drilling by providing a real-time report on drilling conditions, bit and tool performance, and imminent problems (known as Diagnostics While Drilling, or DWD). The driller can use this information to change surface parameters (e.g., weight-on-bit, rotary speed, mud flow rate) with immediate feedback. This adds value to virtually every part of the drilling process.

Commercially available electronic components rated at about 85°C (185°F) are not suitable for use in geothermal environments. Drilling technology developments are a significant Program contribution to geothermal technology. SNL designed an electronic mud-turbine control system based on SOI-SiC (Silicon-On-Insulator and Silicon Carbide) technology that can operate at an ambient temperature of 230ºC for hundreds to thousands of hours paving the way for high-temperature electronics.

4.1.1.7 Site Selection Technology Status

Site Selection

New technologies are needed that will reduce site characterization costs and improve confidence in performance predictions. The table indicates target areas of technological improvement.

Table 4.4. Site Selection Technology Status Summary		
Barrier	**Available Technologies**	**Technology Status**
Barrier B: Site Characterization Inability to characterize the physical parameters of potential EGS reservoirs before stimulation, providing sufficient data to enable successful and replicable EGS development.	Characterize subsurface conditions- Stress measurement inferred from natural breaking of rocks in the wall of the wellbore and “mini-frac”	Principal stress direction and magnitude are estimated from limited testing capabilities. Imaging tools for breakouts currently require a heat shield.
	Detect fluid-filled fractures- Remote (before Drilling) Assessment Techniques	Self-potential is commonly used for shallow hydrothermal systems. Significant research is required to develop and demonstrate surface-based technology with adequate resolution at reservoir depth (e.g., streaming potential). Determination of EGS reservoir rock characteristics from the surface appears out of reach in the near term.
	Predict potential for stimulation- Modeling of Favorable EGS Settings	Data and experience from the oil and gas industries are inadequate for modeling of most projected EGS environments due to lack of sufficient measurements under geothermal conditions.
	Active seismic surveys	Resolution of fracture systems is still poor using standard techniques.

Well Construction

Conditions common in geothermal formations increase the risk that wells will be lost during drilling operations or production will be impaired due to twist-offs, lost tools, lost circulation, casing failures, bad cement jobs, loss of wellbore mechanical integrity, formation damage and other mishaps from which recovery is not possible. Given the sensitivity of EGS to investment costs, these risks must be minimized through technology and field experience.

Drilling methods from the petroleum industry can be adapted to EGS well field requirements, but these technologies are not ideal for geothermal formations, which are often hard crystalline rocks, and subsurface conditions. Rotary bits, which are designed for these conditions, will be required to enable low cost and low risk drilling. Drilling techniques from the mining industry are well suited to hard crystalline rocks, but are generally not designed for holes with large diameters. Revolutionary non-mechanical drilling techniques such as flame jet hold promise but have not been tested in well field conditions.

Service companies do not currently provide all the high-temperature logging and drilling tools required to drill EGS wells. Existing logging tools for measuring temperature, pressure, flow, fracture imaging, and other formation characteristics require heat shielding and can only be used for brief periods. While the drilling industry works within these limitations, tools capable of operating in environment greater than 200°C over extended time periods are needed for EGS. Other reservoir monitoring sensors such as seismometers capable of operating in geothermal conditions will be required. Logging tools and sensors capable of operating under the extreme conditions of EGS will require advances in components, battery technology, materials, and fabrication methods.

Large diameter wells are required for economic EGS production rates. Large initial surface well diameters are costly, and geologic issues, unanticipated borehole stability problems, cold water influx, and other unforeseen events requiring additional casings can reduce the diameter from the original design and reduce the ultimate flow capacity of the well.

Casing and cementing costs make up roughly 30 percent of the cost of constructing a geothermal well. Casing designs and casing material properties required for EGS are not available at low cost or are unsuitable in severe geothermal conditions. "Lean" casing designs such as expandable tubulars, casing-while-drilling, and low-clearance casing systems (i.e., with a minimal annulus between casing strings) now emerging in the oil and gas industry offer cost and performance advantages, but have not yet been applied to geothermal wells.

High temperatures and fluid chemistry and pH make corrosion and scaling a major challenge. Improved anti-corrosion and anti-scaling materials are difficult to develop at reasonable costs.

Table 4.5. Well Construction Technology Status Summary		
Barrier	Available Technologies (U.S. and International)	Technology Status
Barrier C: EGS Well Construction Capability Inability to drill and complete wells meeting EGS requirements (high temperature, high flow rate, low cost).	Monitoring tools, sensors (e.g., tools to measure downhole pressure, flow, temperature, seismicity).	Monitoring tools and sensors are available commercially for sustained operation up to about 150°C. Tools capable of operation at >200°C are still experimental.
	Suitable Drill Bits and Alternative Drilling Methods- Drill Bits	Roller bits are used in hard rock. Advanced bits (e.g., PDC-based drag bits) are used in oil and gas, and they drill 60 percent of footage worldwide.
		Alternatives to mechanical methods (flame jet, etc.) are in experimental stages.
	Suitable Drill Bits and Alternative Drilling Methods- Advanced well steering tools	Wireline based systems are used in geothermal. Commercial advanced steering tools allow control over well trajectories. Tools providing limited steering control are in use by one geothermal firm. Commercial tools are limited to ~150°C.
	High Temperature Logging Tools- Logging while drilling/ Diagnostics while drilling	The technology is commonly used in the oil and gas industry. Commercial tools are limited to ~150°C.
	Metal casing in various diameters and production tubing (e.g., slotted liner)	Fully commercial systems to complete wells are available. Advanced technology, such as expandable tubulars and casing-while-drilling and low clearance casing systems, is emerging in oil and gas applications. Underreamers work only in "soft" rock. Elastomers used in these systems fail at high temperatures.
	Design methods for selective cementing	Various high-temperature cement formulations are available from the drilling service industry. Design methods for selective cementing of casing exist for wells with small temperature fluctuations.
	Design anti-corrosion and anti-scaling materials	Improved anti-corrosion and anti-scaling materials are difficult to develop at reasonable costs.
	Characterize subsurface conditions: Core sampling and evaluation	Routinely used in mineral exploration. Interpretive techniques for geothermal applications are still evolving.
	Monitoring tools, sensors (e.g., tools to measure downhole pressure, flow, temperature, seismicity).	Monitoring tools and sensors are available commercially for sustained operation up to about 150°C. Tools capable of operation at >200°C are still experimental.

4.1.1.8 Site Selection Tasks

The tasks for the Site Selection research area support the objectives of both site selection and well construction.

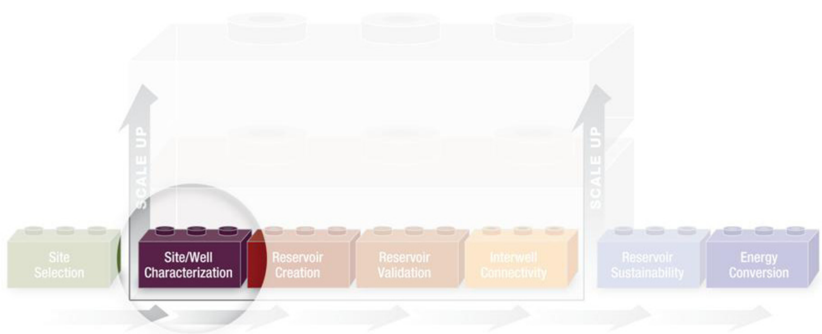
Site Characterization

Table 4.6. Site Characterization Tasks		
Number	Description	Barrier
1	Make available the required data and techniques to analyze the data.	A
2	Prioritize possible locations for commercial EGS based on geologic, topographic, infrastructure and other conditions.	A
3	Develop a working set of criteria for site selection that improves chance of success of EGS.	A
4	Develop effective Remote Sensing Assessment Techniques for pre-drilling site location.	B
5	Improve resolution of geophysical methods for the detection of fractures and water flow. Methods to be investigated include seismic (VSP, 3-D, high frequencies), electromagnetic (CSAMT), and electric (SP).	B
6	Improve accuracy and range to be able to remotely predict subsurface stress regime.	B

Well Construction

Table 4.7. Well Construction Tasks		
Number	Description	Barrier
1	Perform parametric study for well drilling and construction methodology.	C
2	Develop cost and performance evaluation of innovative drilling and completion well construction technologies for higher rate of penetration, improved reliability, and reduced downtime for maintenance to enable prioritization of future research (e.g., high-temperature MWD Diagnostics While Drilling (DWD) with polycrystalline diamond compact (PDC) drill bits, multilateral completions, underreaming, and spallation drilling).	C
3	Demonstrate advanced drilling system (e.g., DWD, PDC) in a variety of EGS conditions (e.g., rock types, depths, temperatures).	C
4	Develop cost and performance evaluation of advanced casing technologies to enable prioritization of future research (e.g., drilling with casing, expandable tubulars, low-clearance casing, and longer casing intervals).	C
5	Perform cost studies for drilling and identify cost-reduction strategies to meet commercial plant requirements.	C
6	Develop lower-cost depth coring.	C

4.1.2 Site/Well Characterization



4.1.2.1 Site/Well Characterization Goal

In the process of preparing a site for an EGS, it is necessary to create a detailed picture of the underlying hot rock system in order to accurately and optimally locate injection and production wells within the site. Better instrumentation and modeling software are needed for this application.

Goal 3: Develop improved tools for the characterization and modeling of the subsurface at EGS project sites.

Many reservoir characterization technologies already exist and are being used by the geothermal industry or by the oil and gas industry, but technical capabilities must be extended for EGS application.

4.1.2.2 Site/Well Characterization Barriers

Barrier D: **Characterization** – Subsurface environments in EGS regimes are inhospitable to existing downhole, in-situ characterization methods.

Barrier E: **Data Interpretation** – Inability to fully exploit data from current oil and gas logging routines for interpretation for EGS needs.

Barrier F: **Modeling** – Insufficient modeling and validation capabilities to effectively couple fluid flow, geochemistry, and thermal-mechanical phenomenon for 1) stimulation prediction, and 2) reservoir simulation.

4.1.2.3 Site/Well Characterization Background

Although many of the field measurements required to characterize the native formation conditions can be obtained commercially through oil and gas industry services firms, the field equipment, procedures, and data interpretation must be adapted to geothermal environments that differ significantly from typical oil and gas-producing reservoirs.

High temperature instrumentation for borehole imaging and other purposes is a key technology deficiency, as described in the Well Field Construction section. Some logging tools and sensors required for reservoir characterization tools are either unavailable or are not suitable for operation at temperatures greater than 150°C to 200°C. Some existing tools can perform for short periods, but for EGS use tools must be capable of collecting data for protracted periods (i.e., days to years) for both well stimulation and reservoir operation.

