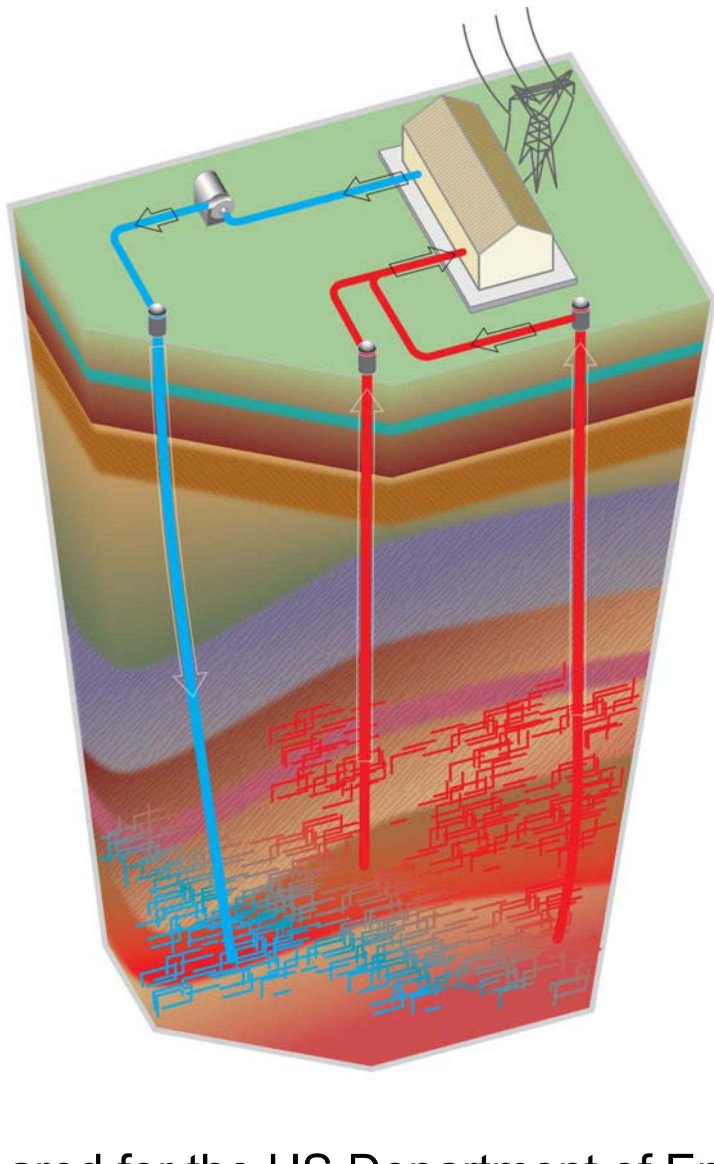
EGS
Program Review Report
December 2006



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by the National Renewable Energy Laboratory

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Acronyms

BLM	*Bureau of Land management*
DOE	*U.S. Department of Energy*
EGS	*Enhanced or Engineered Geothermal System*
GEA	*Geothermal Energy Association*
GW	*Giga-watt*
GRC	*Geothermal Resources Council*
INL	*Idaho National Laboratory*
IEA-GIA	*International Energy Agency (U.N.) – Geothermal Implementation Agreement*
LBNL	*Lawrence Berkley National Laboratory*
MW	*Mega-watt*
NREL	*National renewable Energy Laboratory*
SNL	*Sandia National Laboratory*

Foreword

The 2006 EGS Program Review afforded an opportunity for geothermal researchers to meet in an informal atmosphere and share the results of their research. Each investigator could interact with their peers and discuss topics of mutual interest. For DOE, the meeting represented an important checkpoint on the road towards achieving the EGS Program's goals. The researchers' presentations on the first day were indicators of progress and served to establish the status of technical work. That progress is documented in this report. Workshop discussions on the second day allowed for free exchange of ideas on the future direction of the EGS Program from persons who are vested in EGS research, but not research management. Their unique perspectives, as summarized here, will enable DOE to make better decisions about how to guide the EGS Program in the coming months and years.

Allan Jelacic

Dr. Allan Jelacic, EGS Program Manager,
DOE Geothermal Technologies Program.

Executive Summary

A review of the DOE Enhanced Geothermal Systems (EGS) Program was held July 18 and 19, 2006 in Golden, Colorado. The EGS Program status was assessed through a series of presentations by participating researchers describing their planned research and development (R&D) or field experiments, accomplishments to date, and the significance of accomplishments, along with challenges and opportunities. Individual project presentations, along with discussions during group breakout sessions, provided a basis for identification of programmatic gaps, and for planning future work.

◆ EGS Defined ◆

The EGS concept is to recover heat contained in subsurface rocks by creating a system of fractures in the subsurface rocks. Water is then circulated down injection wells, through the fractures where the water absorbs heat, and back to the surface via production wells. Since temperature increases with increasing depth in the earth, hot rocks can always be reached by deep drilling.

The EGS concept is to recover heat contained in subsurface rocks by creating a system of fractures or enhancing existing fractures in the subsurface rocks. Water is then circulated down injection wells, through the fractures where the water absorbs heat, and returns to the surface via production wells. Since temperature increases with increasing depth in the earth, hot rocks can always be reached by deep drilling. The challenge is to develop technologies to cost-effectively create or enhance, and manage a productive fracture network. Successful application of EGS technologies will increase well productivity and power generation from all geothermal resources, with near term emphasis on changing marginal resources into economically viable resources. Application of EGS technologies will significantly increase the amount of economically viable geothermal resources, ranging from improving currently economic hydrothermal resources to enabling eventual development of reservoirs of hot rock formations with limited permeability and limited unbound water.

The EGS Program is poised to make significant progress, but work remains in planning, analysis, research, and the number of major field projects. The EGS plan must be further developed and defined in greater detail. Additional analyses are needed to provide a success-oriented program direction and for evaluation of the research, development, and demonstration (RD&D) portfolio. While there are field projects at Coso and Desert Peak, these are just the beginning of what must be an extensive series of field experiments to prove the technical capability of enhancing various types of reservoirs.

The primary goal of the EGS Program is to demonstrate use of advanced reservoir engineering and geoscience techniques to predictably create and manage sustainable and viable geothermal reservoirs. This goal has not yet been met. The EGS review made clear that the goal cannot be accomplished with current fiscal resources, and that consistent and adequate funding over at least a decade is imperative to reaching the ultimate potential of EGS. However, in the short term, program planning and execution must be made consistent with available funding.

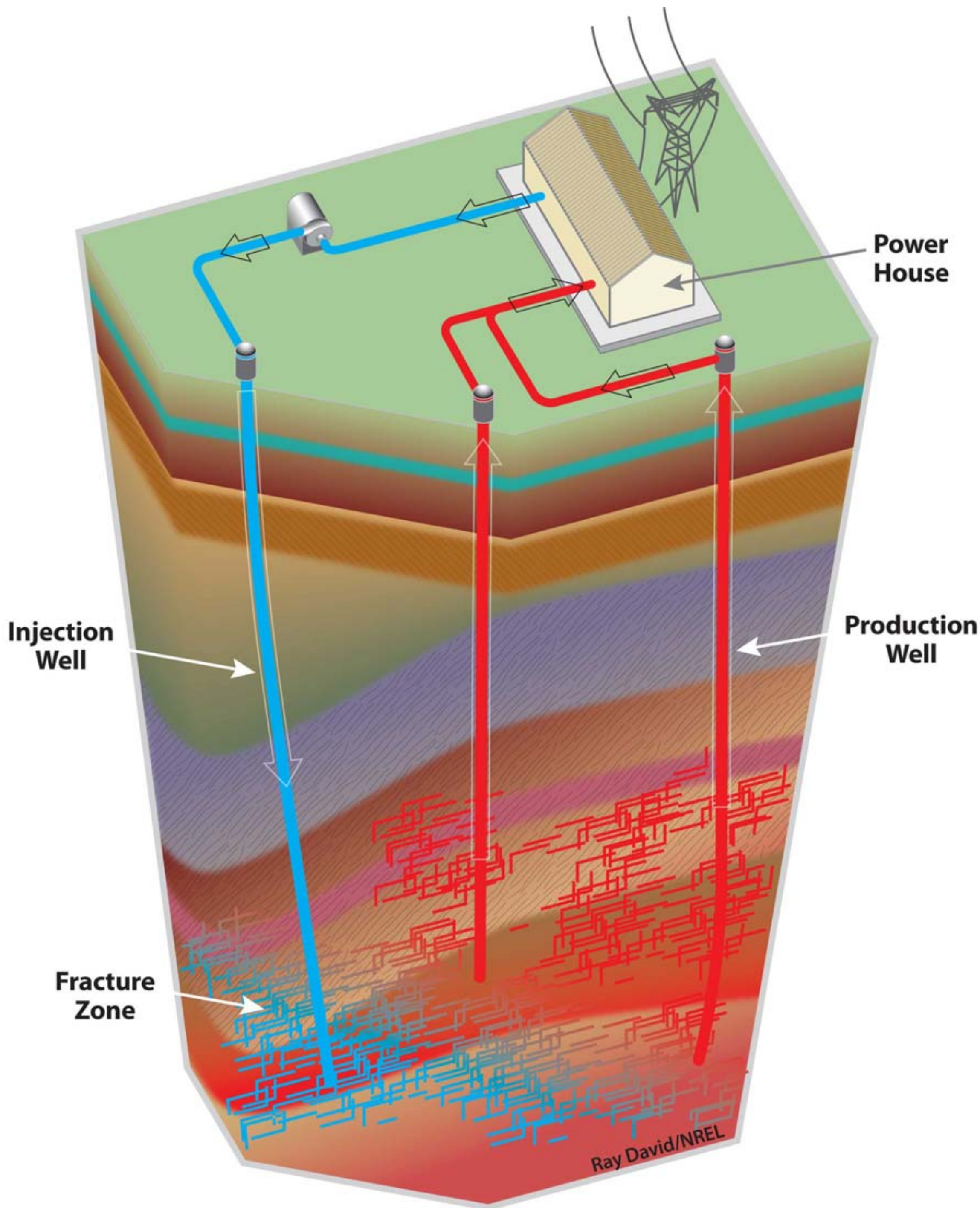
Emphasis must be on field projects that define how to create sustainable and viable, commercial-scale reservoirs, and using field experiments supported by research that provides the necessary technical bases for eventual commercial application of the technology. Field projects and technology must be graded in approach. This starts with current and future field projects at working geothermal fields, such as Coso and Desert Peak, using today's oil and gas reservoir engineering technologies, and proceed to field verification projects in more difficult geologic environments with no current geothermal development and using EGS technologies matched to the special needs of geothermal reservoirs. Ideally, these latter sites should be 'green fields' – geologic sites with no prior geothermal development and with challenging characteristics including low permeability or limited unbound water.

A strong alliance between DOE, the geothermal industry, the oil and gas industry, mining and other allied industries, academia, and various governmental agencies will allow for the free exchange of knowledge and technology. DOE must exert strong leadership to spearhead the creation and maintenance of this alliance.

Conclusions from the review:

- EGS development won't be cheap or fast. It will require a sustained effort.
- EGS technology should be developed initially in a hydrothermal setting in partnership with industry.
- Long-term operation of systems in diverse geothermal environments will be required before the technology can be widely utilized.
- The knowledge base developed through research, development, and demonstration must be maintained and disseminated for the technology to flourish.

It was the consensus of the participants agreed that the EGS Program appears headed in the right direction, but the target and the pathways to that target are not well defined. Adequate funding, additional planning, and completion of planned technology development, including outreach activities, will be required to meet the program goal. Ultimately, the program can provide a robust technology that will allow geothermal energy to become a major component of the national energy supply.


Power
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Ray David/NREL

1. Introduction

This document summarizes the outcomes of the EGS Program Review, and also provides a detailed summary for each project. A compendium of project reports and related documents is included in Section 5, *Project Summaries*.

The objectives of the EGS Program Review, held in Golden, CO July 18 – 19, 2006, were to:

- Assess the present status of the EGS Program
- Identify any gaps in the program
- Provide a basis to plan future work.

Presentations on the first day covered the following topical areas:

- Fracture Mapping and Monitoring
- Fracture Stimulation
- Fracture Mechanics/Permeability
- Fracture Chemistry/Petrology
- Field Projects
- Systems Analysis.

This structure reflects the technology needs of EGS and the structure selected to meet these needs.

The second day included presentations on the future of EGS, as well as two breakout sessions. In addition to the presentations, this report summarizes the findings of the two breakout sessions. The first breakout session, during the morning of the second day, addressed general EGS issues, while the second breakout session, during the afternoon, dealt with technical aspects of the program.

Appendix A provides a list of the general breakout sessions. Appendix B provides a list of the technical breakout-session groups. Appendix C contains the names and contact information for all the attendees.

2. Breakout Sessions

All attendees participated in two breakout sessions, a general session and a technical session. The general breakout portion of the EGS Program Review consisted of three parallel groups addressing common questions, with results reported in Section 2.1. The technical breakout session included three parallel groups, each addressing one of the following technical areas:

- Resource characterization
- Productivity enhancement (reservoir design and development)
- Resource management (reservoir operation and management).

After each breakout session, all the participants met together to hear the findings of each group. This section of the report attempts to summarize the breakout group presentations made to the entire group. Because of the limited time for discussion, a group-wide consensus was not attempted for these sessions.

2.1. General Breakout-Session Findings

The group participants discussed goals, barriers to accomplishing the goals, strategies to overcome the barriers, and actions needed to gain support from the geothermal community for the EGS Program. Where appropriate, time frames are defined as short term (< 30 months), medium term (> 30 months) and long term (3 – 5 years).

Each group discussed the same set of questions:

- What are realistic goals for the EGS Program? What goals would you support?
- What are the barriers (technical and institutional) to making EGS work on a large scale in the US?
- What strategies need to be pursued to overcome barriers?
- What should the EGS Program do through January 2009? In the longer term?
- How can DOE gain support of the geothermal community at large for EGS?

Following is a synthesis of the wide-ranging discussions of the three parallel breakout groups in their attempts to answer the questions.

Goal and Objectives

There was general agreement arising from the general breakout sessions as to the goals and objectives of the EGS Program. This agreement is with the congruent with the approach being taken by DOE in its current activities. A summary of that consensus is:

The primary goal of the EGS Program is to demonstrate use of advanced reservoir engineering and geoscience techniques to predictably create and manage sustainable and viable geothermal reservoirs.

The short-term objective is to provide the technological base to increase the economically available geothermal resources by stimulation at existing geothermal fields.

The longer-term objective is to develop and validate technologies to enable cost-effective stimulation in a variety of geologic settings, especially zones of limited permeability or limited unbound water.

Discussion of Goals and Objectives

Short Term (The next 30 months)

In the short tem, EGS activities should be focused on adapting existing oil and gas technologies to geothermal EGS applications to bring additional power generation on line as quickly as possible using stimulation in hydrothermal fields. The emphasis should be on developing modeling techniques to allow a better prediction of expected stimulation results, better field characterization methods, and a database of enhanced field performance as a function of time.

The EGS Program should develop a large inventory of "wells of opportunity" – oil and gas, and geothermal wells – and support projects to stimulate high temperature oil and gas fields using these wells of opportunity. This includes completing current demonstration projects on the margins of existing fields such as at Coso and Desert Peak. Specific objectives include:

- Develop and demonstrate reliable stimulation and characterization techniques
- Begin to demonstrate long-term sustainability
- Evaluate economics of these projects
- Validate and expand concepts to allow extrapolation to other fields and undeveloped resources.

Short-term demonstration projects such as Coso and Desert Peak, along with follow-on projects using existing wells of opportunity or step-out wells within existing production zones, should enlist geothermal operators and developers, academia, state energy offices, utilities, and the Western Governors' Association as members of the project teams or oversight groups.

DOE should use the information from current EGS projects, along with information from national resource assessments, to begin to identify two or three candidate green-field sites for EGS development. The green-field sites should represent diverse geologic settings to provide a basis for expanding the viable geothermal resource base.

Medium Term (3 to 5 years)

DOE should support deployment of concepts such as coil tubing drilling and horizontal drilling in the geothermal environment, and should evaluate the merits of using carbon dioxide as a supercritical working fluid with possible supplementary benefits of greenhouse gas (carbon dioxide) sequestration.

DOE should develop a bridging strategy to move from short-term field projects to the longer-term projects in more challenging geologic environments. Within five years, the program should try to do 5-MW demonstrations associated with both a hydrothermal field and an oil and gas field. These bridging demonstrations should be expandable, and should use multiple wells of opportunity per site. An approximate cost estimate is about $10 million per year for each of these projects.

DOE should sponsor research combined with field projects to:

- develop hot, but relatively impermeable and marginally productive hydrothermal systems
- continue to develop and refine technologies for resource assessment, stimulation, and evaluation to advance the state-of-the-art and to promote technology transfer to industry
- facilitate installation of additional MW of generating capacity on line, as determined by industry and the competitive market
- Promote technology transfer to industry.

<u>Long Term (>5 Years)</u>

There was no unanimity of opinion about the long term, but the comments below reflect both individual opinions and a rough consensus of the groups, where one existed.

- A demonstration project could be undertaken in crystalline rock below an old oil or gas field. It must be reasonably sized (to attract oil and gas industry interest, about 200 MW) on a large resource to enable expansion. The demonstration target should be seven years out, starting in 2013 or 2014.
- Between 5 and 10 years from now, demonstration projects should be expanded to 30 MW (two 15-MW projects), which is estimated to cost about $180 million, or about $36 million per year.
- Between 10 and 15 years, EGS should expand to 500 MW on line, through several sites with industry coupling. DOE should provide about 25% of the cost, with the rest coming from industry. The total cost is estimated to be about $850 million, or about $170 million per year.
- At 20 years from now, 1 GW in projects should be under development, with an expected cost in excess of about $1 billion.

Specific technology targets of the demonstration projects include:

- Demonstrate fracturing capabilities and predictability, and stimulate a large rock volume
- Improve and demonstrate reservoir characterization and monitoring tools
- Increase the economically productive volume of a geothermal reservoir
- Demonstrate sustainable fluid circulation at a commercial scale
- Demonstrate stimulation and fluid circulation in a variety of lithologic and tectonic settings
- Recommend industry standards and protocols for acquiring required data and processing techniques
- Document and transfer tools and techniques that are developed
- Involve government in risk reduction strategies to encourage private participation. Risk reduction is used in the sense of sufficient government investment to entice the private parties to participate. Explore innovative heat-extraction processes
- Explore innovative heat-extraction processes
- Show a sustained commitment to EGS-related skills development.

Barriers to Accomplishing Goals and Objectives

The barriers are perceptual, programmatic, and technical. Perceptual barriers are those that can easily be dispelled with better information and communication. Programmatic barriers are those that deal with the inadequacy of DOE Geothermal Technologies Program funding and longer-range emphasis. Technical barriers are those that require development of new techniques and performance of fieldwork to perfect and validate technologies.

<u>Perceptual Barriers</u>

Perceptual barriers include the erroneous perception that geothermal is not a large enough resource to justify a national program. This is often accompanied by the perceptions that the resource is strictly classic hydrothermal, and that the resource is environmentally unacceptable, being equated to mining, and oil and gas drilling.

The geothermal industry has the perception that the DOE program as currently constituted is of limited benefit to industry. DOE is seen as bureaucratic and self-interested. DOE has a different focus than industry, for example, expanding the viable resource across the whole U.S. as compared to industry's interest in promoting near-term development. DOE should modify its approach and design its research to address immediate industry needs. *Please note that there was limited representation of industry, so the general validity of these statements should be viewed with caution*.

There exists a perception of a low R&D return-on-investment for EGS. There may be a vague belief that EGS is simply previous technical approaches in a new guise – perception must be viewed with caution.

<u>Programmatic Barriers</u>

Participants expressed the opinion that the major programmatic barrier is the absence of a national imperative to expand the development of geothermal energy, which leads to a lack of sufficient funding and a lack of long-term commitment by the government. This is reflected in the lack of a DOE commitment to supporting a multi-year R&D program to achieve the stated goals.

The opinion was expressed that EGS efforts may suffer from a lack of credibility with industry and government decision-makers, reflected in:

- Absence of realizable goals
- Absence of industry and policy makers' backing
- Absence of a national commitment to geothermal as an essential part of the national energy strategy
- Lack of participation by large, integrated energy companies.

Concerns were raised about the lack of results for the money that DOE has invested in EGS technology. Additional concerns were voiced about lack of sufficient economic and policy incentives to drive EGS development, including absence of accounting for the positive environmental externalities related to geothermal, and lack of a long-term production tax credit.

<u>Technical Barriers</u>

The overall technical barrier – the ability to stimulate a sufficiently productive and long-lived reservoir to enable economic production from a marginal reservoir – has not been demonstrated.

Reservoir engineers at the EGS Program Review stressed the need for better understanding of in-situ stress, including how it changes during stimulation and production. This need also includes to ability to create sufficient underground heat-transfer area with low-flow impedance flow paths and no short-circuiting. The geochemists stressed the importance of better understanding of geochemical and physical interactions between water and reservoir rock. These technical needs equate to requirements for a better understanding of all aspects of advanced reservoir engineering and management, based on a fundamental knowledge of rock mechanics and fracturing.

Some Strategies to Overcome Barriers

The initial strategy must be to work with industry to establish a demonstration and research program that is supported by, and is of benefit to, the geothermal industry.

An early focus should be on transferring and adapting existing technology from oil and gas reservoir engineering to the geothermal environment. The ongoing field tests at Coso and Desert Peak should be completed. These field tests should be followed by extensive stimulation tests in geothermal fields and in high-temperature oil and gas fields. Emphasis should be on development and documentation of stimulation methods for geothermal systems.

Technical strategies include projects to:

- Create and maintain optimal inter-well permeability
- Adapt existing hydraulic-stimulation techniques to geothermal conditions
- Decide on fluids, proppants, flow rates, fracturing pressures
- Characterize and monitor created EGS reservoirs
- Improve state-of-the-art for microseismic monitoring (improve relative and absolute location accuracy)
- Expand current tracer and geochemical monitoring techniques for characterizing and tracking reservoir performance
- Develop new borehole diagnostic tools to assess fracture flow and connectivity

The DOE Geothermal Technologies Program should serve as the kernel of an extensive team that would include the geothermal industry, the oil and gas industry, utilities, mining and other industries, and state energy offices, in development and commercialization of enhanced geothermal systems. The review panel suggested that DOE work with industry groups such as GRC, GEA, and environmentally motivated groups to:

- Foster a 'national imperative' for EGS in US energy portfolio
- Educate the general public and policy makers about the many benefits of geothermal, ranging from small-scale heat pumps to EGS
- Build a constituency in both the geothermal community and oil and gas community
- Examine industry needs and what DOE can do to meet those needs
- Provide appropriate funding for geothermal R&D
- Create long-term governmental incentives for geothermal electricity production

Discussion of Strategies

In the shorter term, EGS efforts should stress technology transfer and dual-use technologies, building on existing oil and gas, and mining technologies to support early successes. Methods in addition to hydrofracturing should be examined, including chemical well-fracturing and stimulation. DOE should use a collaborative program with industry to test unproven technology.

DOE activities should stress development of:

- More robust high-temperature pumps with industry support
- Better proppants
- Cheaper and longer-lived high temperature instrumentation
- Reliable sonic/gamma/density/imaging technology, both surface and downhole
- Simple downhole samplers; piggybacking on oil and gas technology
- Zonal isolation tools including packers and diverters
- Stress/strain mapping tools and methods.