Structural Data: Knowledge of the structural geology of the EGS site and target formations is critical for modeling and designing a successful reservoir stimulation operation. Fracture mapping using geophysical well logs has relatively poor resolution. Equipment improvements and to measure rock surface area, rock volume in contact with circulating fluids, and other parameters required for accurate predictive models of reservoir performance and lifetime.

Subsurface EGS models will require joint interpretation of geological, geochemical, and geophysical data sets, which avoids the limitations of any individual data collection and interpretation method. Many earth science industries are investigating joint data set interpretations including the petroleum and mineral industries and the nuclear and chemical waste disposal industries. Increased computational power is allowing increasingly sophisticated manipulation and display of critical data in these applications and others.

Stress State: The in-situ stress state in the target EGS volume is critical in designing stimulation programs and predicting results. Tests used to determine stress states during and after drilling (e.g., detailed borehole geometry [breakout analysis] and mini-frac breakdown) are slow and costly, and must therefore be improved. As discussed in the well field construction section, reliable zonal isolation for high-temperature applications at high differential pressures is needed to conduct mini-fracs and other stress state diagnostics.

Active Seismic: Active seismic surveys are commonly used in the oil and gas industry to locate resources and to reveal subsurface structures favorable to the concentration of hydrocarbons. These methods are highly effective for detection of hydrocarbons, but have limitations in some common geothermal environments where the geologic structures are typically massive rather than stratified in nature. Geothermal structures are more complex than most oil and gas environments and have larger velocity and reversing velocity contrasts; both of these characteristics make seismic interpretation more difficult. Additionally, seismic studies in geothermal areas are generally hampered by low signal-to-noise ratios. Equipment positioning and signal interpretation must be improved to attain resolutions similar in quality to those attained in oil and gas surveys. Advanced seismic methods hold promise for fracture mapping, and the geothermal industry may benefit from increasing petroleum industry emphasis on the use of these methods in fractured environments.

Modeling: An EGS' reservoir size and productivity depend on: rock type; local stress field; pre-existing fractures; stimulation technique; reservoir depth; temperature; pressure; system flow impedance; water leakage; reservoir growth; geochemical reactions; and other variables. Modelers must know the rock properties of a site to design a successful stimulation operation.

Standard petroleum and hydrothermal reservoir engineering and modeling techniques must be modified to account for differences between EGS, petroleum and hydrothermal reservoirs. Capable, robust and reliable numerical models must be developed and verified to couple rock- and fluid-mechanics theory with the measured properties and structure of the rocks, enabling reliable prediction of stimulation results and identification of the best options for creating the EGS.

Stimulation Design: Stimulation design involves selecting target zones for stimulation as well as the rate, pressures, volumes of injectate, type(s) of stimulation fluids, and use of proppants. Field experience and data will provide vital to information for developing and revising the design tools required for commercial EGS development

The petroleum industry has demonstrated the ability to model and create hydraulic fractures in sedimentary environments. Likewise, the hazardous waste management industry has used models for the behavior of rock when fluids are injected. Adaptation of tools from the petroleum and hazardous waste management industries will accelerate for development of models for stimulation in EGS environments.

4.1.2.4 Site/Well Characterization Objectives

The objectives of the Reservoir Characterization research area address the issues of instrumentation environment and accuracy, and the use of this improved instrumentation to create better models of the underground environment. The emphasis is on providing hardened instrumentation capable of withstanding the extremely harsh thermal and chemical environments associated with EGS, with improved accuracy, especially in the case of in-situ stress regime measurement, which is crucial to the prediction of fracture propagation.

Table 4.8. Site/Well Characterization Objectives		
Number	Description	Barrier
1	By 2012, demonstrate downhole logging & monitoring instruments and sensor capabilities that can be employed at a depth of 350 Bar and operation temperatures of 250°C.	D
2	By 2015, demonstrate downhole logging & monitoring instruments and sensor capabilities that can be employed at a depth of 600 Bar and operation temperatures of 275°C.	D
3	By 2020, demonstrate downhole logging & monitoring instruments and sensor capabilities that can be employed at a depth of 1200 Bar and operation temperatures of 300°C.	D
4	By 2010, identify candidate oil and gas logging technologies to be used in EGS.	E
5	By 2015, test and adapt chosen candidate logging technologies to EGS applications.	E
6	By 2010, assess the current available models.	F
7	By 2012, perform comparison (inputs vs. outputs) of currently available models.	F
8	By 2013, develop technical criteria for adaptation of these models to EGS requirements.	F
9	By 2015, develop and apply newly developed models in EGS projects.	F

4.1.2.5 Site/Well Characterization Technical Approach

New and improved techniques will be used to characterize the target rock mass and design the stimulation plan. Near-term field projects will utilize existing wells at or near developed hydrothermal systems. Mid- to long-term field projects will begin outside or remote from existing, developed hydrothermal systems.

4.1.2.6 Site/Well Characterization Programmatic Status

Early seismic surveys in highly-faulted volcanic and igneous environments suffered from high noise levels, poor to incoherent reflections, and complex reflection environments. State-of-the-art surface (seismic reflection) and borehole seismic methods including vertical seismic profiling (VSP) have been evaluated and used to locate and quantify geothermal reservoir characteristics. The premise of this work was to determine if new developments in theory and modeling, as well as in data acquisition and processing, could result in a more detailed subsurface image.

Table 4.9. Site/Well Characterization Technology/Program Activities		
Task	Approach	Organization
Reservoir creation and management using stimulation prediction models	Develop and adapt coupled numerical models and software to accurately predict fracture growth and permeability development under stimulation	TBD
Stress determination, geothermometry, logging tools, log interpretation methods, numerical models of stimulation	Improve resource assessment techniques	TBD through future solicitations

4.1.2.7 Site/Well Characterization Technology Status

Logging and borehole imaging tools enable detailed characterization of lithology, fractures, stress field, and the status of well construction, a major source of risk in deeper wells. Borehole logging technology has largely been developed by the petroleum and water well industries, with some minor contribution from the minerals industries. As oil and gas wells are drilled into deeper and hotter rock, improved equipment is being developed to operate in these high-temperature, corrosive environments. While some logging tools are usable in geothermal conditions, wells often must be cooled prior to logging to avoid exceeding the instruments' temperature limitations. Logging techniques include: electrical and electromagnetic (EM) methods, seismic methods, radioactive methods,temperature, pressure, and fluid-flow velocity (spinner), as well as advanced logs such as the borehole televiewer, Formation Microscanner, and others.

SNL chose a precision pressure-temperature tool as one of its first projects in designing high-temperature logging devices. The tool has been commercialized by a geothermal service company, and has been a cornerstone of SNL's program for geothermal logging.

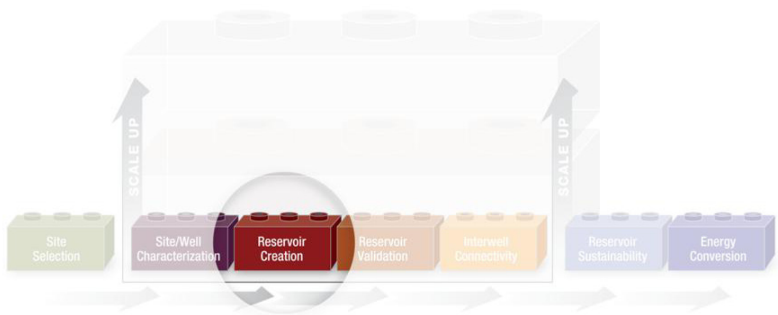
Table 4.10. Site/Well Characterization Technology Status Summary		
Barrier	Available Technologies (U.S and International)	Organization
Barrier D: Site/Well Characterization Subsurface environment in EGS regimes are inhospitable to current downhole sensors	High Temperature Logging Tools- Logging Tools (e.g., tools to measure downhole pressure, flow, temperature, image fractures)	Logging tools and sensors are available for operation up to about 150°C. Higher temperature versions of some tools are available but have limited lifetimes or require heat shielding.
		Unshielded prototypes for pressure and temperature are experimental.
Barrier E: Site Characterization Insufficient tool accuracy and range to obtain in-situ subsurface stress regimes	Perform stress measurements: Micro-fracs and borehole breakouts, core-based measurements	Suitable technology available for lower-temperature applications. Technology lacks zonal isolation capability. Routinely used in mineral exploration. Interpretive techniques for geothermal applications are still evolving.
	Characterize subsurface conditions: Core sampling and evaluation	
Barrier F: Modeling Insufficient understanding of the rock and fluid mechanics and geochemistry to validate model algorithms	Plan and design stimulation (e.g., zones, pressures, volumes, fluids, proppants)	Stimulation models for oil and gas exist, but stimulation modeling techniques for geothermal systems are not a mature technology (i.e., basic numerical models). Current models have not been effective in a geothermal environment.

4.1.2.8 Site/Well Characterization Tasks

The following tasks support the objectives of the Characterization research area.

Table 4.11. Reservoir Characterization Tasks		
Number	**Description**	**Barrier**
a	Develop high-temperature, high-pressure downhole instruments and sensors to monitor wellbore conditions such as fracture detection, temperature, pressure, flow rates, and seismic events.	D
b	Develop robust tools for making in-situ stress measurements at high temperatures and pressures for reservoir creation model input.	E
c	Write a report documenting candidate technologies.	E
d	Create database to document logging data and interpretations for future applications.	E
e	Gather and catalog data from field projects for continuous model validation.	F
f	On an ongoing basis, continually update and validate code with data as it is gathered from field projects.	F

4.1.3 Reservoir Creation



4.1.3.1 Reservoir Creation Goal

The greatest technical challenge and uncertainty in the EGS approach is the ability to create the required volume of fractured reservoir rock/heat exchange surface required for decades-long production at sufficiently high rates for commercial production. Because of the inherent thermal insulation capacity of rock (low thermal conductivity) the rate of replenishment of heat extracted by fluid production is exceedingly slow. Large surface areas for fluid/rock heat exchange and large volumes of fluid flow are required in the EGS reservoir to maintain temperature over time.

Goal 4: Develop the ability to create EGS reservoirs with the technical characteristics required for economic viability.

4.1.3.2 Reservoir Creation Barriers

Barrier G: **Reservoir Fracturing** – Stimulation technology and methodology used in the oil and gas industry has not sufficiently been demonstrated for EGS reservoir creation.

Barrier H: **EGS Well Zonal Isolatio**n – The capability has not been sufficiently demonstrated to isolate sections of the wellbore to: 1) enable stimulation; and 2) seal off unwanted flow regions in unknown EGS completion schemes and high-temperature (>200°C) environments.

4.1.3.3 Reservoir Creation Background

A key technical challenge in reservoir creation is to achieve sufficient productivity for commercial EGS energy generation (identified by the MIT report as 80 kg/sec of fluid production) while maintaining appropriate temperatures for at least six years. Important next steps will be to (1) create new, pervasive permeability rather than enlarging a few existing fractures, (2) avoid short circuits and repair them if they develop, (3) measure the fractured rock volume and water-accessible fracture area, and (4) maintain open fractures in a variety of stress regimes.

Research and field projects have demonstrated that reservoirs can be created, but the control required to create large volumes of fractured rock, free of short circuits, has not been thoroughly demonstrated. Key requirements include improved fracturing technology, rheologically controllable fracturing fluids, and high-temperature borehole packers for isolating fracture zones. Alternate technologies such as high-pressure gas fracturing (possibly using controlled-burn explosives) should be tested, and hydraulic fracturing techniques improved to provide fracturing methods for varying geological environments. Although large fractured volumes (several km3) have been created in experiments, circulating fluid through these full volumes has proven difficult.

Fracturing technology for sedimentary formations is highly advanced. The petroleum industry's state-of-the-art equipment creates fracture half-lengths of 200 to 400 feet or more. While a viable EGS heat exchanger will likely be created for use in sedimentary rocks using methods developed for stimulating petroleum wells, it will need to be demonstrated in the field with industry cooperation. Hydraulic fracturing has had mixed results in hydrothermal settings, in part due to inadequate characterization of the host rock (including the stress state and the location, direction, and permeability of pre-existing fractures). This shortfall results in inadequate data and modeling for effective fracture treatment design.

While it is possible to create or stimulate enough fractures to support high flow rates, targeting specific fractures is not yet possible. Once fractures have been created, hydraulic stimulation can be used to increase the length and complexity of the fracture system. Because developers who enhance well productivity work with service companies that view their efforts as proprietary, little data is available relating treatment design and geologic environment to well productivity improvement.

Tests used to determine stress states during and after drilling, such as detailed borehole geometry (breakout analysis), leak-off tests and mini-frac breakdown pressures are standard in the petroleum industry. The stress field can also be estimated from borehole elongation and regional stress field considerations. The usefulness of these techniques has not been validated in geothermal environments.

Proppants used by the oil and gas industry to keep fractures open have not yet been successful in geothermal settings. The temperature, stresses, corrosive brine chemistry and high-volume circulation in many potential EGS reservoirs would destroy the majority of the most widely used proppants. Research is needed to develop high-strength propping agents (such as advanced ceramics and coatings), and/or to develop compositions that will reduce the risk of rapid proppant dissolution. Temperature-hardened proppants may be required for EGS applications.

Zonal isolation is essential for many EGS reservoir development activities. Packers and other zonal isolation tools are required to eliminate fluid loss, to help identify and mitigate short circuiting of flow from injectors to producers, and to target individual fractures or fracture networks for testing and validating reservoir models. General-purpose open-hole packers do not exist for geothermal environments, with the primary barrier being the poor stability of elastomeric seals at high temperatures. Existing borehole packers are incapable of handling temperatures above 175 °C. Experimental packer systems have been developed for geothermal environments but they currently only operate at low pressure, they are not retrievable and they are not commercially available. Cased-hole isolation tools suitable for high-temperature environments are emerging, and these tools have the advantage of metal-to-metal seals.

4.1.3.4 Reservoir Creation Objectives

The following objectives represent important benchmarks in overcoming the technical obstacles to EGS commercialization imposed by the barriers described above.

Table 4.12. Reservoir Characterization Objectives		
Number	Description	Barrier
1	By 2011, set technical objectives for improvement of EGS reservoir stimulation.	G
2	By 2015, develop tools and techniques for the determination of fracture surface area, fracture spacing and rock volume in stimulated reservoirs.	G
3	By 2015, demonstrate the ability to consistently and predictably fracture a range of hard-rock lithologies and geological environment.	G
4	By 2015, develop improved-resolution stimulation monitoring tools, the images of which can be used to adjust stimulation real-time.	G
5	By 2012, demonstrate affordable, reliable, reusable borehole packers that can be employed at a differential pressure of 350 bar and operation temperatures of 250oC. (TBR)	H
6	By 2015, develop chemical or other treatment methods for well treatment to seal unwanted fractures.	H
7	By 2015, develop tools for mechanical sealing of wellbore skin (e.g. expandable liners) for sealing of unwanted fractures.	H
8	By 2015, demonstrate affordable, reliable, reusable borehole packers that can be employed at a differential pressure of 500 bar and operation temperatures of 275oC. (TBR)	H
9	By 2020, demonstrate affordable, reliable, reusable borehole packers that can be employed at a differential pressure of 750 bar and operation temperatures of 300oC. (TBR)	H

4.1.3.5 Reservoir Creation Technical Approach

New and improved techniques will be used to characterize the target rock mass and design the stimulation plan. Near-term field projects will utilize existing wells at or near developed hydrothermal systems. Mid- to long-term field projects will be outside of or remote from developed hydrothermal systems.

4.1.3.6 Reservoir Creation Programmatic Status

The industry has shouldered some of the early responsibility in this area. Some incipient efforts in Reservoir Creation are shown in the table below.

Table 4.13. Reservoir Creation Technology/Program Activities		
Task	Approach	Organization
Enhanced reservoir size and heat transfer capability	Establish the effectiveness of high-pressure gas, thermal methods, and chemical methods for stimulation	TBD
Learn in-situ stress, rock properties, and MEQ behaviors	Pre Stimulation and Recompletion activities	Industry

4.1.3.7 Reservoir Creation Technology Status

Projects underway in France and Australia currently define the state of the art in reservoir characterization technologies. The Soultz project collaboration began in 1987, between the European Union and the governments of France, Germany and Italy. The first phases of the project created a reservoir at 3,900 m in 165 °C rocks that produced 25 l/s of water at 140 °C at low injection pressure. In 1998, the production well was extended to 5,000 m, where a predicted rock temperature of 200 °C was verified. Hydraulic fracturing in 2000 produced a 1.1 km3 reservoir that has been stimulated to create a circulation loop. The next phase of development, to be carried out from 2005 to 2008, is designed to achieve 100 l/s production rates and drive a 1.6 MWe power plant. If this is successful, an expansion to 6 MWe is planned.

A second project, at Landau, Germany has leveraged the results of the Soultz project to create a small operating EGS. This project produces at a rate of 100 l/s due to the connection of the created reservoir with a pre-existing fracture system. Geodynamics Geothermal, a private sector developer, is undertaking a large-scale EGS project at Cooper Basin, Australia. Rock temperatures of 250 °C have been confirmed at 4,400 m depth. Horizontal fractures from hydraulic stimulation have created a horizontally-oriented underground heat exchanger more than nine times larger than originally projected. Overpressure in some wells may indicate a natural geothermal field capable of flowing under its own pressure.

Packers and other zonal isolation tools are required to eliminate fluid loss, to help identify year and mitigate short circuiting of flow from injectors to producers, and to target individual fractures or fracture networks for testing and validating reservoir models. General-purpose open-hole packers do not exist for geothermal environments, with the primary barrier being the poor stability of elastomeric seals at high temperatures. Existing borehole packers are incapable of handling temperatures above 175 °C. Experimental packer systems have been developed for geothermal environments but they currently only operate at low pressure, they are not retrievable and are not commercially available. Cased-hole isolation tools suitable for high-temperature environments are emerging, and these tools have the advantage of metal-to-metal seals.

Table 4.14. Reservoir Creation Technology Status Summary		
Barrier	**Available Technologies (U.S and International)**	**Technology Status**
Barrier G: Reservoir Creation Fracture technology used in the oil & gas industry has not sufficiently been demonstrated for EGS reservoir creation.	Scaling, dissolution, and permeability control	Scaling and dissolution control technologies are available but may not be adequate for EGS conditions.
	Effective real-time decision-making capability for stimulation: Oil and gas industry stimulation modeling and control technology	The oil industry has modeling and control capability for petroleum environments, but experience in geothermal systems is lacking.
	Keep flow paths open: Proppants for both near well bore and far field use	Proppants are typically used in oil & gas stimulations. Temperature-hardened proppants have not been evaluated in geothermal environments.
	Create/enhance flow paths: Hydraulic stimulation;	Geothermal stimulations for EGS use water or water weighted with dense chemicals such as barium sulfate salts. Chemical and other stimulation methods have been used in hydrothermal systems.
	Chemical stimulation; and Rate Controlled explosives	
	Mitigate reservoir- Short Circuiting to prevent pressure drop and fluid loss	Cements are routinely used in the hydrothermal industry for lost circulation.
		Coupled modeling tools and simulators are needed.
Barrier H: EGS Well Zonal Isolation The capability has not been sufficiently demonstrated to isolate sections of the wellbore to: 1) enable stimulation; and 2) seal off unwanted flow regions.	Zonal isolation for stimulation: Stimulation packers, slotted liners	Packers that can operate at stimulation pressures and temperatures are not available. Slotted liners and related technologies may not perform adequately for EGS
		Retrievable packers for high pressure operations in high temperature (>150°C for extended operation) wells are not available.
	Open and cased hole packers and expandable tubulars and screens	Elastomer and cement packers are not available for high-temperature applications.
		Experimental versions of low-pressure packers developed for geothermal applications are not generally available.

4.1.3.8 Reservoir Creation Tasks

The following tasks will be undertaken in support of the Reservoir Creation research area.

Table 4.15. Reservoir Characterization Tasks		
Number	Description	Barrier
1	Develop stable (temperature-hardened and chemical-hardened) proppants for enhancing permeability and water flow, if necessary.	G
2	Establish the effectiveness of high-pressure gas generation, thermal methods, and chemical methods as compared to the baseline of hydrofracturing using field test data.	G
3	Test candidate methods for creating an EGS reservoir.	G
4	Test candidate techniques for fracturing in the subsurface.	G
5	Develop and test additives for controlling the attributes of fracturing fluids.	G
6	Develop and test methods of controlling short-circuiting and fluid loss.	G
7	Conduct field demonstrations to determine best stimulation techniques for various geological environments.	G
8	Demonstrate affordable, reliable, reusable borehole packers, especially open-hole packers applicable to EGS environments.	H

4.1.4 Reservoir Validation

4.1.4.1 Reservoir Validation Goal

Goal 5: Demonstrate ability to accurately describe the physical characteristics of created EGS reservoirs.