In the longer term, DOE should stress research and field projects to provide the technology basis to:

- Verify long-term reservoir management to create an efficient and sustainable underground heat exchanger
- Understand and manage fluid flow paths to minimize short-circuiting and parasitic pumping power while maximizing well productivity
- Evaluate other working fluids such as CO_2
- Understand fundamental rock-fluid interactions to ensure flow path sustainability
- Validate technology in the field
- Pursue with caution experiments with geothermal systems in deep crystalline rock due to potential problems with:
  - Large capital expenditure
  - Engineering studies and protocols
  - Energy systems analysis

Gaining Support from Industry

Activities by DOE and the EGS team to gain industry support should include enhancing communication between DOE and the geothermal industry. This includes better communication of past and current EGS activities, and results from EGS technical projects around the world. Some specific communication opportunities include:

- Establish a common definition of EGS. A possible start to a new EGS definition was stated as "EGS is a "tool kit" of technology options to enhance the performance or productivity of geothermal resources."
- Encourage a merger between "hydrothermal" and "EGS" 'communities', starting by using the above definition of EGS as a tool kit, rather than a resource that can be viewed as separate from hydrothermal.

- Focus on common technical problems, especially by showing the application of an EGS tool kit in a sequential manner. Start with projects to enhance productivity within existing geothermal fields, with extension to marginally productive fields as the EGS technology develops.
- Involve industry and academia in all DOE planning, in the execution of those plans, and in evaluation of the results of research, development, and demonstration. This includes substantial cost sharing of the work by industry.
- Develop EGS demonstration projects in collaboration with industry, academia, national laboratories and public agencies.
- Show success by additional power on line.
- Communicate results to decision makers, taxpayers, stakeholders, industry, etc.

Planning by DOE should be more extensive than in the past, and should be performed in partnership with industry, the U.S. Navy Geothermal Program, the U. S. Geologic Survey, interested states, and others. In particular, a success-based plan must be based on expectations that are achievable. Execution of the plan must be such that the desired results are delivered. EGS Program plans must be developed in more detail than are existing plans.

DOE must demonstrate to the geothermal industry that EGS research is of benefit to existing, but poorly producing, geothermal systems. DOE should focus near-term on technologies that enhance the viability of existing low-productivity geothermal operations, and on projects that also develop technologies needed for the future. This will increase recognition of the value of EGS, and will encourage industry collaboration. DOE should use successful EGS demonstrations to get buy-in from oil and gas interests that could lead to development of larger scale (>200 MWe) EGS operations.

A major concern of the existing geothermal industry is risk, particularly risk associated with discovery and characterization of the resource. EGS technology should be used to reduce risks through development of better exploration methods, and through enhancement of marginal resources to enable economic development.

2.2. Technical Breakout Session Findings

A second session of the breakout groups considered specific areas of technical interest, with each group assigned one of the following topics:

- Site Characterization
- Productivity Enhancement (Reservoir Design and Development)
- Resource Management (Reservoir Operation and Management).

Site Characterization

The major question discussed by this group was how to determine subsurface temperatures without costly drilling of many temperature-gradient holes. Extrapolation of heat flow data and tabulation of temperatures from mineral resource evaluation and water-well drilling are options that should be followed to evaluate existing data. In addition, the panelists suggested that remote sensing technology should be investigated. However, the subtle differences between regional temperatures and temperatures above hidden thermal anomalies may require greater thermal sensitivity than can be routinely obtained through remote sensing.

Beyond temperature measurements, better techniques for defining fault structures in the subsurface are needed. Geodetic data, InSAR and hyperspectral imaging may be helpful. Regional seismic networks may provide additional information on regional structures and stress. Stress field analysis does also provide information useful in determining fracture orientation and production potential.

The final topic was downhole-logging capability. Better techniques are needed to collect logs in higher-temperature wells, and interpreting the meaning of logs in environments dramatically different than the sedimentary environments of oil and gas. Technology for cross-hole and surface-to-borehole measurements also needs improvement for the geothermal environment.

As discussed in the General Breakout-Session Findings (Section 2.1):

- EGS development won't be cheap or fast. It will require a sustainable effort.
- EGS technology should be developed in the hydrothermal setting.
- Long-term operation of systems in non-hydrothermal geothermal settings is the ultimate goal leading to widespread utilization.

Productivity Enhancement (Reservoir Design & Development)

The key task is creating or enhancing the productivity of a reservoir. Since reservoir creation will be a complex task, the breakout group suggested that the first step should be to do a critical path analysis.

The EGS Program should also review existing stimulation technology, in particular, that developed by the oil and gas industry. Existing predictive stimulation codes, such as STARS (from the petroleum industry) and the geothermal stimulation code developed by Geowatt, should be evaluated.

In the shorter term, technology to stimulate reservoirs needs to be proven in a variety of geologic settings. Can suitable reservoirs be created in existing low-quality hydrothermal systems? The EGS Program also will need to determine the mix of fracturing modes suitable for long-term production. In the longer term, technology must be developed that can sustain large, extensively fractured zones that are not susceptible to premature breakthrough of cool fluids.

Field projects will be necessary in a variety of geologic settings to demonstrate that reservoir creation can be accomplished on a commercial scale and to determine appropriate stimulation methods. The group suggested that partnerships between industry and DOE would be needed.

Specific needs beyond fracturing include a better understanding of rock-water interaction in order to sustain permeability, proppant materials, downhole high-temperature pumps, and additional methods to determine the zone of stimulation. Most recent geothermal stimulations have relied heavily on microseismic measurements to determine the zone of fracturing. Self-potential methods and tiltmeters may also be useful.

Improved tracer technology should also provide improvements in understanding of flow within enhanced reservoirs, and the heat transfer surface within a reservoir. Traditional tracer tests or "huff-puff" methods during stimulation may be useful.

To assist in development of stimulation methodology for reservoir management, it will be important to determine pre and post stimulation permeability and temperature distributions. Volumes and timing of stimulation, and the sequence of stimulation operations are also important parameters needed for proper understanding of stimulation methodology.

Resource Management (Reservoir O&M)

This breakout group assumed its starting point was a formed reservoir just initiating production. The purpose of reservoir management is to predict and manage reservoir performance. The group believes that resource management should include:

- Reservoir characterization – volume, flow paths, and heat transfer
- Monitoring flow and production
- Modeling and integration of reservoir performance and physical measurements.

This breakout group asked, "What do we want to know, and what techniques should be used to characterize, monitor, and model an enhanced geothermal reservoir?" They believed that starting in hydrothermal systems and adapting methodology for less productive environments could accomplish much.

Laboratory measurements of both rock properties and geochemical reactions are necessary for understanding of flow path mechanics and rock-water interactions. Microseismic methods, InSAR, smart tracers, and improved tracer-test interpretation will aid in characterizing geothermal reservoirs. In the future, nano-machines may be able to provide real-time measurements within a reservoir.

Monitoring of flow and production could be improved with better subsurface information that would provide more accurate understanding of changes to flow paths, heat transfer, and permeability within the reservoir. In particular, methods to forecast thermal breakthrough are needed.

Numerical modeling methods must be developed to predict the future of a reservoir, and to determine optimal production methods. Numerical models should fully couple fluid flow, reservoir mechanics, and rock-water interaction. Separate modeling codes are now available for all three areas, and several groups are working on coupling them into multi-disciplinary codes. The group suggested that the ability to attain highly accurate chemical modeling is limited due to the lack of high-quality chemical data. Furthermore, it is unlikely that the data will become available because few research groups are collecting the necessary data.

3. Comments of Potential Interest

The entire group of attendees participated in a general discussion near the conclusion of the review meeting. Some of the general points discussed have already been described earlier in this report, but the fact that they often recurred makes them worthy of emphasis here.

Strategy

The EGS Program needs to look for potential "quick wins" to establish value and to attract partners. This should be done in partnership with industry so that they recognize the value to them. The program needs to build the desire for industry to shoulder an ever-increasing role to develop, field verify, and ultimately, to commercialize EGS technologies.

Industry Support

Industry has higher priorities than EGS. There is often a conflict between long-term research and the need for short-term benefits to industry. One approach to resolving this conflict is to pursue activities that provide short-term benefits that support long-term goals. The EGS Program can do exploration with industry, and require that industry use and test new technologies as a condition of funding. Conventional hydrothermal resources have to be linked to EGS technologies through early applications that clearly establish EGS value.

There is a tendency to differentiate between the hydrothermal resource and EGS. This is erroneous as there is just one geothermal resource. EGS is not a resource, but is a set of technologies for extending the economically viable geothermal resource. This is an important point since the existing geothermal industry appears at times to believe that EGS diverts resources from critical industry needs.

The EGS Program must have the geothermal industry's support, and the oil and gas industry is not going to step up until they recognize the value of the large resource base that will be available for production though enhancement of marginal geothermal systems. The EGS Program needs to carefully consider the geothermal community and the primary players of interest within oil and gas, mining, and allied industries. Mechanisms and research projects should be structured to show how the EGS Program can collaborate with industry and gain industry's support and willingness to do an ever-increasing portion of the work.

Sedimentary versus Crystalline Rock

One issue is whether to look at sedimentary or crystalline rock in the short term. The EGS Program should see whether there is enough energy in sedimentary rock formations to justify placing effort on these areas. Current stimulation technology is better developed for sedimentary formations, and that could be the medium-term focus, with the longer-term focus on developing systems in more difficult crystalline rock.

DOE should clearly establish that EGS is just a new set of methods to more cost-effectively and universally get heat out of the ground. The EGS Program seeks to establish technology that will stimulate development of currently marginal hydrothermal resources, and will also be of use in developing ever-lower grade resources in the future. *The U. S. is underlain by an immense store of heat if researchers can develop the technology that will allow its economic conversion from thermal energy to electricity*.

Demonstration Projects

The EGS Program should start field experiments at existing, partially developed hydrothermal sites where EGS technologies can be of benefit. The EGS Program should consider experiments associated with existing operating fields, and later step out to new, dedicated test sites. The EGS Program can't bring industry in to a test site after the fact. Industry must be in on the project from the beginning. Coso and Desert Peak are projects that involved industry from the start. Participation in international projects such as the IEA-GIA EGS project at Soultz, France, is of significant value to the EGS Program, with emphasis on maintaining an in-depth monitoring effort, as opposed to providing direct funding.

The group then addressed the question, "Should the Program do a large new demonstration project, including drilling?" The EGS Program could prepare a site through reservoir creation, with the government funding all the field development. A dedicated site, government owned and operated would reduce the risk associated with an EGS project, but obtaining approval and funding may be difficult. The problem with large capital expenditures through DOE is that it requires a long, involved process to obtain approval. The issue of how to structure and do field experiments should be a continuing topic, with emphasis on getting the maximum benefit for minimum funding – field experiments are expensive!

Other Points

The EGS Program should consider the applicability of the EGS approach for future demonstration work on power production from hot water co-produced with oil and gas. Geothermal power production could continue long after the fossil fluids are depleted, with possible benefits from EGS technologies to enhance water flow from these wells of opportunity.

The oil and gas industry is using CO_2 for enhanced oil recovery, and the federal government is funding work on sequestration experiments. The EGS Program could piggyback on that work, or at least have geothermal researchers on site when the experiments are done to identify lessons learned and bring them into the DOE Geothermal Technologies Program.

4. EGS Review Summary

The EGS Program Review provided a basis to: 1) assess the status of the EGS Program, 2) determine what the gaps are, 3) define a strategy to overcome challenges, and 4) provide a basis for commercial use of EGS technologies. Summaries for the first three areas are provided below. Please note that some of the review participants made recommendations that may be difficult or inappropriate for DOE. In addition, there is no prioritization, except where the reviewers may have stressed the extreme importance of the work.

4.1. EGS Technology Status

The existing activities of the EGS Program are necessary to accomplish its goals and objectives. The focused research projects and field experiments are being performed at a reasonable level of quality with no projects found lacking in quality or relevance. The general opinion was expressed that both the research activities, and especially the field experiments, must be expanded to accomplish the goals and objectives within a reasonable timeframe.

However, while the existing EGS subsection in the Multi-Year Program Plan is appropriate, it was characterized as lacking in detail, particularly in describing the path for the next 10 years. There was great concern expressed about the lack of a national commitment as evidenced by limited current funding, and the real potential for decreased funding in the future. This would necessitate even more detailed planning and analysis to focus EGS activities toward those of highest priority.

The highest priority within the EGS Program should be to define and demonstrate the technologies necessary to enhance marginal geothermal reservoirs. *This translates to a primary EGS Program activity to perform field experiments to validate new and improved technologies, and to provide substantiation of the capability to engineer cost-effective reservoirs in almost any geologic setting.* While domestic field tests were deemed to be of critical importance, meeting participants also stressed the importance of participation in international field experiments such as that at Soultz, France, as a significant opportunity to leverage valuable EGS Program funds by learning from the experiences of a collaborative field experiment. Participation is interpreted as maintaining awareness through in-depth monitoring as opposed to participation by direct funding.

4.2. Technology and EGS Program Gaps

A major perception on the part of the review participants is that the program has not completed solid analyses to define and prioritize the activities in the EGS Program Plan. This was viewed as critical given the situation of perhaps limited and uncertain future funding – coupled with the realization that achieving success will be expensive because of the size, complexity, and difficulty of reducing the technology to common and replicable practice in the field.

Another significant perception is the lack of an appropriate bond between the EGS Program and the existing geothermal industry, as reflected in the lack of understanding of the purpose for EGS, and the sense that industry has more pressing near-term goals and objectives than those expressed within the current EGS Program Plan. Industry support is critical and DOE must develop an appropriate team, with industry involved in all phases ranging from planning to execution. The EGS Program, its researchers, and field projects should also avail themselves of past and ongoing activities of the oil and gas industry, and international geothermal operations that relate to both mechanical and chemical stimulation of permeability in the subsurface.

Field experiments at Coso and Desert Peak were perceived as appropriate, as making progress, and of central importance to the EGS Program. However, the general feeling was that substantially more field experiments would be required with intimate involvement and performance by industry, which will eventually commercialize the technology. Field experiments should start with enhancing existing hydrothermal reservoirs that are marginal, then step out to the field edges that have limited permeability, then address the more challenging sites (i.e., hot, but low permeability) with no prior geothermal development ("green fields"). As EGS technology is developed, green field sites should to used to show the capability of the technology for geothermal power production throughout the United States.

4.3. Possible Next Steps

General Program Steps and Strategic Approaches

The EGS Program should aim for early successes to establish the benefits of EGS technologies to industrial partners. The EGS Program should continue in efforts to adapt existing oil and gas technologies to geothermal EGS applications, and to support getting additional power generation on line by working in existing hydrothermal fields. Success must come soon and should be clearly evidenced as additional power on line.

The EGS Program should develop strategic partnerships with industry to establish a demonstration and research program that is supported by, and is of benefit to the geothermal industry. Partnerships should focus on common technical problems, particularly by showing the application of EGS technologies in a sequential manner that maximizes impacts of improvements to existing geothermal reservoirs. DOE should start with projects to enhance productivity within existing geothermal fields, with extension to marginally productive fields as EGS technology develops. Short-term benefits can be provided to industry through EGS activities that address long-term goals. Much stronger support for EGS activities will result when industry realizes the value of EGS as evidenced by positive benefits.

The EGS Program should do significantly more detailed planning, particularly for the 'next-10-years' timeframe. The plan should be based on analyses, and should include good metrics such that the value added by the efforts can be measured. Industry and academia should be involved in all DOE planning for EGS field experiments, in execution of those plans, and in evaluation of the results of research, development, and demonstration. This includes substantial cost sharing of the work by industry. The EGS Program should perform appropriate analyses to define return-on-investment for its R&D, with detailed consideration of various technical options. Critical path analysis should be used to finalize the EGS Program Plan. All analyses and planning should be based on thorough reviews of applications of existing technology. Planning should evaluate the merits of potentially game-changing technologies, including CO_2 as a supercritical working fluid, with possible supplementary benefits of sequestration.

DOE should consider use of a collaborative program with industry to test unproven technology to establish value and to attract partners. A requirement of funding to industry and academia could be the eventual use of EGS technologies in field tests to provide for definitive validation.

Outreach Steps

The EGS Program needs to better convey to decision makers, taxpayers, stakeholders, industry and others that EGS is an opportunity to significantly enhance domestic geothermal electricity production. The EGS Program needs to overcome erroneous perceptions such as geothermal is not a large enough resource for a national program, the resource is strictly classical hydrothermal, and the resource is environmentally unacceptable (i.e., equivalent to mining or oil and gas drilling). Communication of potential benefits, status, plans, successes, and significance is imperative to developing support for EGS activities.

Technical Steps

The EGS Program has more technical advancement opportunities than it can conceivably fund in the foreseeable future, necessitating use of analyses and expert opinion to prioritize the investment portfolio. Major technical opportunities can be categorized as: how to predictably create fractures in all types of rock mechanics settings, how to characterize fractures, how to condition the reservoir as needed to ensure desired flow and thermal performance, and how to manage the reservoir for sustainability.

The permeability of hot rock, expressed generically as the extent of the fracture cloud, is a dominant factor in determining potential cost-effectiveness of a geothermal energy system. The recommended starting point for fracture creation is adapting existing stimulation techniques used in oil and gas reservoirs to geothermal conditions. While addressing a variety of geologic settings, a fundamental understanding of rock mechanics and the effects of stress on pre-existing fractures, and appropriate stimulation methods, will be required to demonstrate EGS on a commercial scale. Technology needs to be developed to provide better understanding of in-situ stress, including how it changes during stimulation and production. Improved stress and strain mapping tools and methods will be invaluable for field tests. Methods to create fractures other than hydro fracturing should be examined, including acid and chemical well fracturing and stimulation.

A technical need is how to characterize the reservoir by improved microseismic methods. Relative and absolute location accuracy for defining fault structures in the subsurface are required. InSAR, smart tracers, and improved tracer-test interpretation will also aid in characterizing geothermal reservoirs. Geodetic data and hyperspectral imaging may be helpful. Stress field analysis may also provide information useful in determining fracture orientation and productivity. The EGS Program should consider developing new borehole diagnostic tools to assess fracture flow and connectivity.

Technical opportunities in reservoir management include developing a better understanding of rock-water interaction to sustain permeability and to ensure longevity of proppant materials. Laboratory measurements of both rock properties and geochemical reactions are necessary for understanding of flow path mechanics and effects of rock-water interactions. Improved tracer technology should also provide insight into flow within enhanced reservoirs and the heat transfer surface within a reservoir. Numerical modeling methods must be extended to fully couple fluid flow, reservoir mechanics and rock and water interactions, and to forecast thermal breakthrough.

Specific opportunities for improving measuring techniques and equipment include the need to:

- Develop more robust high-temperature pumps with industry collaboration.
- Provide the scientific base for industry to develop cheaper and longer-lived high temperature instrumentation.
- Improve downhole-logging capability. Better techniques are needed to collect logs in higher-temperature wells and interpreting the meaning of logs in environments that may be dramatically different than the sedimentary environments of oil and gas.
- Develop advanced system concepts such as coil tubing drilling and horizontal drilling.
- Refine and show applicability of existing predictive stimulation codes such as STARS from the petroleum industry and the geothermal stimulation code developed by Geowatt.
- Investigate refined remote sensing technology with greater sensitivity to show subtle temperature differences between regional temperatures and temperatures above hidden thermal resources.
- Learn how to determine subsurface temperatures beyond just drilling temperature gradient holes. This may require extrapolation of heat flow data and tabulation of temperatures from mineral resource evaluation and water-well drilling.
- Develop reliable sonic/gamma/density/imaging technology for both surface and downhole measurements.
- Work with industry to develop geothermal downhole samplers, and by piggybacking on oil and gas technology.
- Provide better zonal isolation tools.

Field Verification Steps

The EGS Program should approach field verification in a stage by stage manner. This should start by enhancing marginal, existing hydrothermal reservoirs. As technology is developed, emphasize green field sites to show the capability to establish geothermal power production at sites throughout the United States. Current field experiments at Coso and Desert Peak are important to the EGS Program and should be completed.

The EGS Program should develop an inventory of wells of opportunity, and as funding is available, perform extensive stimulation tests in geothermal fields and in high-temperature oil and gas fields. The initial focus should be on transferring technology from oil and gas reservoir engineering to the geothermal environment. The geothermal industry, and as appropriate, the oil and gas industry, should be cost-sharing partners. Field-testing must be performed with the newest and best reservoir engineering, geoscience, and drilling technology

The EGS Program should begin now to identify two or three green field sites for EGS development. The green field sites should represent diverse geologic settings to show the existence of a large viable geothermal resource base. General test plans should be developed, suitable for use in funding opportunity announcements. Funding should be competitively awarded, with industry completing the detailed test plans, and performing field experiments jointly with DOE. As mentioned previously, industry and academia should be essential team partners with DOE and its laboratories in field test performance.

The EGS Program should be alert for other potential demonstration opportunities, such as the possible applicability of the EGS approach for future demonstration work on power production from hot water co-produced with oil and gas. Geothermal power production could continue long after the fossil fluids are depleted, with possible benefits from EGS technologies to enhance water flow from these "wells of opportunity." This could be an opportunity to build partnerships with the oil and gas industry.

Other Discussed Actions

The EGS Program should work with industry to show success sufficient to support a national imperative to expand development of geothermal energy as an essential part of a National Energy Plan. This would provide a base for DOE geothermal energy funding requests. Likewise, the EGS Program should work with industry on evaluating the potential of government incentives for increasing geothermal electricity production.

Conclusions

The reviewers believe that:

- DOE must demonstrate to the geothermal industry that EGS research is of benefit to existing, poorly productive geothermal systems.
- DOE must focus on technology that supports existing low-productivity geothermal operations, and also develop technology needed for the future.
- DOE, through successful demonstrations of EGS technology, should get a buy-in from the oil and gas industry that will allow development of larger scale (>200 MWe) geothermal operations
- DOE must continue its follow-through and complete the Coso and Desert Peak demonstration projects.