After the fracturing of a potential EGS resource has been performed, it is essential to establish that the desired result has been achieved and is replicable.

4.1.4.2 Reservoir Validation Barrier

Barrier I: **Images of Fractures After Stimulation** – Inability to characterize the physical parameters of potential EGS reservoirs after stimulation.

4.1.4.3 Reservoir Validation Background

Because of the small number of successfully stimulated resources, the reliability of the stimulation process has not been firmly established. After a potential EGS reservoir has been stimulated, the subsurface environment has necessarily been altered, in many cases significantly. The accurate prediction of the stimulation results can validate the process used to create the reservoir. These predictions can be verified with improved fracture imaging.

Reservoir validation will require many of the same methods and tools described in RD&D Sections 1, 2 and 3.

4.1.4.4 Reservoir Validation Objectives

The following objectives support the goal of Reservoir Validation.

Table 4.16. Reservoir Validation Objectives		
Number	Description	Barrier
1	By 2010, characterize needs for quantification of fracture detection and water flow.	I
2	By 2010, set technical objectives for improvement of geophysical methods for the downhole detection of fractures and water flow.	I

4.1.4.5 Reservoir Validation Technical Approach

New and improved techniques will be used to characterize the target rock mass and design the stimulation plan. Near-term field projects will utilize existing wells at or near developed hydrothermal systems. Mid- to long-term field projects will begin outside or remote from existing, developed hydrothermal systems.

4.1.4.6 Reservoir Validation Programmatic Status

Some early work in Reservoir Validation has begun, as shown in the table below.

Table 4.17. Reservoir Validation Technology/Program Activities		
Task	Approach	Organization
Identification of flow paths during and post-stimulation	Improve resolution of geophysical methods by (TBD) percent for detection of fractures and fluid flow	LBNL and others TBD
Improve temperature and chemical sensitivity of down-hole sensors	TBD	TBD

4.1.4.7 Reservoir Validation Technology Status

Streaming Potential (SP) is a method for identifying flow paths through rock based on the detection of charge imbalances at the interface of fluid and rock that are generated by flow of electrolytic fluid. SP monitoring has the potential to be a valuable tool for geothermal water flow characterization. SP uses electrodes connected to a data logger to make low-cost remote measurements of water flow. Laboratory testing suggests that SP combined with interpretation and modeling may be able to effectively map fluid flow in three dimensions throughout a geothermal reservoir.

Passive Microseismic: Passive seismic techniques enable the monitoring of reservoir stimulation through the analysis of induced microseismic events. Although the petroleum industry is advancing the state-of-the-art active seismic technologies, passive seismic technologies are not receiving the same level of research despite the potential value as an essential tool for tracking and evaluation of results from reservoir stimulation. Microseismic monitoring is a promising technique, but the relationship between the MEQ cloud and the created fractures is not fully understood. New and improved real-time methods are needed to monitor fracturing progress and to indicate when and how to modify the stimulation program. Increased resolution and accuracy of passive seismic mapping techniques will require downhole tools that can withstand the temperatures associated with EGS. While remote sensing of fracture growth via microseismic analysis indicates possible fluid flow paths, the ability to directly map the flow through the created reservoir does not currently exist.

The resolution of remote sensing techniques such as SP can be improved by joint interpretation (joint inversion) with other data sets including geological data (e.g., rock type, structures such as faults or contacts, hydrothermal alteration), geochemical data (e.g., fluid chemistry, soil geochemistry) and geophysical data (e.g., electrical and electromagnetic survey data, seismic data, magnetic data, gravity data, well logging data).

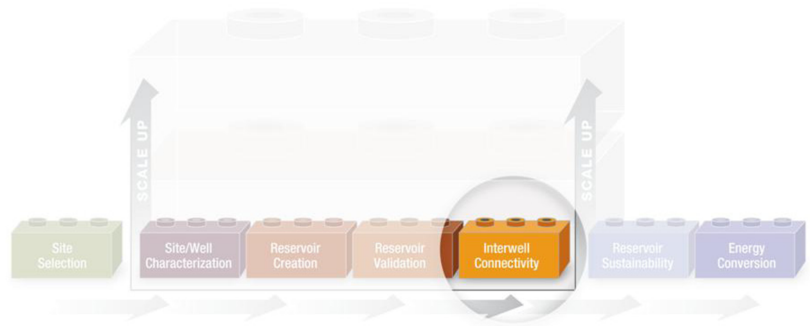
Table 4.18. Reservoir Validation Technology Status Summary		
Barrier	**Available Technologies (U.S. and International)**	**Technology Status**
Barrier I: Imaging of Fractures After Stimulation Inability to characterize the physical parameters of potential EGS reservoirs after stimulation, providing sufficient data to enable successful and replicable EGS development	Passive Microseismic techniques	Currently the best method for monitoring the reservoir creation. Used at hot dry rock and hot fractured rock field sites in the past.
	Identification of flow paths during and post-stimulation-Remote Sensing techniques (e.g., Microseismicity, gravimetry, SP, tiltmeter arrays)	The utility of existing techniques for tracking fluid flow has not been demonstrated. Microseismic techniques are not hardened for downhole use. Suitable downhole instrumentation for standard flow tests is available up to 200ºC.
	Imaging and mapping of fractures: Microseismicity, gravimetry, self potential (SP), tiltmeter arrays	Surface microseismic and gravity tools are adequate for most purposes, but the resolution may be insufficient for EGS. Self-potential is not proven for this purpose. Tiltmeter results are difficult to interpret in zones of multiple fractures.
	Conduct flow tests: Pressure, temperature, and fluid-flow measurement tools	Suitable downhole instrumentation for standard flow tests available up to 200ºC. Some existing tools can perform for short periods, but for EGS use they must be capable of collecting data for protracted periods.
	Logging and borehole imaging tools to enable detailed characterization of wells-Logging Tools	Logging techniques include electrical and electromagnetic, seismic methods, radioactive methods, temperature, pressure, and fluid-flow velocity, as well as advanced logs such as the borehole televiewer, Formation Microscanner, and others. As oil and gas wells are drilled into deeper and hotter rock, improved equipment is being developed to operate in these high-temperature, corrosive environments.

4.1.4.8 Reservoir Validation Tasks

The following tasks support the Reservoir Validation research area.

Table 4.19. Reservoir Validation Tasks		
Number	Description	Barrier
1	Perform technical assessment and needs quantification of fracture detection and water flow.	I
2	Improve resolution of geophysical methods for the downhole detection of fractures and water flow.	I

4.1.5 Interwell Connectivity



4.1.5.1 Interwell Connectivity Goal

Goal 6: Demonstrate ability to accurately detect reservoir characteristics including fluid pathways, dynamics, residence time, etc.

The tracing of the fluid pathway is essential in the determination of important heat transfer surface area, permeability, pressure drop, and fluid residence time in geothermal reservoirs, all of which enable the construction of accurate predictive models of reservoir behavior.

4.1.5.2 Interwell Connectivity Barriers

Barrier J: **Tracers** – Inadequate tracers and/or tracer methodology to accurately define the subsurface system of fractures and mapping of fluid flow.

Barrier K: **Downhole Pumps** – Inadequate pump technology available for EGS downhole conditions of temperature, depth, pressure, and pump diameter-vs.-casing-diameter.

4.1.5.3 Interwell Connectivity Background

Tracers do not exist that can reliably measure and/or monitor the surface area responsible for rock-fluid heat and mass exchange, thereby allowing for the quantification and prediction of EGS heat extraction efficiencies. Pumps capable of sustaining the necessary flow rate through the reservoir, given the temperature of the working fluid and the small diameters of the production wells, have not yet been developed.

4.1.5.4 Interwell Connectivity Objectives

The following objectives represent important benchmarks in overcoming the technical obstacles to EGS commercialization imposed by the barriers described above.

Table 4.20. Interwell Connectivity Objectives

Number	Description	Barrier
1	By 2012, demonstrate tracer technologies at operation temperatures of 250°C.	J
2	By 2015, demonstrate tracer technologies at operation temperatures of 275°C.	J
3	By 2020, demonstrate tracer technologies at operation temperatures of 300°C.	J
4	By 2010, validate the capabilities and limitations of current pump technologies.	K
5	By 2012, improve the performance of downhole pumps, especially ESPs, to operate at temperatures of 250°C, mass flow rates of up to 80 kg/s, setting depth as great as 1 km, for wellbore diameters of 6 5/8” to 10 5/8”, and operating at pressures up to 200 bar.	K
6	By 2015, improve the performance of downhole pumps, especially ESPs, to operate at temperatures of 275°C, mass flow rates of up to 80 kg/s, setting depth as great as 2 km, for wellbore diameters of 6 5/8” to 10 5/8”, and operating at pressures up to 200 bar.	K
7	By 2020, improve the performance of downhole pumps, especially ESPs, to operate at temperatures of 300°C, mass flow rates of up to 80 kg/s, setting depth as great as 3 km, for wellbore diameters of 6 5/8” to 10 5/8”, and operating at pressures up to 200 bar.	K

4.1.5.5 Interwell Connectivity Technical Approach

New and improved tracers will be developed to better determine the fluid flow pathways. Improved downhole pumps will be developed to withstand EGS environments while providing EGS- quality flow.

4.1.5.6 Interwell Connectivity Programmatic Status

Some early work in Interwell Connectivity has begun, as shown in the table below.

Table 4.21. Interwell Connectivity Technology/Program Activities		
Task	Approach	Organization
Tracers and tracer interpretation	Develop improved tracers and interpretation methods to define reservoir surface area and validate reservoir models	LBNL and others TBD

4.1.5.7 Interwell Connectivity Technology Status

Tracer compounds can be divided into two groups: chemically inert and physio-chemically reactive. Inert tracers are useful in providing model-independent information, such as the degree of well-to-well connectivity, dispersive characteristics and fracture volume, and tracking of the thermal front when used in conjunction with reservoir simulation. Temperature-sensitive chemically-reacting/adsorbing tracers can provide insight into fracture surface area and heat extraction efficiency along a flow path and track the thermal front, leading to construction of detailed reservoir models with predictive capabilities.

Tracers are invaluable tools for detailed reservoir studies. Theoretical work has shown that tracer tests can be analyzed to quantify numerous reservoir variables that are of value for modeling including sweep efficiency, total pore volume, flow geometry, and others; however, only limited field work has been done to demonstrate the effectiveness of quantitative tracer analysis. Although DOE-sponsored research has significantly advanced the sophistication and use of tracers for characterizing hydrothermal systems, development of new “smart” tracers is warranted.