5. Project Summaries

Initiating Office	CID	Recipient Name	Project Title	Project Period Start	Project Period End	Principal Investigator	Cumulative Obligations	Total Recipient Share	Total DOE Share	Total Project Value
GO	14289	The Pennsylvania State University	Stress and Chemistry Mediated Permeability Enhanced/Degradation in Stimulated Critically Stressed Fractures	10/1/2004	12/31/2007	Derek Elsworth	$ 476,195	$ 128,956	$ 476,195	$ 605,151
GO	14290	University of North Carolina	Real-time fracture monitoring in Engineered Geothermal Systems with seismic waves	10/1/2004	12/31/2007	Dr. Jose Rial	$ 518,627	$ 134,828	$ 518,627	$ 653,455
GO	14291	SAIC - Science Applications International Corporation	Evaluating Permeability Enhancement Using Electrical Techniques	10/1/2004	12/31/2007	John Pritchett	$ 458,732	$ 86,258	$ 458,732	$ 544,990
GO	14292	University of Utah	Geochemical Fracture Characterization - Water Rock	10/1/2004	9/30/2007	Dr. Joseph Moore	$ 393,187	$ 215,000	$ 393,187	$ 608,187
GO	14293	Pinnacle Technologies, Inc.	Evaluation of Oil-Industry Stimulation Practices for Engineered Geothermal Systems	10/1/2004	12/31/2006	Leen Weijers	$ 288,327	$ 96,108	$ 288,327	$ 384,435
GO	14294	Duke University	ICEKAP 2004 - Collaborative Joint Geophysical Imaging Project at Krafla & IDDP	6/5/2004	12/31/2006	Peter Malin	$ 170,384	$ 96,446	$ 170,384	$ 266,830
GO	14300	University of California, San Diego	Enhanced Geothermal Systems Research and Development: Models of Subsurface Chemical Processes Affecting Fluid Flow	10/1/2004	12/31/2007	Nancy Moeller Weare	$ 498,646	$ 124,804	$ 498,646	$ 623,450
GO	16057	Hattenburg Dilley & Linnell, LLC	Identifying Fracture Types and Relative Ages Using Fluid Inclusion Stratigraphy	6/1/2006	12/31/2007	Ms. Lorie M. Dilley	$ 148,400	$ 37,881	$ 148,400	$ 186,281
GO	16058	Foulger Consulting	Seismic (MEQ) Characterization of EGS Fracture Network Lifecycles	9/1/2006	12/31/2007	Ms. Gillian R. Foulger	$ 125,071	$ 60,674	$ 125,071	$ 185,745
GO	16059	University of North Dakota	Fracture Propagation and Permeability Change under Poro-thermoelastic Loads & Silica Reactivity in Enhanced Geothermal Systems	9/1/2006	3/31/2009	Mr. Ahmad Ghassemi	$ 321,322	$ 121,824	$ 321,322	$ 443,146
GO	16060	University of Utah	Fracture Evolution Following a Hydraulic Stimulation within an EGS Reservoir	9/1/2006	12/31/2007	Mr. Pete Rose	$ 159,976	$ 40,000	$ 159,976	$ 199,976
GO	16061	Massachusetts Institute of Technology	Experimental and Analytical Research on Fracture Processes in Rock	6/1/2006	6/30/2008	Mr. Herbert H. Einstein	$ 169,815	$ 42,494	$ 169,815	$ 212,309
ID	14186	University of Utah	Creation of an enhanced geothermal system through hydraulic and thermal stimulation	8/15/2001	12/31/2006	Peter Rose	$ 5,646,361	$ 3,296,819	$ 5,646,361	$ 8,943,180
ID	14405	Calpine Corporation	Geysers Permeability Enhancement	9/20/2002	3/31/2007	Mitchel Stark	$ 425,000	$ 287,687	$ 425,000	$ 712,687
ID	14406	Ormat Nevada, Inc.	Desert Peak East EGS Project	9/20/2002	12/31/2007	Stuart Johnson	$ 2,413,323	$ 691,509	$ 2,413,323	$ 3,104,832
ID	14416	University of Utah	Structural Controls, Aleration, Permeability and Thermal Regime of the Dixie Valley Geothermal Area from New Generation, Magnetotelluric-galvanic Array Surveying	9/1/2002	8/31/2007	Philip Wannamaker	$ 165,808	$ -	$ 165,808	$ 165,808
						TOTALS	**$12,379,174**	**$5,461,288**	**$12,379,174**	**$17,840,462**

5.1. Fracture Mapping and Monitoring

Evaluating Permeability Enhancement – John Pritchett

Objective

To create "artificial" geothermal reservoirs, most proposed EGS techniques seek to increase the flow capacity by hydrofracturing hot but impermeable rock, pumping high-pressure fluid into one or more injection wells and enhancing permeability by opening pre-existing sealed fractures and/or creating new ones. Although there is little question that fracturing rock and creating permeability in this way will often be feasible, the real difficulty is appraising, in detail, the permeability structure of the fracture network thereby induced. It is important that the hydraulic connections between the production and injection wells be neither too poor (resulting in no fluid flow) nor too good (resulting in "short-circuiting" and rapid cooling). Unless the permeable fractures can be accurately mapped, the cost of subsequent trial-and-error drilling to establish a suitable fluid circulation system is likely to dominate project economics and render EGS noncompetitive in the energy market for the indefinite future.

The current state of the art in hydrofracture evaluation and characterization is micro-earthquake (MEQ) monitoring, but this technique, by itself, does not provide sufficient precision concerning fracture locations and cannot distinguish permeable fractures (connected to the fracture network) from impermeable (isolated) ones. But combining micro-earthquake monitoring with downhole self-potential (SP) electrical monitoring has the potential to provide more information than either technique alone.

Specific objectives of the project are to employ theoretical analyses, numerical simulation techniques and supporting laboratory measurements to appraise the feasibility of hydrofracture characterization using a combination of downhole SP monitoring and MEQ monitoring techniques, and to identify recommended measurement and analysis techniques that are practical in the field.

Status

During the first year of the project (October 2004 – September 2005), theoretical calculations were carried out to characterize the SP signals caused by the pressurization of a hydrofracture. The influence of the key parameters (fracture size, transmissivity, compressibility and geometry; the porosity, permeability, compressibility and electrical properties of the surrounding rock; and the temperature and composition of the *in-situ* and injected fluids) was assessed.

During the second year (October 2005 – September 2006), core samples from the Coso EGS test site were tested in the laboratory in Japan to appraise key electrical parameters relevant to SP signal generation and propagation. Specific techniques and design concepts were formulated for the deployment of the technique using downhole SP detectors in observation wells.

During the final year (October 2006 – September 2007), computer software suitable for routine interpretation of SP signals caused by hydrofracturing operations to help characterize the fracture network (in combination with microseismic measurements) will be developed and distributed.

Real-Time Fracture Monitoring – Jose Rial

Objective

This three-year project deals specifically with the development of software to detect and locate the seismicity induced by the EGS operation and processes recorded seismic waves to image crack geometries, crack intensity and volume of rock affected, as the seismic signals stream into the array. In the field, laptop computer displays show the expanding cloud of seismic events, followed by images of crack geometry and fracture intensity that grow clearer as newer data arrives and the inversion of the measured SWS parameters stabilizes. The multiple programs necessary for this project are being consolidated now into a major code written in C-language.

Approach/Background

A number of well-established techniques to detect seismograms automatically are used in the approach. This year the focus is in consolidating the shear-wave splitting automatic measurement, inversion codes and visualization programs to make the entire process of crack detection and characterization fully automatic. The main steps are:

- Real-time micro-earthquake detection and location
- Delayed-time seismic velocity model inversion
- Real-time detection of shear-wave splitting
- Delayed-time inversion of shear-wave splitting.

Project Status

The project is on schedule.

Accomplishments

Researchers have developed a new method to automatically measure the polarization and delay times of the split waves that performs much better than any of the traditional methods based on cross correlation. Researchers estimate the values of polarization and delay time by using of existing automatic wave arrival picking techniques. The idea is to use the automatic picking algorithm to detect significant arrival time differences (significant = difference between the arrival times of the fast and slow shear waves is larger than 10 samples) between the two horizontal components in a rotated coordinate. Researchers rotate the coordinates from 1 to 180 degrees (1 degree increments), and for each rotated coordinate the variance of the interval in the slow component is calculated. The polarization will be the angle corresponding to the rotated coordinate in which the differential arrival time is significant and the variance in the slow component reaches its minimum. The automatic method performs with 85% success (85 out of 100 seismograms are correctly identified compared to measurements made by hand). The 15% remaining are ambiguous recordings even to a human operator. A complete description of the method is available on request.

Induced Seismicity – Ernie Majer

Objective

In 2006 LBNL initiated and maintained MEQ monitoring at the Desert Peak EGS project. This work is being integrated and augmented with the Desert Peak project to correlate seismicity with production and injection rates, volumes, location of injection/ production with reservoir engineering properties and thermo-mechanical analysis. Locations of MEQ's, source mechanisms, rates of seismicity, rates of energy release, and magnitudes of the events will be calculated and correlated with known faults and geology. This work will be in collaboration with GeothermEx and ORMAT who are performing hydrofracture stimulation in a selected well. Several phases of the work will be established to aid in the design and planning of seismic monitoring of seismicity associated with EGS operations. ORMAT has agreed to drill dedicated wells for the MEQ. The work will be coordinated with any results from the core analysis (LLNL) and other work scheduled to be carried out as part of the EGS project by Ormat.

Approach and Accomplishments

The project coordinating with the IEA on EGS induced seismicity was essentially completed in FY06 but a few minor tasks such as the completion of the peer reviewed publication of the white paper and finishing the final version of the protocol remain.

Seismic Characterization of EGS – Gillian Foulger

Objective

Enhanced Geothermal Systems (EGS) have the potential to significantly improve the ability to efficiently utilize the nation's geothermal potential and thus warrant research and technological development. A crucial tool for monitoring EGS experiments, and understanding the formation and evolution of fracture systems thereby produced is seismic monitoring of the induced microearthquakes (MEQs) that are generated as fractures form and evolve. The anticipated benefit from this work includes a detailed understanding of the size of the fractured volume, the degree and type of fracturing, and the evolution of its characteristics with time.

What is being done?

a) Currently existing state-of-the-art seismic techniques will be enhanced, including computer programs to determine i) relative earthquake locations with sufficiently high resolution to image individual fracture planes, ii) highly accurate three-dimensional reservoir structure, and changes in structure associated with reservoir evolution, and c) full moment tensors, which provide information on opening and closure of fracture planes and cast light on fluid flow into and out of fractures. b) These new programs will be applied to EGS-related MEQs from the Coso geothermal area, where several EGS experiments have been conducted or are planned. c) The results will be integrated with other geophysical and operational data available to provide a holistic interpretation and final model of seismic characterization of EGS-fracture-network evolution.

Approach and background

Task 1. Software development

Subtask 1.1 High-resolution MEQ Hypocenters

Subtask 1.2 Three- and Four-Dimensional Crustal Structure

Subtask 1.3 Microearthquake Mechanisms

Task 2. Application of new techniques to the Coso geothermal area

Subtask 2.1 High-resolution MEQ Hypocenters

Subtask 2.2 Three- and Four-Dimensional Crustal Structure

Subtask 2.3 Microearthquake Mechanisms

Task 3. Integration of results with other knowledge

The results will be interpreted together with other data and results available from the area, including other geophysical, operational and EGS-related data. *Expected outcome:* a generic seismic (MEQ) characterization of the EGS-stimulated fracture network life cycle.

Project status and accomplishments

The project will commence January 1st, 2007.

5.2. Fracture Stimulation

Chemical/Hydraulic/Thermal Stimulation of EGS – Pete Rose

Objective

An alternative to hydraulic fracturing in the stimulation of wells within Engineered Geothermal Systems is chemical stimulation. In chemical stimulation, minerals are dissolved within the formation through the addition of dissolution agents to the circulation fluids. Chemical stimulation works by dissolving minerals within fractures, thereby increasing fracture apertures and enhancing fracture permeability. The objective of this project is to design, develop and demonstrate methods for the chemical stimulation of candidate EGS reservoirs as well as the chemical treatment of scaled wellbores. The laboratory dissolution process will be modeled using a reactive transport code and the resulting model will be

Injection of a Calcite Dissolution Agent into Coso Well 32A-20.

used to predict the effectiveness and economics of using the emerging-candidate dissolution agents for field-scale chemical stimulation.

Project Status and Accomplishments

First, a set of candidate chemical compounds capable of dissolving calcite was identified. A series of tests was then performed on each candidate in order to screen it for thermal stability and reactivity towards calcite. The leading candidate dissolution agent to emerge from the screening tests was nitrilotriacetate (NTA). It was tested in a field experiment at the Coso geothermal field, where it proved very effective in removing wellbore- and near-wellbore-calcite scale. The laboratory flow reactor was redesigned and a TOUGHREACT reactive transport model of the dissolution of calcite using NTA was constructed. Initial results indicate that the current reactive transport model much more accurately simulates the laboratory reaction than did the previous model. Experiments are being designed for the purpose of calibrating the model output with the flow-reactor data in order to improve the predictive power of the model. The research objectives of this grant were recently augmented to target the dissolution of silica and quartz. Initial experiments show that silica and quartz can be dissolved in the presence of calcite using solutions of NTA at high pH's, providing for a much more economical approach to silica dissolution than the conventional one using hydrofluoric acid.

In addition to the modeling of the mineral dissolution agents, the TOUGHREACT model is being used as a tool to better understand the mineral dissolution processes associated with the Coso/EGS hydraulic stimulation experiment being conducted under the related cooperative agreement DE-FC07-01ID14186. First, petrologic analyses of wellbore cuttings from Coso wells 46A-19RD were conducted in order to identify the mineral assemblages likely to be lining the fracture walls and that would be in contact with injection fluids. Next, these mineral compositions were input as data into a simplified 1-D version of the TOUGHREACT model. The model will then run under a variety of conditions in order to characterize the mineral dissolution/precipitation processes and aid in the design of injection strategies.

Evaluation of Oil Industry Stimulation Practices – Leen Weijers

Geothermal energy extraction is typically achieved using long open-hole intervals in an attempt to connect the wellbore with the largest possible rock mass. This presents a problem for the development of EGS, due to the challenge of obtaining uniform stimulation throughout the interval, which can prevent efficient heat transfer and thus feasible energy costs. The creation of complex, extensive fracture networks from hydraulic stimulation, as used in oilfield reservoirs, allows for the economical heat extraction from low permeability rock. Consequently, researchers evaluated a variety of techniques that are commonly used in hydraulic fracturing of oil and gas wells to increase and evaluate the stimulation effectiveness in EGS. The significance of successful hydraulic fracturing treatments of EGS is to maximize the production of geothermal energy, minimize the costs of stimulation and production, and minimize risk.

The approach is to transfer the knowledge obtained from and the techniques used for the stimulation of oilfield reservoirs by hydraulic fracturing to the stimulation of geothermal reservoirs. The methodology is based on three principal tasks:

1 Identify oilfield equivalents for EGS applications: Evaluate existing mapping datasets, account for fracture growth physics in EGS applications, develop calibrated fracture models, and conduct a sensitivity study for stimulation treatment design tests.
2 Evaluate methods to improve fluid diversion and penetration: Evaluate propped versus water fracturing, evaluate zonal isolation and diversion techniques, and evaluate methods for alternating fracture growth mode or fracture reorientation.

3 Study the applicability of fracture growth diagnostics: Evaluate the applicability of various fracture diagnostic techniques for EGS, evaluate EGS field test data, and reconcile with calibrated model.

Researchers are in the final stages of completing tasks 1 and 2. Unfortunately, researchers had to cancel task 3 due to problems with the designated EGS well at Desert Peak. However, due to recent developments at Desert Peak, researchers are currently investigating whether researchers can reestablish task 3. In addition to the final report, which is still in progress and currently for the most part in the review phase, researchers published three peer–reviewed journal papers that were presented at international meetings:

1 "Evaluation of oil–industry stimulation practices for Enhanced Geothermal Systems: Lessons learned from the Barnett Shale," *GRC Transactions*, 2005.

2 "Developing calibrated fracture growth models for various formations and regions across the United States," Society of Petroleum Engineers (SPE) paper, 2005.

3 "Creating extensive and complex fracture networks for Enhanced Geothermal Systems: An overview of oilfield stimulation and diversion techniques," *GRC Transactions*, 2006.

It is the intent that the publications will be used as inspiration to discover novel and improved techniques to improve EGS reservoir design and development (i.e., isolating stimulation zones, design of reservoir stimulations, reservoir stimulations, and fracture propping). However, the results also highlight the fact that differences between oilfield and EGS necessitate further study.

EGS Potpourri – Joel Renner

Numerical Tools for Reservoir Management (Shook)

Given the complexity of geothermal reservoirs, numerical models are frequently used to help manage the resource. These models require as input reservoir properties such as permeability, porosity, fracture spacing, etc., whose values are typically not known with any certainty. Good agreement between prediction and observation implies the reservoir parameters input to the model are "correct" and the model can then be used to forecast future reservoir behavior. This "history matching" is frequently a time consuming and subjective exercise.

The approach taken in this project is to enhance the suite of numerical tools available to the geothermal industry for reservoir management. As the most widely used reservoir model by the domestic geothermal industry, TETRAD was identified as the reservoir model core. New software and program interfaces have been written to couple TETRAD to other codes in order to enhance the effectiveness of reservoir modeling.

The public domain inverse model PEST (Parameter ESTimation) was identified as the most appropriate inverse engine to couple to TETRAD. PEST operates only on input/output files, modifying input parameters as it minimizes the differences between model output and field observations. PEST furthermore treats the forward model (TETRAD in this case) in a "batch mode" sense. The flexibility of the PEST code, and the ability to add more model instructions, make it an ideal candidate for this project.

Accomplishments

Tet^{-1} was released in FY03 to geothermal users (CalEnergy, Unocal, Caithness Operating Company), and has been used in 3 reservoir field studies by the operators. The project has been completed.

The following papers have been presented, submitted, and/or are in preparation for submittal to journals under this project.

Shook, G.M., "Preliminary Efforts to Couple TETRAD with Geophysics Models," **Trans.**, 27th Stanford Workshop on Geothermal Reservoir Engineering, Jan. 2002.
Shook, G.M., "An Inverse Model for TETRAD: Preliminary Results," **Trans.**, Geothermal Resources Council, Vol. 26, Sept. 2002.
Shook, G.M., "New Data and File Requirements for Tet^{-1}," **Trans.,** 28th Stanford Workshop on Geothermal Reservoir Engineering, Jan. 2003.
Shook, G.M., and J. Doherty, "Tet^{-1} v. 2 Users Manual," January 2005.
Shook, G.M., and A.H. Wylie, "Parameter Estimation from Tracer Testing at OK Tools," internal report for EPA Region 1, January, 2005.
Shook, G.M., and A.H. Wylie, "Improved parameter estimation procedures in inverse modeling: Incorporating data analysis as field constraints," 2005, submitted to Water Resources Research, in review.

Reservoir Characterization for EGS and Hydrothermal Systems (Shook)

The purpose of this project is to continue to identify reservoir parameters that can be determined from tracer testing, to develop the appropriate tracer interpretation toolkit for the geothermal industry's use, and to work with the industry in deploying and interpreting tracer testing for geothermal reservoir characterization. Despite decades of conducting tracer tests, geothermal tracer test interpretation remains in its infancy. Developing simple tools and educating the community in their use will remove this deficiency. The methods apply equally to EGS and hydrothermal geothermal reservoirs.

Tracer testing is one of the most powerful reservoir characterization methods. Appropriately designed tracer tests yield information such as reservoir volume and geometry, fluid velocities and thermal sweep efficiency, thermal velocities, surface area, and other reservoir properties. Specific goals for this project include:

- Determination of heat transfer surface areas and thermal velocities in single-phase liquid and superheated steam, fractured, geothermal reservoirs.
- Develop new interpretation methods to evaluate EGS well stimulation.
- Document and distribute tracer interpretation requirements and procedures.
- Conduct training for the geothermal industry.

Project research has been completed and the final report has been released (http://geothermal.inl.gov/publications.shtml)

Induced Seismicity (Karner)

The United States Department of Energy has set long-term national goals for the development of geothermal energy that are significantly accelerated compared to historical development of the resource. To achieve these goals, it is crucial to evaluate the performance of previous and existing efforts to create enhanced geothermal systems (EGS). Understanding the processes that enhance fluid flow in crustal rocks is a key step towards extracting sustainable thermal energy from the Earth. To achieve these goals, geoscientists need to identify the fundamental parameters that govern how rocks respond to stimulation techniques, as well as the factors that control the evolution of permeability networks. Also, these factors must be suitably monitored and/or characterized over a range of temporal scales before the evolutionary behavior of geothermal fields can be properly assessed.

Laboratory experiments provide a wealth of information related to mechanics of fracture initiation, fracture propagation processes, factors influencing fault strength, and spatio-temporal evolution of fracture properties. This project reviewed laboratory observations of strength and fluid transport properties during deformation of simulated faults. When related to geophysical and geologic measurements obtained from engineered geothermal systems (e.g. microseismicity, wellbore studies, tracer analysis), laboratory results provide a means by which the evolving thermal reservoir can be interpreted in terms of physico-chemical processes.

To date, microseismicity has provided an invaluable tool for delineating the fracture network produced by hydraulic stimulation of geothermal reservoirs. While the locations of microseismic events are of fundamental importance, there is a wealth of information that can be gleaned from the induced seismicity (e.g. fault plane solutions, seismic moment tensors, source characteristics). When related to observations from laboratory experiments, these systematic trends can be interpreted in terms of mechanical processes that most likely operate in the fracture network. This study considered the mechanical properties that can be inferred from observations of microseismicity in geothermal systems. These properties lead to interpretations about fracture initiation, seismicity induced after hydraulic shut-in, spatial evolution of linked fractures, and temporal evolution of fracture strength. The correlations highlight the fact that a combination of temperature, stressing rate, time, and fluid-rock interactions can alter the mechanical and fluid transport properties of fractures in geothermal systems.

The project has been completed and a final report has been released by the Idaho National Laboratory (http://geothermal.inl.gov/publications.shtml).

Fracture Evolution after Hydraulic Stimulation – Pete Rose

Objective

Fracture networks within both conventional geothermal reservoirs and Enhanced Geothermal Systems (EGS) have been observed to evolve in response to fluid circulation. This evolution is manifested by changes in pressure and flow rate at injection and production wells, which, in turn, results from changes in reservoir permeability. No systematic approaches have been developed, however, whereby operators can predict the rate of such change or even foretell whether the changes will be beneficial or deleterious to reservoir performance. Furthermore, no systematic studies have been conducted to compare the rate of fracture evolution within an EGS to that in conventional hydrothermal systems. Nevertheless, this is a critical element in predicting the long-term performance of an EGS.

The Navy I geothermal power plant in Coso Hot Springs, California.

The objective of this project is to evaluate changes to fluid-flow patterns within an EGS reservoir as the result of long-term injection following a hydraulic stimulation. Through reactive transport modeling, the transient behavior of hydrothermal fractures will be simulated and predicted. A series of high-resolution tracer tests will then be conducted to measure changes in fluid flow parameters over time. The model-predicted changes in tracer response will then be compared to the tracer data. The model will be updated and calibrated as necessary in order to be capable of predicting variations in flow capacity over time. The forward modeling capability of the proposed reactive transport modeling will allow for the prediction of fracture life cycles.

Project Status and Accomplishments

The eponymous project was designed as a follow-on experiment to the Coso/EGS project currently under way under the cooperative agreement DE-FC07-01ID14186 entitled "Creation of an Enhanced Geothermal System through Hydraulic and Thermal Stimulation. This project therefore has no progress to report, since the research cannot start until DE-FC07-01ID14186 is complete.

5.3. Fracture Mechanics and Permeability

Fracture Prediction – Jeff Roberts

Objective

Effective implementation of EGS demands improved understanding of the processes that alter fracture permeabilities during forcings induced by reservoir operation. Particularly important is the development of improved conceptual and computational models of fracture alteration due to the influence of coupled geochemical and mechanical processes. The overall goal is to perform laboratory experiments and conduct hydraulic and geochemical modeling to quantitatively assess permeability evolution of artificial and natural fractures as a function of effective stress, fluid chemistry, and temperature. Results from these experiments will lead to improved understanding of the coupled mechanisms that lead to permeability alteration and facilitate development of optimal strategies for sustaining permeability in support of DOE EGS field experiments. The results will also provide a data set that will aid in the diagnosis of system response to EGS operations. Researchers are coordinating these efforts with the ongoing field experiment at Desert Peak through collaboration with industry partners at ORMAT and GeothermEx.

Approach and background

Researchers measure permeability and fracture evolution in EGS rocks at reservoir conditions to determine what physical and chemical properties of rocks and fluids control permeability evolution in geothermal fields. Experimental studies have consisted of two distinct components: 1) long term fracture permeability evolution experiments with fluids that are not in chemical equilibrium with the host rock to measure the influence of alteration of fracture surfaces; and 2) shorter term experiments to quantify the effects of thermal stress on fracture permeability when the fluid and rock are not in thermal equilibrium. In both types of experiments, the fracture surfaces are characterized using high-resolution surface profilometry and, in some cases, scanning electron microscopy (SEM). These experimental efforts are integrated with computational modeling of fluid flow, geochemical reactions and heat transfer in the fractured cores to both aid in experimental design and interpretation of experimental results. Furthermore, these modeling techniques will allow us to extend the results to environments consisting of different mineral-fluid combinations.