EGS reservoir are expected to be hot and high in pressure; downhole pumps capable of withstanding EGS conditions while sustaining sufficient EGS flow rates do not yet exist.

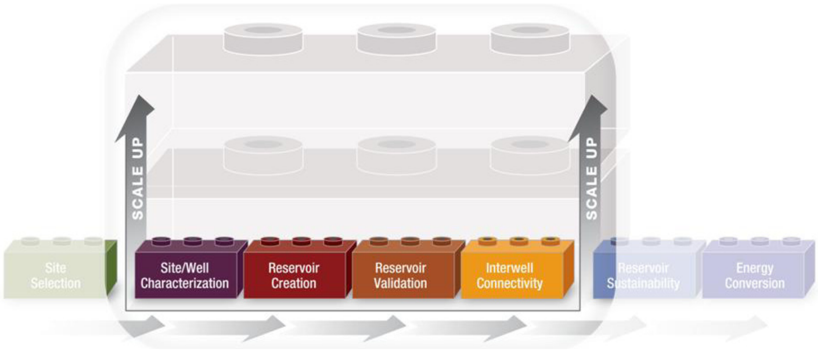
Table 4.22. Interwell Connectivity Technology Status Summary		
Barrier	**Available Technologies (U.S. and International)**	**Technology Status**
Barrier J: Tracers Inadequate tracers and/or tracer methodology to accurately define subsurface system of fractures and mapping of fluid flow	Development of new "Smart" Tracers	Tracer tests are an established method of validating reservoir models, but "Smart" tracers needed for EGS have not been developed.
Barrier K: Downhole Pumps Inadequate pump technology available for downhole chemistry, depth, pressure, and volume-vs-casing-diameter needed	TBP	TBP

4.1.5.8 Interwell Connectivity Tasks

The following tasks support the Reservoir Validation research area.

Table 4.23. Interwell Connectivity Tasks		
Number	**Description**	**Barrier**
a	Perform technical assessment and needs quantification of tracer and tracer interpretation technology.	J
b	Develop improved tracers and tracer interpretation methods to define heat exchanger surface area (for thermal drawdown) and validate the reservoir model.	J
c	Improve the performance of downhole electric submersible pumps to operate at higher temperatures and deeper setting depths.	K
d	Initiate a program to develop improved downhole pumping technologies for deep, high-temperature meter wells, and the conversion of large pumps to DC operation.	K
e	Improve pump and motor seals to withstand harsh downhole chemical environments.	K

4.1.6 Reservoir Scale Up



4.1.6.1 Reservoir Scale Up Goal

Goal 7: Develop technologies and methods for achieving low-cost scalability of EGS.

Since no commercial-scale EGS have been deployed in the US, it is unknown how best to expand an EGS wellfield to optimally utilize the potential resource.

4.1.6.2 Reservoir Scale Up Barrier

Barrier L: **Well Field Design** – Inability to assess and select the most efficient well-field design.

While some schemes for drilling new wells in a hydrothermal field have been developed, it is not known to what degree these can be applied to EGS because of temperature profiles, variable lithology and depth including optimization of parameters such as well diameter, spacing, multiple small wells vs. fewer large wells, etc.

4.1.6.3 Reservoir Scale Up Objectives

The following objectives are associated with Barrier L.

Table 4.24. Reservoir Scale-up Objectives		
Number	Description	Barrier
1	By 2010, understand current standard (lessons learned from Soultz and Cooper Basin) for well layout and use of sidetracks for efficient EGS reservoir systems.	L
2	By 2012, develop methods to integrate well development schemes with overarching needs of reservoir development.	L

4.1.6.4 Reservoir Scale Up Technical Approach

New and improved procedures will be developed to better determine the best layout of an EGS wellfield for the generalized EGS case.

4.1.6.5 Reservoir Scale Up Programmatic Status

TBD.

Table 4.25. Reservoir Scale-Up Technology/Program Activities		
Task	Approach	Organization
Assess the most effective use of wells and sidetracks	TBP	TBP

4.1.6.6 Reservoir Scale Up Technology Status

TBD

Table 4.26. Reservoir Scale Up Technology Status Summary		
Barrier	Available Technologies (U.S. and International)	Technology Status
Barrier L: Inability to assess the most effective use of wells and sidetracks	Design field expansion-monitoring & modeling of reservoir evolution	Existing reservoir simulation models are not fully coupled to enable planning of field expansion. Sufficient data to validate models is not available.
	Validate reservoir model using field data- monitoring & modeling of reservoir evolution	Few monitoring tools and sensors (e.g., tools to measure pressure, flow, temperature, and seismicity) can operate at high temperature for long periods. A temperature sensor is available, but it must be hardened for geothermal conditions.

4.1.6.7 Reservoir Scale Up Tasks

The following tasks supports the Reservoir Scale-up research area.

Table 4.27. Reservoir Scale-up Task		
Number	Description	Barrier
1	Conduct parametric studies for better understanding of interaction between various well-field designs and the stimulated reservoir.	L
2	Optimize methodology to economically exploit EGS resources using the most efficient well-field design.	L
3	Investigate cost trade-off between increased power plant efficiency vs. increased well productivity.	L
4	Understand well productivity index.	L

4.1.7 Reservoir Sustainability

4.1.7.1 Reservoir Sustainability Goal

Goal 8: Develop the ability to manage EGS reservoirs for maintenance of reservoir lifetime and productivity

The ability to manage an EGS resource over time is crucial to creating an economically feasible energy source from EGS.

4.1.7.2 Reservoir Sustainability Barrier

Barrier M: **Long-Term Sustainability** – Unknown ability to manage long-term rock temperature, transmission, fluid quantity and fluid chemistry.

4.1.7.3 Reservoir Sustainability Background

The most critical aspects of EGS sustainability depend on achieving the same general operating parameters as commercial hydrothermal systems. A good hydrothermal well yields about 35 MWt, which can be used to generate about 5 MWe at an energy conversion efficiency of 14 percent. An average hydrothermal well must produce for seven years or more to permit recovery of the capital investment. The operating time of a well in an EGS must be at least as long given the added cost of drilling and fracturing the reservoir.

Corrosion and Scaling: High temperatures and fluid chemistry and pH make corrosion and scaling a major challenge. Improved anti-corrosion and anti-scaling fluid management are difficult to develop at reasonable costs.

4.1.7.4 Reservoir Sustainability Objectives

Long-term economic operation will require systematic management of the EGS reservoir. Technologies are required to mitigate problems that are expected to arise in the course of reservoir operation. The following objectives support the stated goal for reservoir sustainability:

Table 4.28. Reservoir Sustainability Objectives		
Number	**Description**	**Barrier**
1	By 2012, re-evaluate hydrothermal technical objectives for adaptation to EGS reservoir sustainability.	M
2	By 2012, complete feasibility studies of utilizing various working fluids.	M
3	By 2015, understand current standard (lessons learned from Soultz and Cooper Basin) for reservoir sustainability.	M

4.1.7.5 Reservoir Sustainability Technical Approach

The focus of the Reservoir Operations and Maintenance program element is to maintain the technical and economic performance of the EGS reservoir through design life. Applicable essential technologies for reservoir maintenance exist and are being used by the geothermal industry or by the oil and gas industry, but have not been tested under EGS conditions.

4.1.7.6 Reservoir Sustainability Programmatic Status

Work to date in the Reservoir Sustainability research area has been performed at LBNL and has focused on improving understanding of rock-fluid geochemistry for scale and dissolution prediction and maintaining fluid flow and reservoir lifetime.

Table 4.29 Reservoir Sustainability Technology/Program Activities		
Task	**Approach**	**Organization**
Stimulation and management of created reservoir	Improve understanding of rock-fluid geochemistry for scale and dissolution prediction	LBNL and others TBD
	Improve stress measurement technology for reservoir creation at a depth of 3 km.	
	Develop temperature-hardened proppants and emplacement technology	
Maintaining fluid flow and reservoir lifetime	Improve understanding of rock-fluid geochemistry for scale and dissolution prediction	LBNL

4.1.7.7 Reservoir Sustainability Technology Status

Reservoir operation and management requires detailed knowledge of the rock and geometric properties of the circulation system. Wells must access the entire reservoir volume and create an efficient heat-mining system. Geophysical techniques must be able to map the reservoir in three dimensions and monitor changes with time. Numerical models of reservoir performance are needed that account for hydraulic, thermal and chemical properties and changes, and that model the fracture-dominated EGS reservoir environment. The combined use of chemical tracers, natural-fluid tracers, microseismic monitoring, active seismic surveys, and advanced forms of electrical geophysical methods have shown potential for determining heat exchange area and the useful volume of fractured rock, monitoring changes with time, detecting thermal drawdown before it effects production wells, and for targeting new production and injection wells.

On a short-term basis, downhole tools can measure temperature, pressure, flow and natural-gamma emissions; however, these instruments cannot be used for long-term monitoring because of temperature limitations, as noted previously. MEQ monitoring tools are limited to 120°C. Downhole tools must be developed to withstand temperatures above 200°C for extended periods. Temperature-hardened tools for real-time down-hole monitoring of temperature, pressure and flow along with in-stream surface monitoring of fluid chemistry would significantly enhance the ability to track the hydrologic and thermal evolution of the reservoir, monitor rock-fluid interactions and provide the appropriate field data for validating and updating reservoir models and simulators. Tools for logging and recording pressures and temperatures during testing are needed for long-term, high-temperature deployment. Surface and down-hole geophysical, seismic, electrical, geochemical, and other techniques must be adapted for reservoir monitoring.

Understanding and forecasting reservoir evolution is crucial for reservoir operation and management. After stimulation, the reservoir expands as the rock cools and shrinks, transferring mechanical load to adjacent rock and propagating fractures. Fracture growth is affected by the local and regional stress regimes, so growth can be managed by controlling injection and production well pressures. As the local stress is relieved due to thermal and pressure gradients, the reservoir grows and the system permeability increases. Once the desired size is achieved, the pressure can be adjusted to prevent further growth and reduce fluid losses.

Reservoir management and operation relies heavily on models and simulators that can accurately predict reservoir behavior. For optimum EGS operation, fully coupled Hydrologic-Thermal-Mechanical-Chemical (H-T-M-C) models and simulators will be necessary to predict fluid flow, heat extraction, temperature drawdown, rock-mechanical processes, and chemical processes that will have either beneficial or deleterious impacts on reservoir performance and longevity.

Increased permeability is a primary requirement for improving economics, but the creation of high-flow channels in the rock (short circuits) that lead to cooling of the reservoir must be avoided. Reservoir flow short-circuiting is not well understood, and techniques for sealing short-circuit pathways are not available for use in geothermal systems. There are no methods to measure short-circuiting directly, although tracer testing can help determine its magnitude.

Additionally, new technologies for control of fluid flow between injection and production wells are required to mitigate short circuiting. Rheologically controllable fluids hold potential for repairing short circuits, directing fluids to specified parts of the reservoir, and preventing excessive water loss. The temperature limit for fluid additives that control rheology is around 175°C, well below the target of 200°C. Industry has revived research on extending the temperature range for fluid additives as production of higher-temperature oil and gas fields has become economic due to increased oil prices.

Operation of an EGS reservoir will require injection of fluids that are not at equilibrium with the reservoir rock mass. As fluid flows through a geothermal reservoir, the chemistry of the reservoir is affected by fluid flow, reinjection of fluid with different chemistry than the original reservoir fluid, and temperature changes. These changes in chemistry lead to variations in the dissolution and precipitation of minerals in the system. Such mineralogic changes may affect the permeability of the system.

Rock/water interactions are likely to have a significant impact on the evolution of the reservoir. Although understanding of the chemistry of rock/water systems is improving, long-term predictive models are still under development. Better technology is needed for control of scale formation and rock dissolution. As a result, scaling and/or dissolution will likely occur in the wellbore or the reservoir. Treatments available today may not be adequate for long-term operation.

The chemical and transport processes that influence the creation and maintenance of permeability in typical geothermal rock types have not yet been determined. Accumulation of deposits in geothermal wells, caused by the dissolution and redeposition of soluble chemicals, gradually reduces production by narrowing and eventually blocking flow paths, including the wellbore. Better methods are required for controlling scaling and dissolution of rock. Silica behavior at high temperature and pressure is not well understood.

Creating and operating a reservoir will result in some induced seismicity and perhaps some degree of subsidence. Experience at The Geysers and Soultz, as well as numerous other sites, has shown a correlation between injection and induced seismicity. Geothermal energy production is occasionally associated with seismic events large enough to be felt by people nearby. Repeated seismicity may cause structural damage to buildings and public annoyance. Induced seismicity has the potential to halt if not end a project, as demonstrated in Soultz, France, and Basel, Switzerland.

Studies of induced seismicity, including one released under the auspices of the International Energy Agency, conclude that damaging earthquakes as a result of EGS reservoir operation are unlikely. The initial impact in the United States is believed to be low, since many candidate sites for early development are in unpopulated areas. Unfortunately the current state of knowledge does not point to technological solutions. Protocols for operation of EGS facilities to manage induced seismicity have been proposed, but have not yet been adopted or even proven effective.

Controlling the pressure regime can control reservoir fluid movement. Artificial lift (pumping) in production wells increases the pressure drop across the system without increasing injection pressures. High injection pressures may open undesirable fractures and allow short circuits. High-pressure pumping also adds to energy consumption. Pumping of production wells to decrease pressures may prevent microseismicity.

An ideal EGS system will have little or no water loss. Water losses must be minimized because of the negative implications of excessive parasitic pumping power, and because makeup water is cooler than re-circulated water, hastening cooling. Methods are needed to control water loss in EGS by proper injection- and production-well siting and pressure-regime control, as water cost and availability particularly in the western United States, can be a roadblock to development.

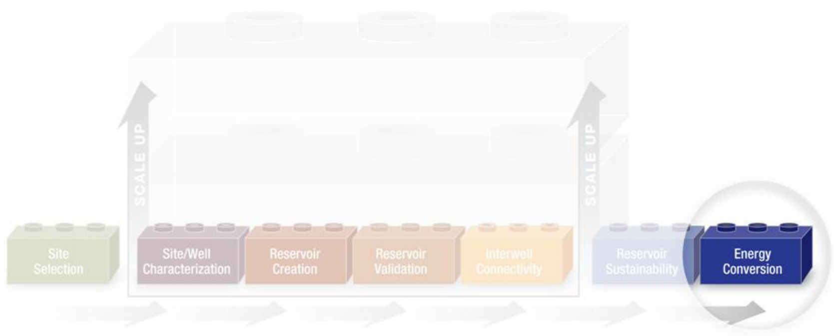
Table 4.30. Reservoir Sustainability Technology Status Summary		
Barrier	**Available Technologies (U.S. and International)**	**Technology Status**
Barrier M: Long-Term Sustainability Unknown ability to manage long-term rock temperature, fluid quantity and fluid chemistry	Maintain reservoir and track reservoir evolution- long-term monitoring	Monitoring tools and sensors (e.g., tools to measure pressure, flow, temperature, and seismicity) are available for sustained operation up to about 150°C. Downhole monitoring tools capable of sustained operation at >200°C do not exist.
	Monitor rock/fluid interactions- monitoring & modeling of reservoir evolution	Geochemical analytical techniques are understood for a large subset of relevant chemicals, but real-time detection technology has limited scope and poor accuracy.
		Geochemical models lack confirmatory field data.
	Manage induced seismicity	Operation protocols that limit injection/production pressures are considered a useful management tool. Rock mechanics models are available, but cannot predict seismicity.
	Managing system geochemical effects	Chemical management (e.g., additives for pH control) and scale control technologies are used in the hydrothermal industry to mitigate well bore and known geothermal resource scaling. Technologies for hydrothermal systems may not be as effective for EGS which will operate in chemical disequilibrium.
	Keep flow paths open- power and flow management	Proppants (for both near well bore and far field use, scaling, dissolution, and permeability control) are typically used in oil & gas stimulations. Temperature-hardened proppants have not been evaluated in geothermal environments.
		Scaling and dissolution control technologies are available, but may not be adequate for EGS conditions.
	Water loss minimization- due to parasitic pumping power, reservoir water cooling and water scarcity in western United States	Methods are needed to control water loss in EGS by proper injection- and production-well siting and pressure-regime control.

4.1.7.8 Reservoir Sustainability Tasks

The following tasks support the goal of Reservoir Sustainability.

Table 4.31. Reservoir Sustainability Tasks		
Number	Description	Barrier
1	Define processes and surface equipment to manage fluid chemistry.	M
2	Develop commercial-scale technology to minimize water loss per water circulation cycle over the lifetime of the well.	M

4.1.8 Surface Facility (Energy Conversion)



4.1.8.1 Energy Conversion Goal

Goal 9: Develop low-cost, high-efficiency energy conversion technologies for EGS.

Economically viable energy conversion from EGS will require total project minimization. While performance improvements to the energy conversion system and its components will decrease the contribution of the wellfield and EGS reservoir to the energy conversion cost, it is probable that these improvements will also increase the energy conversion system contribution to generation cost. For generation to be economically feasible, it is imperative that increases in the cost of more efficient energy conversion system be minimized.

Research to utilize the energy produced from EGS resources will focus on the generation of electrical power. Given the likelihood that wells for EGS will be deeper than conventional hydrothermal wells and need deeper production pump setting depths, the non-power plant costs (both in terms of capital dollars and parasitic power) will probably be significantly higher for an EGS resource than for an equivalent hydrothermal resource. If so, in order for power production from EGS to become economically feasible, it will be necessary to develop more efficient energy conversion systems that maximize the power generated from the produced fluids.

4.1.8.2 Energy Conversion Barrier

Barrier N: **Energy Conversion at Low Temperature** – Inability to lower the temperature conditions under which EGS power generation is commercially viable.

Barrier O: **Chemical Conditions** – Insufficient understanding of effects of high temperature fluid chemistry from EGS resources on EGS power systems.

Viable energy conversion from EGS resources will require energy conversion system characteristics not found in commercial technologies used with hydrothermal resources. Requirements include:

- Energy conversion systems are needed that increase the amount of power that can be produced from a given geothermal fluid flow.
- In order to sustain the economic life of the EGS resource, the operation of the energy conversion system must be integrated into the reservoir management. This will require energy conversion systems that have more operational flexibility than existing commercial hydrothermal plants.
- Issues related to water availability may preclude the use of evaporative heat rejection systems in EGS plants as in many operating hydrothermal systems. Improvements to sensible heat rejection technologies will improve plant performance and lower generation costs.
- Specific issues regarding both the scaling and corrosion potential of fluids produced from EGS resources will be addressed subsequent to the initial field testing. Because of their potential adverse impact, new treatment technologies and/or materials of construction may be required.

4.1.8.3 Energy Conversion Objectives

The following objectives support Goal 9.

Table 4.32. Energy Conversion Objectives

Number	Description	Barrier
1	By 2009, complete baseline technical assessment of existing energy conversion technology.	N
2	By 2012, determine energy conversion technology requirements for commercial viability of low temperature (<150°C) EGS resources in various geologic settings.	N
3	By 2015, demonstrate energy conversion technology that can economically be employed at temperatures of 150°C.	N
4	By 2012, perform assessment of severity of P-T and chemistry effects on energy conversion.	O

4.1.8.4 Energy Conversion Technical Approach

Existing energy conversion technologies should be adequate for the demonstration of the technical feasibility of producing power from an EGS resource. As such, research to improve energy conversion system technologies will have a lower priority in the near-term, but will have increasing importance once research has validated the feasibility of creating an EGS reservoir and extracting energy from that resource. A rigorous energy conversion technology gap assessment with estimated development timeline is important for synchronizing R&D efforts with future field demonstration and commercialization efforts.

In Fiscal Year 2009, the Program will evaluate the current state of energy conversion technology and assess R&D requirements in this area to support the Program's EGS development goals. The objectives of this effort are (1) to provide a thorough assessment of the technologies needed for EGS energy conversion surface facilities and the improvement of EGS energy conversion efficiency and economics and (2) to evaluate the ability of current technologies to meet those needs with the primary purpose of identifying gaps in technology that must be addressed for long-term EGS viability. This analysis will draw from the experience of project personnel, past DOE-sponsored assessments, existing literature, and interviews with geothermal and other industry professionals. It will provide baseline specifications of future EGS surface plants, evaluate the ability of current technologies to meet envisioned energy conversion targets of future EGS, delineate gaps in current capabilities, and estimate the timeline of the R&D effort needed to close defined gaps. The intent is to minimize anecdotal assessments of technology suitability and provide a more rigorous assessment of improvements needed for EGS development. In parallel to this initial assessment, a workshop will be held with participants from government, industry, academia, and the national laboratories. A report of the energy conversion assessment and workshop will be prepared, and results will inform the Program's ongoing R&D planning and prioritization.