Project status and accomplishments

In FY06 the experiments showed two distinct regimes of fracture permeability evolution. One where relatively low flow injection fluid causes a marked decline in effective hydraulic aperture over time in quartz-rich Desert Peak quartz monzonite and a second where rapid non-equilibrium (chemical/thermal) fluid flow results in permeability increases. The ongoing low flow experiments demonstrate that fluids far from equilibrium (undersaturated) result in more rapid reduction in permeability than silica-rich fluids where the potential for both dissolution and precipitation exists. This suggests the dissolution of contact points between the fracture surfaces controls the permeability evolution. Alternatively, fast flow experiments exhibit permeability increases, which, researchers hypothesize, result from microfracturing along fracture surfaces caused by large thermal gradients during injection. Ongoing experiments and modeling are aimed at testing this hypothesis through characterizing the fracture surfaces before and after experiments, and by modeling the evolution of the temperature distribution within the core during these experiments.

Stress and Chemistry Mediated Permeability – Derek Elsworth

Objective

The development of a long-lived, low impedance, broadly swept, and high heat transfer system is essential in addressing the 5 cents/kWh goal for EGS. This project is examining the interactions between stress and chemistry that control the magnitude and longevity of permeability-enhancement that is central to creating and sustaining a viable reservoir. Specifically, researchers are examining mechanisms of permeability evolution on hydraulically- and chemically-stimulated critically stressed fractures that represent principal methods of developing the reservoir.

Approach

Researchers are examining the respective roles of stress in dilating fractures or in plugging them by the development of wear products, and of chemical effects by the partially competing roles of dissolution and precipitation. These interactions are being examined on fractured core samples under recreated reservoir conditions: one suite in an X-ray transparent hydrothermal reactor, and a second suite in an opaque reactor with controls over applied shear stresses. The data from these experiments contribute to constitutive relations that relate the respective roles of stress and chemistry in the evolution of permeability and strength of fractures. These data are then up-scaled to reservoir conditions by the linking of numerical models which couple the influence of evolving fields of stress, temperature, chemistry and fluid-throughput on the evolution of prototype and real reservoirs.

Project status and accomplishments

Flow-through experiments extending to durations of one-half-year have indicated the important interaction of stress and chemistry in controlling the evolution of fracture permeability in systems pushed far from equilibrium. These systems have demonstrated permeability declines of multiple orders of magnitude occurring over the test duration, with late-time recovery occurring in some instances. Short-duration tests on critically-stressed and sheared fractures have shown the important influence of wear products generated on the fracture surfaces in modulating permeability; these experiments will be extended to examine the evolution of chemical conditions within the fracture, and the influence of this on permeability. These limited data have been used to define preliminary constitutive laws for the evolution of fracture permeability, constrained by the influence of both effective stresses and temperatures on the mechanical response, and also on the dissolution behavior of major components. These constitutive relations have been incorporated within models for the coupled mechanical, fluid transport and chemically reactive response of the system, and applied to represent the evolution of prototype reservoirs.

Together, these data contribute critically to the ability to create and to sustain low-impedance but high-heat-transmission EGS reservoirs, to engineer permeability augmentation, and potentially to manage the effects of micro-seismicity.

Fracture Propagation and Silica Precipitation Effects – Ahmad Ghassemi

Objective

The purpose of the project is to *(I)* investigate the fracture propagation and the response of a fracture (or a fracture zone) to water injection with reference to EGS; and *(II)* investigate the variation of fracture permeability and fluid pressure near injection regions of EGS while considering coupled poro-thermoelastic effects and mineral precipitation/dissolution processes.

Relevance

It is generally accepted that the geological conditions favorable for the creation of an EGS include optimally oriented and stressed fractures that can be made permeable (and maintained) through shear failure resulting from hydro-thermo-chemical stimulation. Therefore, it is necessary to understand and be able to make predictions regarding fracture behavior under site-specific EGS conceptual models. These models used in conjunction with field data from Coso and Desert Peak will aid in cost efficient development of EGS and also increase the resource base through technology development.

What is being done?

Part (I) of the project involves development of poro-thermo-mechanical models to study fracture propagation and slip (3D) in geothermal reservoirs, including advanced numerical algorithms for modeling mode I and II fracture propagation and interaction. The numerical models and analytical algorithms will be used to investigate the influence of the coupling between temperature, pore pressure, and stress on fracture initiation and propagation in rock, including slip along pre-existing natural fractures. Part (II) consists of development and use of fundamental analytical/numerical models to infer the individual & combined influences of thermal, poroelastic, and silica dissolution/precipitation processes on fracture permeability and pressure change over the time and spatial scale of interest to reservoir development in the Basin and Range environment (stress state, pore pressure, temperature, rock type).

Approach

In *Part I* project objectives will be attained by (i) development of a fully-coupled poro-thermo-mechanical boundary element code for modeling transient fracture behavior in enhanced geothermal systems, with reference to various stress states and lithologies; including mixed-mode propagation of natural cracks and hydraulically-driven fractures, (ii) development of a three-dimensional poro-thermoelastic fracture model to study (a) the impact of injection/extraction on the reservoir's state of stress, and fracture slip with reference to Coso injection experiments. In *Part II* researchers will (i) consider coupled effects of temperature, pore pressure, and silica precipitation/dissolution by development of analytical and hybrid finite difference-boundary element model (FD-BEM), and (*ii*) apply the models to study fracture permeability and pressure evolution in injection/extraction operations involving fractures, as a functions of injection rates, in-situ pore pressure, rock properties, temperature and silica saturation of the injected fluid. The proposed numerical models will be used in conjunction with field data and injection results/observations provided by GeothermEx.

Project status and accomplishments

Project started on 10/01/2006 and is moving along as planned.

Rock Fracture Processes Research – Herbert Einstein

Objectives

- Understand fracture propagation and interaction
- Create basis for methods allowing one to indirectly infer fracture mechanisms in the field

Accomplishments

The project negotiations were finalized by the end of August 2006 and the actual work on the project started. Mr. J. Miller is the RA on the project. He has used most of his time on the project to familiarize himself with sample preparation and testing. At this stage (end of September) he is now ready to do everything by himself. Although mostly a learning experience, what Mr. Miller did fits actually into the proposed project program Task 1, Basic Experiments.

Project Status

As mentioned above, the project only started on September 1 but work on Task 1 as proposed for this phase has been done.

Monitoring of pressure and fracture
experimental equipment during tests

5.4. Fracture Chemistry/Petrography

ToughReact – Karsten Pruess

Objective

The overall purpose is to develop new engineering tools and a better understanding of the coupling between fluid flow, heat transfer, chemical reactions, and rock-mechanical deformation, to demonstrate new EGS technology through field applications, and to make technical information and computer programs available to the technical community.

Project Activities

The research has focused on two main areas, (1) chemical interactions between rocks and fluids and their impact on EGS development and operation, and (2) investigating the novel concept of using CO_2 (carbon dioxide) as heat transmission fluid in EGS, to achieve enhanced energy recovery with simultaneous sequestration of carbon.

Approach and Background

This project has been active for several years and has focused on developing, enhancing and applying mathematical modeling capabilities for fractured geothermal systems.

Project Status and Accomplishments

Modeling of chemical interactions between rocks and fluids was performed with strong focus on EGS experiments at Coso, and supporting laboratory tests. Researchers have identified new ways for controlling rock-fluid interactions by tuning injection water chemistry, and are developing techniques to prevent or remedy scale deposition in EGS operations. The efforts on EGS with CO_2 as heat transmission fluids have demonstrated enhanced heat extraction as compared to water systems. Researchers have also performed studies to identify future research needs for EGS with CO_2.

Selected Publications

Mella, M., K. Kovac, T. Xu, P. Rose, J. McCulloch and K. Pruess. Calcite Dissolution in Geothermal Reservoirs Using Chelants, *Transactions, Geothermal Resources Council,* September 2006.

Pruess, K. Enhanced Geothermal Systems (EGS) Using CO_2 as Working Fluid – A Novel Approach for Generating Renewable Energy with Simultaneous Sequestration of Carbon, *Geothermics,* Vol. 35, No. 4, pp. 351–367, August 2006.

Pruess, K. and M. Azaroual. On the Feasibility of Using Supercritical CO_2 as Heat Transmission Fluid in an Engineered Hot Dry Rock Geothermal System, *Proceedings, Thirty-First Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, CA, January 30 - February 1, 2006.

Pruess, K. and M. Goggin. Enhanced Geothermal Systems with Carbon Dioxide as the Heat Transmission Fluid – A Game-Changing Alternative for Producing Renewable Energy with Simultaneous Storage of Carbon, presented at Annual Meeting, *Geological Society of America,* Philadelphia, PA, October 2006.

Geochemical Effects of Injection – Mack Kennedy

Objective

Develop chemical and isotope techniques for probing the thermal and chemical evolution of natural and induced fractures and the quantification of thermal extraction efficiencies.

Project 1: Monitor changes in chemical and isotopic composition of gases induced by injection at The Geysers. Determine how these changes are related to reservoir processes and coupled to microseismicity. Data will be integrated into and augment a California Energy Commission project aimed at linking microseismicity, reservoir engineering, and thermo-mechanical properties of the reservoir.

Project 2: Develop and test isotope techniques for estimating fracture spacing, which when coupled to reservoir geometry can lead to an estimate of the effective water-rock interaction area and heat extraction efficiency of a fluid circulation loop.

Project status and accomplishments

Project 1: Status: completed. Future work will be funded by the CEC. A combined field and modeling study was initiated to evaluate the effects of injection, production, and fracture-matrix interaction on produced noble gas contents and isotopic ratios in the Aidlin steam field, an isolated sector of The Geysers Geothermal Field. Gas samples collected periodically from the Aidlin steam field between 1997 and 2006 have been analyzed for their noble gas compositions, and reveal systematic shifts in abundance and isotopic ratios over time. These changes appear to be related to the introduction of air-saturated injectate into the reservoir and to diffusion-controlled variations in noble gas compositions related to gases derived from fluids within the rock matrix. Samples collected in 2005 and 2006 were also analyzed for water isotopes and ^{13}C and ^{14}C in the CO_2 to monitor the effect of increased injection related to the Santa Rosa – Geysers Recharge Project, using ^{14}C in the Santa Rosa wastewater as a proxy for the new injectate fluids. Numerical modeling using TOUGHREACT was conducted to evaluate the relative impacts of magmatic gas input, *in situ* radiogenic production of ^{4}He, and the withdrawal and injection of fluids into and out of the reservoir on the He composition of reservoir fluids over time. A paper was presented at the 2006 Annual Meeting of the Geothermal Resource Council, San Diego, CA.

Project 2: Status: continuing. Samples were collected in October, 2006 as part of the monitoring of spatial and temporal changes in the chemical an isotopic composition of fluids produced at the Casa Diablo Power plant, Long Valley, CA. Sampling is conducted quarterly to coincide with natural oscillations in the regional hydrologic head related to recharge from snowmelt. Arrangements are being made for a baseline study of fluid chemistry and isotopic composition at the Coso Geothermal Field in the vicinity of well 46A-19RD that has been selected for the DOE funded EGS pilot test well.

Geochemical Fracture Characterization – Water/Rock – Joe Moore

Background

The effects of mineral deposition on Enhanced Geothermal System (EGS) reservoir performance is poorly understood and underestimated. Because EGS reservoirs have inherently low permeabilities, any mineralization that reduces fracture apertures and hydraulic conductivities can have a significant effect on production and injection rates. This problem can affect EGS reservoirs where power is produced by flash and binary cycle plants. Mineral deposition or dissolution can occur in response to fluid/rock reactions, mixing between injection and indigenous fluids and to changes in injection fluid temperature. Permeability losses following injection at Coso, the Salton Sea and The Geysers have required the drilling of costly replacement wells. At each of these fields, the loss of permeability occurred within relatively short time periods; at Coso, significant losses were observed within periods as short as 1.5 years. The injection fluids in these cases ranged from hypersaline brines at the Salton Sea to condensate and treated waters at The Geysers. The relatively short time periods suggest permeability plugging by mineral deposition, a conclusion confirmed by analysis of the reservoir rocks. The primary objective of this investigation is to improve reservoir performance by developing injection strategies for mitigating and reversing the potential effects of mineral deposition resulting from fluid injection. The proposed work will result in enhanced productivities through improved stimulation strategies.