Research efforts will focus on more efficient energy conversion systems. In the near-term, these efforts will build upon the 30-plus years of energy conversion system R&D, as well as the technology advances that the geothermal industry has made and incorporated into commercial hydrothermal plants. This prior work will provide the basis for the specification of the energy conversion systems used in the initial EGS plants to be built. More innovation will be incorporated into each subsequent plant design and construction. Information provided by the initial technology demonstrations will provide information needed to improve the plant design and performance, including the corrosion and scaling potentials of produced fluids, temperature/flow decline rates, and the non-power plant costs.

Using CO2 instead of water as a heat exchanging fluid for EGS offers several benefits. At the temperature and pressure conditions expected for EGS, CO2 is a supercritical fluid with characteristics that make it a very effective medium for heat transmission. Supercritical CO2 will have exceptional mobility vs. liquids in closely spaced, finely fractured EGS reservoirs. Some of the problems of water-based systems can be avoided because CO2 is not a strong solvent for rock minerals, nor is it corrosive to metals. Thus some of the problems of water-based systems can be avoided. CO2 -based EGS would also avoid the heat losses associated with a binary system. In addition, since water is a scarce and valuable commodity in many areas, CO2 -based EGS might provide an economic alternative as the working fluid.

As information is gleaned from the initial demonstration projects, more specific energy conversion system research needs will be identified. Demonstration sites will serve as test locations for subsequent field research to validate energy conversion technologies.

4.1.8.5 Energy Conversion Programmatic Status

Energy conversion systems baseline assessment is to be performed in Fiscal Year 2009.

Table 4.33. Energy Conversion Technology/Program Activities

Task	Approach	Organization
Assessment of current technology and identification of R&D needs for EGS energy conversion systems	Utilizing industry and research experiences, literature searches, prior studies and a workshop to provide a current status of energy conversion technologies and to provide initial specifications of the requirements for EGS energy conversion systems.	UTC Power, Chena Hot Springs

4.1.8.6 Energy Conversion Technology Status

Current hydrothermal facilities typically operate in the 10 to 20 percent efficiency range. A comprehensive survey of hydrothermal energy conversion technologies will be performed.

Table 4.34. Energy Conversion Technology Status Summary

Barrier	Available Technologies (U.S. and International)	Technology Status
Barrier N: Energy Conversion Unknown ability to manage long-term rock temperature, fluid quantity and fluid chemistry	A rigorous power conversion technology gap assessment with estimated development timeline	TBP

4.1.8.7 Energy Conversion Tasks

The following tasks support the Energy Conversion research area.

Table 4.35. Energy Conversion Tasks		
Number	Description	Barrier
1	Establish costs/ benefits of recuperated binary cycles for high-temperature EGS to optimize reinjection temperatures.	N
2	Evaluate opportunities for energy conversion technology advancements, such as: air cooling, “flexible power plant,” and supercritical CO_2 working fluid.	N
3	Determine needs for chemical control for a given EGS reservoir.	O
4	Evaluate technologies for mitigating scaling and corrosion.	O

4.2 Enhanced Geothermal Systems Validation

The most salient feature of EGS is the intentional fracturing of hot rock to create or increase permeability and, as necessary, allow for the introduction, either naturally or artificially, of a heat transfer fluid (typically water) into the fracture system. The MIT study recommended that the program conduct multiple EGS demonstrations in different regions of the country to reduce risk and uncertainty. Lessons learned from DOE findings will feed into the R&D portion of field project development and support the system demonstrations and technology validation efforts. The program will perform system demonstrations of reservoir enhancement techniques and technology validation to accelerate EGS commercialization.

The Systems Demonstration part of this plan calls for the installation of 5 MWe of new generating capacity by utilizing existing technology adapted to EGS use by 2015. It is understood that this capacity will be installed at or near existing hydrothermal production sites where there is sufficient heat in the underlying rock formations at a well-characterized depth, but insufficient permeability and/ or water flow. Thus, this heat source will require enhancement by localized fracturing, in order to allow water flow through the formation that can be used for power generation. The location of the EGS near an existing hydrothermal field, where the new flow from the EGS can be piped into the existing power plant, allows the focus of this endeavor to be placed on the localized fracturing of the rock, which is the crux of EGS.

This portion of the plan is conceptualized using existing commercial technologies from the oil and gas and mining industries, but any new technologies developed and validated in the R&D area could be considered. This is depicted in Figure 4.2.

There is a continuum between hydrothermal reservoirs, which have enough natural permeability for economic extraction of heat, and enhanced geothermal systems. Sub-economic hydrothermal systems are candidates for remedial reservoir stimulation, making them potential sites for EGS. Sites on the margins of producing geothermal fields can take advantage of known thermal gradient and existing infrastructure. These marginal hydrothermal sites are expected to provide an early proving ground for a number of technologies while leveraging industry support for relatively near-term development.

As the critical enabling technologies for EGS are successfully demonstrated and refined, EGS development will move to previously unidentified geothermal resource sites away from existing hydrothermal areas. While a variety of rock types and subsurface settings may be conducive to EGS reservoir creation, it is unlikely that all reservoir creation techniques will be equally successful in every subsurface situation. A distinct learning curve can be expected for different geologic and lithologic settings.

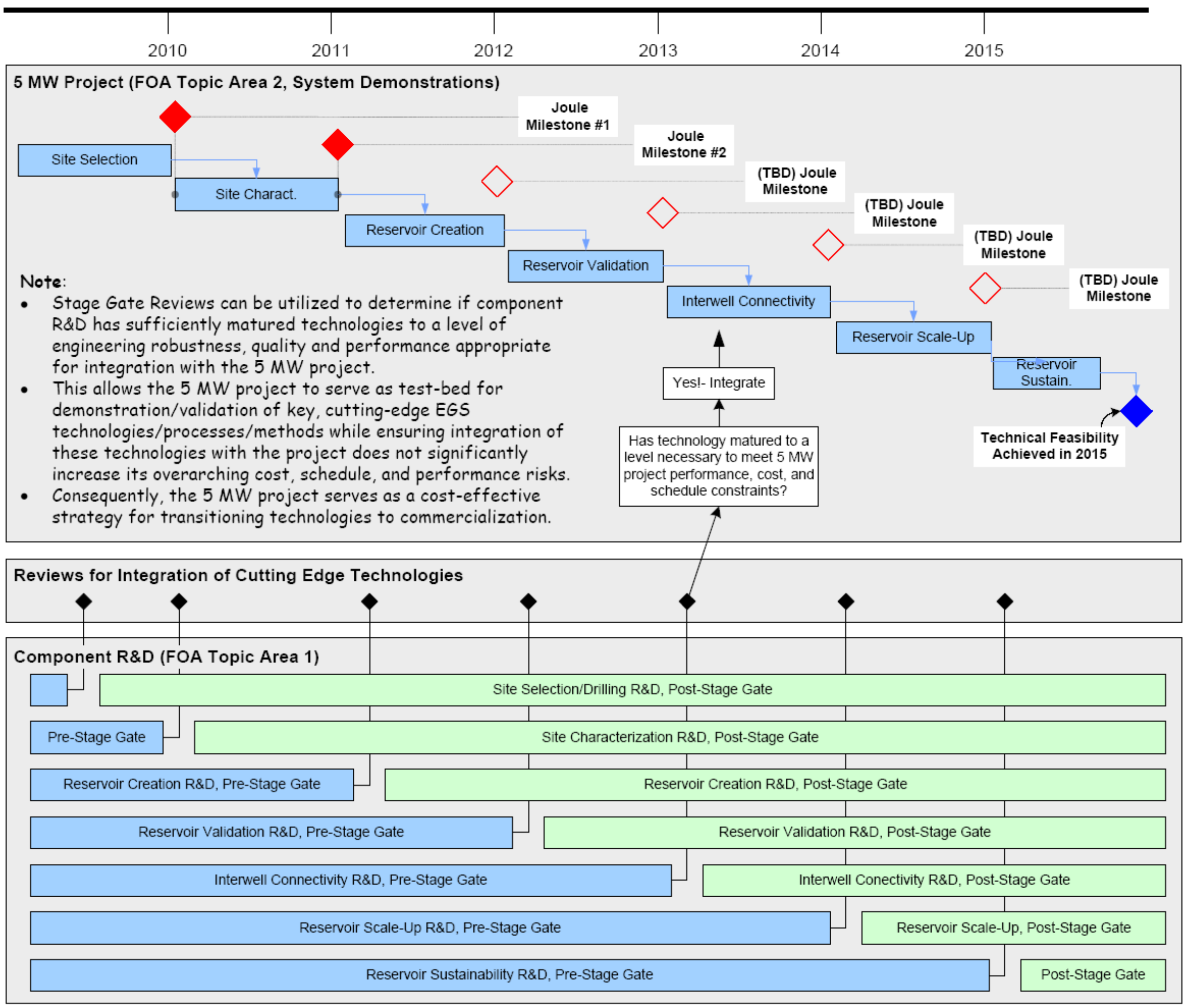


Figure 4.2. Overview of the System Demonstrations and Program R&D Activities

4.2.1 System Demonstrations

System demonstrations are taking place through industry cost-shared projects at and near producing geothermal fields. This approach was chosen to avoid the cost associated with surface development and increase the immediacy of economic benefits. Further site selection criteria (other than proximity to a developed reservoir) will be developed to initiate projects in unknown geothermal resource fields.

Comprehensive data collected from these demonstration projects will feed back into the R&D planning and guide the next steps of research projects. At that point, the projects will be defined as low risk or high risk based on the outcome of industry cost-shared project. Low-risk technology development will be incorporated into new demonstration projects with the focus of study determined by the successes and/or failures of previous project activities. High-risk projects will proceed to independent validation sites. The process for these high-risk projects will be determined at a later date, when the need is more defined. Upon the successful completion of this strategy, the program will have validated the existing technologies, collected the knowledge base necessary for unknown geothermal resources and documented further research and development needs.

Goal 10: Demonstrate the viability of EGS principles.

4.2.1.1 System Demonstrations Barriers to Commercialization

The barriers to creating, sustaining, and optimizing the economics of reservoirs for EGS commercialization are as listed above in the R&D section, and include: limited fracture detection capability, insufficient stimulation prediction models, limited zonal isolation technology, lack of high-temperature monitoring tools and sensors, limited flow path identification capacity, inadequate submersible pumps, and a lack of suitable tracers.

In order to create an EGS reservoir able to operate for six years at 80 kg/s with wellhead temperature of 250+/- 10°C, certain issues must be resolved. Some of these are:

- Enhance rock's permeability and/or porosity (flow rate);
- Increase swept area (reservoir volume);
- Efficient heat mining (temperature); and
- Avoid short circuits/cooling (tools to isolate reservoir).

Barrier P: **Crew Inexperience** – Because of the infancy of domestic EGS technologies, drill rig crews are inexperienced in drilling, construction and completion of geothermal wells for EGS use.

Barrier Q: **Risk of Damage** – Stimulation techniques have the potential risk of damaging existing hydrothermal fields.

Barrier R: **Drilling Rig and Crew Availability** – Because of the increased market price of hydrocarbons, the availability of drilling rigs and crews is diminished.

There may be as-yet-unidentified technology improvements that will be required for optimizing the economics of EGS reservoirs.

4.2.1.2 System Demonstrations Technical Goals, Objectives, and Targets

Table 4.36 lists the two objectives for the Systems Demonstrations.

Table 4.36. System Demonstrations Objectives	
Number	**Description**
1	Characterize the reservoir at a minimum of 75 percent of the selected field sites within two years of initiating field operations while meeting prescribed standards for quality and quantity of data.
2	Successfully stimulate reservoirs at one or more of the field sites within two years of initiating field operations, with at least one EGS of the created reservoirs meeting commercial EGS requirements of flow rate and heat extraction sustainability.

There are two technical targets for the Systems Demonstrations area that were set forth as Joule targets for the Program.

Table 4.37. System Demonstrations Technical Targets		
Number	**Description**	**Year**
1	Determine actual pre-stimulation reservoir flow rate for at least one EGS field site.	2009
2	Select a stimulation design plan predicting an increased reservoir flow rate of 10 percent or at least 10 kg/second.	2010

Three principles will be followed in pursuing the goals of systems demonstrations:

1. Validate the applicability of existing technologies.
2. Create a broad knowledge base covering existing technologies. The systems demonstration effort will apply historical knowledge from the previous geothermal stimulation research and the oil and gas and mining industries to develop a critical knowledge base on stimulation techniques and applicability.
3. Thoroughly document the lessons learned. Lessons learned will inform Program decision making, research and development planning, and ensure that systems demonstrations are of greatest value to industry stakeholders engaged in commercialization of EGS.

4.2.1.3 System Demonstrations Technical Approach

The Program plans to meet the broad goals listed above by establishing financial assistance awards with industry and academia through EGS solicitations. These awards will address particular barriers to EGS development– primarily the ability to create and map permeability, and to maximize heat recovery from the enhanced system.

Reservoir characterization will include collection of all geologic and engineering data needed to plan successful stimulations of the candidate wells. Creation of the stimulation models may include (but is not limited to) the following: petrologic/petrographic analysis, rock mechanics tests, magnetotelluric studies, geochemical analysis, background seismology/ micro-seismic analysis, borehole imaging/logging, fracture analysis, existing flow and/or injection tests, and fracture stimulation modeling. This approach also includes deployment of micro-seismic networks and conduction of a mini-fracs of the targeted interval to assist in designing stimulation plans. Data on in-situ stress and natural fracture distributions shall be developed from borehole testing and logging.

Reservoir creation will include any necessary wellbore modification, redesign of the micro-seismic network if needed to further understand seismicity during stimulations, other monitoring techniques such as tiltmeter, and finally execution of full well stimulations. Work may include mobilization/ demobilization of stimulation equipment, execution of well stimulations, running geophysical or production logs, fluid sampling, monitoring of stimulations through use of microseismicity, tiltmeters or other techniques, flow tests, and tracer tests. Data collected for the first two years of the project will include (at a minimum):

- Microseismic data and interpretation;
- Production and/or injection rates over time and analysis;
- Logs run in the wells (PTS, sonic, natural gamma, tool-head temperature, etc.);
- Borehole imaging logs (e.g., televiewer, FMS, other) for both pre- and post-stimulation;
- Well flow rates and well head temperatures;
- Chemistry of produced fluid and mineral dissolution/precipitation;
- Formation response/evolution data;
- Tracer data, analysis and results of tracer tests if the wells are in communication with other wells in the field or to determine such connection; and
- A populated database documenting the lessons learned and providing feedback to further research and development.

The technical approach for completion of Phase Three includes running a suite of logs necessary to characterize the near wellbore responses of the targeted formation in order to characterize the sustainability of the EGS reservoir. Phase Three work also includes tracer tests, geochemistry, and geochemical analysis for the candidates and associated wells. Data collection and analysis will include:

- Microseismic data and interpretation;
- Productivity or injectivity data and analysis;
- Well flow rates and well head temperatures;
- Chemistry of produced fluid and mineral dissolution/precipitation;
- Tracer data, analysis and results of tracer tests if the wells are in communication with other wells in the field or to determine such connection; and
- A populated database documenting the lessons learned and providing feedback to further research and development.

4.2.1.4 System Demonstrations Programmatic Status

The Program paved the way for EGS technology advancement by supporting the first EGS field demonstration project at Fenton Hill, New Mexico. Although this project met with numerous technical difficulties, it significantly advanced the geothermal community's understanding of the complexity of engineering a fracture network suitable for energy conversion. Numerous important lessons learned from the Fenton Hill project have helped guide EGS projects worldwide. Since Fenton Hill, there have been seven EGS projects in Japan, Europe, (France, Germany, Switzerland), and Guatemala. Two projects have been supported by the GTP: the Coso and Desert Peak geothermal fields. The GTP also participates in an International Energy Agency (IEA) annex for EGS research that fosters cooperation among the various programs worldwide.

Because of its key role in geothermal reservoir development, the practice of reservoir modeling and tool development have been a Program since the 1970s. In the early phase, efforts were directed at clarifying the important physics to be included in models, as well as developing accurate, robust, and efficient methods for solving the governing equations. Models were developed to accurately predict the chemical behavior of geothermal fluids and their associated phases over a wide range of compositions and thermodynamic conditions. New techniques were developed to treat fluid and heat flow in fractured media, and to perform flow simulations with aqueous fluids that include dissolved solids and non-condensable gases. These methodologies permit solution of many geothermal reservoir problems, and have been widely adopted by the national and international geothermal community.

In the near term, the Program has had two projects to demonstrate inter-well connectivity in hydrothermal fields. At one project site, drilling crew errors led to the suspension of work at the first well chosen. The project has completed much of the pre-stimulation phase at a second well. Data has been collected and the geology of the site has been thoroughly characterized. A stimulation plan is being developed. Reservoir stimulation is scheduled for April of 2009. The stimulation plan will include designs for testing and validating the stimulation techniques.
At the second project site, data revealed that deepening the well could result in a permeable reservoir. The well will be deepened and stimulated.

Table 4.38. Fiscal Year 2008 System Demonstrations Technology/Program Activities

Approach	Organizations	Project Focus
Pursue the Funding Opportunity Announcement (FOA 1)	Golden	Select Industry cost-shared projects
Pre-stimulation and recompletion activities	Industry	Learn in-situ stress, rock properties, and MEQ behaviors
FOA 3	Golden	Select wider range of Industry cost-shared projects

4.2.1.5 Systems Demonstrations Technology Status

The following table summarizes the status of Systems Demonstrations Technology.

Table 4.39. System Demonstrations Technology Status Summary		
Barriers	Available Technologies (U.S. and International)	Technology Status
All barriers from Section 4.1: technical challenges to creating and sustaining a reservoir include: limited fracture detection capability, insufficient stimulation prediction models, limited zonal isolation technology, lack of high-temperature monitoring tools and sensors, limited flow path identification capacity, inadequate submersible pumps, and a lack of suitable tracers. Additionally, stimulation may damage existing fields.	Develop fracture detection capability and stimulation prediction modeling	The GTP will provide awards to industry and academia partners to be conducted in three phases: pre-stimulation, enhanced reservoir, and long-term collection and monitoring For the first stage, Pre-stimulation, the GTP has two projects to demonstrate inter-well connectivity in hydrothermal fields. At one project site, mistakes of a drilling crew led to the suspension of work at the first well chosen. A second well has been chosen, and the project has completed much of the pre-stimulation phase at this well. Data has been collected and the geology of the site has been thoroughly characterized. A stimulation plan is being developed. Reservoir stimulation is scheduled for April of 2009. The stimulation plan will include designs for testing and validating the stimulation techniques. At the second project site, data collected revealed that deepening the well could result in a permeable reservoir
Barrier P: Crew Inexperience: Because of the novelty of EGS technologies, drill rig crews are inexperienced in drilling, construction and completion of geothermal wells for EGS use.	TBD	TBD
Barrier Q: Risk of Damage: Stimulation techniques have the potential risk of damaging existing hydrothermal fields.	TBD	TBD
Barrier R: Because of the increased market price of hydrocarbons, the availability of drilling rigs and crews is diminished.	TBD	TBD

4.1.2.6 System Demonstrations Tasks

The following tasks support the Systems Demonstrations area.

Table 4.40. System Demonstration Tasks

Number	Description	Barrier
1	Collect and analyze data from reservoir creation projects to learn about the factors (geological and engineering) which contributed to success or failure of reservoir stimulation and sustainability.	TBD
2	Test the wells and collect data over a number of years following well stimulations to assess long-term performance of both the stimulated wells and non-stimulated wells.	TBD
3	Create a complete geologic model to enable planning, execution, and learning from well stimulation. Critical reservoir characterization data includes core samples, stress field data, lithology and structural models, permeability.	TBD

4.2.2 Technology Validation

4.2.2.1 Technology Validation Technical Goals and Objectives

The goal of the program is to validate the tools and processes being developed in the research and development community swiftly and successfully.

4.2.2.2 Technology Validation Technical Approach

The approach to validating technologies will have a major experimental component that tests representative configurations of the system. The progression of tests must be chosen to ensure that new findings build upon earlier work.

Past experience will be carefully analyzed and used to predict short-term performance of the EGS. The knowledge thus gained will direct the next step. Technology validation tests will be run under carefully controlled conditions to assure that the results can be compared to predictions.

4.2.2.3 Technology Validation Technical Programmatic Status

Currently, there are no validation sites.

4.2.2.4 Technology Validation Technology Status

Technology Validation status is summarized below.

Table 4.41. Technology Validation Technology Status Summary		
Barriers	Available Technologies (U.S. and International)	Technology Status
Site characterization will be needed for EGS technology in order to find appropriate unknown geothermal resource sites in different geological settings where testing can be performed.	Identify appropriate unknown geothermal resource sites in varying geological settings for EGS reservoir development.	In addition to the Soultz project, a second French project at Landau and a large-scale EGS project at Cooper Basin, Australia (Geodynamics Limited) are currently being developed. There are no technology validation sites in the United States

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