Significant Results

This investigation combines field observations with numerical simulations of water-rock interactions. Direct information on the effects of the injection fluids has been obtained from samples of redrilled injection wells. Thin section petrography, X-ray diffraction analyses, and scanning electron microscopy demonstrate that the permeability losses at Coso were caused by the deposition of amorphous silica; at the Salton Sea, barite, fluorite, and minor anhydrite, copper arsenic sulfides and amorphous silica were deposited. Simulated interactions between the reservoir rocks and injected fluids using the computer code ToughReact have yielded time periods and mineral assemblages consistent with the field observations. Furthermore the models indicate that the effects of mineral deposition occur primarily within a few meters of the injection well.

Chemical analyses of fluid inclusions trapped in the reservoir rocks sampled by the original and redrilled injection wells show that the injected fluids leave a distinctive signature, characterized by low gas/water ratios. In contrast, fluid inclusions trapped prior to injection have high gas/water ratios. These results suggest the variations in the fluid inclusion compositions can be used to track the movement of the injected fluids beyond the limits of scale deposition.

Models of Subsurface Chemical Processes – John Weare

Background

To efficiently produce energy from geothermal wells there must be an adequate flow of high temperature fluids from the reservoir to the power plant. Chemical interactions control fluid flow in both hydrothermal and enhanced fluid limited reservoirs. For example, ascending hot hydrothermal water or injected fluids that are out of equilibrium with rock formations can precipitate new mineral phases that alter or seal flow paths and drastically degrade the performance of the resource. However there is an insufficient knowledge of subsurface fluid/rock chemical interactions to successfully predict their effect on rock permeability and fluid flow with the accuracy needed to optimize the economical production of geothermal energy.

Objective

The objective of the research project under DOE grant DE-FG36-04GO14300 is to develop the first highly accurate chemical models of hydrothermal fluids and aluminum rock-forming minerals, tailored to the solution mixing properties, for composition, temperature and pressure ranges of interest to geothermal energy production processes. The focus is on aluminum aqueous chemistry and aluminum minerals because of the abundance of aluminum throughout the earth's crust and its high content (≈ 15% Al_2O_3) in a wide range of rock types. Knowledge of the thermodynamics of aqueous fluid interactions with aluminum minerals is critical for understanding geothermal resource and process chemistry (e.g., mineral dissolution/precipitation and alteration, changes in rock permeability affecting fluid flow, resource evolution.) In this project researchers treat temperatures below 350°C and pressures close to atmospheric, ranges suitable for most EGS R & D.

Approach

In the previous development of evaporate, carbonate and silica solubility models, researchers have shown that the Pitzer free energy modeling approach can calculate solute activities and solid-liquid-gas equilibria in complex aqueous systems to high concentration and temperature with high accuracy. In this project researchers use this approach to develop a model of mononuclear aluminum aqueous chemistry and aluminum mineral solubility to ≈ 250°C in sodium and potassium chloride solutions using available activity and solubility data. In combination with the TEQUIL aqueous silica chemistry model, this model allows us to initiate development of a comprehensive thermodynamic database for aluminosilicate minerals (alkali feldspars) that is consistent with the solution models.

Progress

The progress up to this point has satisfied most of the important milestones identified for the proposed work. Researchers have completed a model of the highly complicated aqueous aluminum chemistry from very low to high pH and solid phase solubility in NaCl solutions to 300^{o}C and high solution concentration ($I \approx 5\ m$). Combined with the silica model, researchers have added equilibria with several hydrothermal aluminosilicate minerals including important Na feldspars. The recent addition of potassium interactions significantly broadens the model's application to formation permeability problems because of the many K/Na, K feldspars found in nature. Solubility data for hydrothermal minerals are scarce. Recently researchers demonstrated that the model could be consistently used with literature values of the Gibbs free energies of reaction available from high temperature extrapolations allowing us to include many more hydrothermal minerals in the database. This model will provide an efficient method to evaluate potential chemical problems with reservoir development and utilization, to analyze laboratory and field flow data in terms of the saturation properties of the observed minerals and provide a means to develop chemical strategies to improve the performance of the reservoir.

Fracture Type and Ages – Lorie Dilley

The principal objective is to demonstrate that Fluid Inclusion Stratigraphy (FIS) analysis of drill cuttings identifies fractures, indicates fracture size, and that gas chemistry from fluid inclusions can determine if a fracture is at one of three different stages: present and transmitting fluid; recently closed; or ancient. FIS would provide a rapid, inexpensive technique to locate fractures within a borehole prior to commencement of an EGS project. Knowledge of location of fractures and their state (open, recently closed, or ancient) will assist in targeting areas for further fracture stimulation. Identifying dense fracture areas, as well as large open fractures from small fracture systems will also assist in fracture simulation selection.

The work will primarily involve logging cores from select geothermal fields, obtaining FIS samples and comparing the results. In addition, fluid inclusion thermometry and alteration patterns will be considered in determining past history of the cores. From this work, researchers hope to develop a technique for using FIS to identify fractures as well as their relative ages. Currently researchers have collected samples, received analysis back from the laboratory and are starting to compare the results to the well logs.

Geothermal systems are constantly generating fractures and fluids passing through rocks in these systems leaving small fluid samples trapped in healed microfractures. These fluid inclusions are faithful records of pore fluid chemistry and are not subject to evaporation during sample storage or loss during sampling. The fluid inclusions trapped in the minerals as the fractures heal are characteristic of the fluids that formed them, and this signature can be seen in the fluid inclusion gas analysis. Fluid inclusion stratigraphy (FIS) uses the gas analysis to determine fluid types. One of the underlying assumptions of FIS is that observed peaks in the data relate to location of fractures. Researchers see evidence for both open fractures as well as closed fractures.

Knowledge of fracture location and their relative age will assist in targeting zones within a well for fracture stimulation and enhancement. This technique will then become part of the tool bag for generating and managing Enhanced Geothermal Systems.

5.5. Field Projects

Coso Field Project – Pete Rose

Objective

Key to the creation of an Engineered Geothermal System (EGS) is an understanding of the relationship between natural-fracture distribution, fluid flow, and the ambient tectonic stresses that exist within a potential hydrothermal resource. Once these relationships are determined, it is possible to design a hydraulic and thermal stimulation of a candidate injection well as the first step in the creation of a heat exchanger at depth. With this in mind, the focus of this project for FY2006 was the preparation for the stimulation and testing of injection well 46A-19RD in the southwest region of the Coso geothermal field. This well was drilled into the hottest portion of the field to a total vertical depth of approximately 12,700 ft. Injection into the well has been very limited because permeability in the bottom of the well, where injection is needed, is very low. The objective of this hydraulic stimulation experiment is to increase the injectivity of well 46A-19RD to the point that it will accept separated brine at a rate of 500 gpm at a wellhead pressure of 100 psi or less. An additional objective is to gain an understanding through experiment, analysis, and modeling of the associated scientific and engineering processes in order that the stimulation approach might be extended to other candidate EGS resources where appropriate tectonic and thermal conditions exist. All preparations have been made for initiating the workover as soon as the required drill rig can be leased and delivered to the site.

Project Status and Accomplishments

DP23-1 logging operations at Desert Peak.

Accomplishments during FY2006 include the purchase of 10,000 ft of 9-5/8-in steel liner for casing the recompleted hole from the top of the 'open-hole' to surface; the purchase of a new 5,000-psi wellhead for use in the stimulation; the redeployment and testing of a new microseismic network including 16 permanent and 12 temporary stations and the upgrading and installation of new cabling and protection devices for use in monitoring the hydraulic stimulation experiment; the development of interactive graphical software for determining microearthquake moment tensors; an integration of available east-flank stress data from well-bore failure and hydraulic fracturing tests; a determination of the petrophysical properties of core obtained during the 2005 experiment involving well 34-9RD2 including rock strength, porosity and density for correlating P-wave velocity with strength as a function of depth in 46A-19RD; the development of a method for identifying and analyzing petal-centerline fractures and thus improving wellbore stress analysis from image logs; the petrologic and petrographic analysis using microscopy, X-ray diffraction, and fluid-inclusion analysis of drill cuttings from 46A-19RD to determine lithology, vein mineralogy, pervasive alteration, and vein mineral paragenesis; and the development of a 1-D TOUGHREACT reactive transport model of injection into 34-9RD2 incorporating the vein and rock mineralogies, and injection-fluid chemistry.

Desert Peak Field Project – Ann Robertson-Tait

Objective

The Desert Peak EGS project is one of two DOE-funded projects aimed at evaluating EGS concepts in the field. The overall objective of this Phase I feasibility assessment is to assess the technical and economic feasibility of developing an EGS project at the Desert Peak geothermal resource area. This is being accomplished by undertaking a series of evaluations to: 1) determine the petrologic and physical characteristics to suggest an appropriate EGS reservoir; 2) characterize the geologic structure of the area as defined by geological, drilling and geophysical data; 3) evaluate the overall stress field and the nature of specific fractures in various target EGS reservoir rock units; 4) estimate (through numerical simulation) the size and complexity of enhancements required to support long-term EGS production for a Desert Peak-type reservoir and develop correlations applicable to other EGS developments; and 5) to develop stimulation and drilling plans to support a 2-5 MW EGS project at Desert Peak.

The Desert Peak EGS project will help demonstrate the feasibility of EGS development generally in the Basin and Range geologic province. Desert Peak was chosen because it offers a combination of existing operational infrastructure, reasonably well-known geologic conditions, a significant existing resource database, and well availability. These attributes allow EGS concepts to be investigated and EGS energy to be potentially utilized in a favorable economic setting. Demonstration of EGS feasibility at Desert Peak East will allow the results to be applied to numerous other comparable EGS sites in the Basin and Range province. Field projects like Desert Peak are critically important to demonstrating the viability of EGS as the major energy source that it could be.

Project Status and Accomplishments

To date, the project has undertaken a feasibility assessment of developing EGS adjacent to the Desert Peak hydrothermal field in an area centered on well DP23-1, and has evaluated the potential for applying EGS concepts within the hydrothermal portion of the field. The work in the area surrounding well DP23-1 has included petrological analysis, geophysical well logging and analysis, injection testing, determination of the orientation of the ambient stress field and stress field modeling to constrain the magnitudes of the principal stresses, identification of intervals for stimulation, an attempted (but unsuccessful) re-completion of well DP23-1 to prepare it for stimulation, and development of stimulation plans. The project report from this part of the work is in preparation, and numerous technical papers have been prepared and presented at geothermal industry conferences (GRC, Stanford and WGC). For the in-field area, two candidate wells are considered for further analysis. Some of the in-field work will follow a methodology similar to that used to evaluate the area around well DP23-1. The first step, already completed, was to investigate the physical conditions in the two wells. Since one is blocked at a fairly shallow depth, it has been eliminated from consideration. Therefore well DP27-15 will be investigated further. The project will undertake petrological and mineralogical analyses of 27-15 and several other recently drilled wells, and will use the results of these analyses to refine the stratigraphic and structural model of the hydrothermal portion of the field. Standard geophysical logs will be run to better understand the physical properties of the rock units encountered in this well. The USGS will run its high-temperature borehole televiewer tool to gather the data needed to evaluate the stress field; USGS will undertake the analysis of stress field orientation, while GeoMechanics International will evaluate the natural fracture population. From these analyses, the most prospective interval for hydraulic and/or chemical stimulation will be identified, and stimulation plans will be developed.

5.6. Systems Analysis

CO_2 Sequestration – Karsten Pruess

The objective of this project is to evaluate the feasibility of using CO_2 as heat transmission fluid for EGS, and compare with "conventional" water-based systems. Assess the potential for combining energy extraction with sequestration of CO_2. (CO_2-based EGS represents a new initiative in the project on "Geothermal Reservoir Dynamics." This has grown to a major priority in the FY06 work that had not been anticipated in earlier planning.)

EGS Databases – Susan Petty

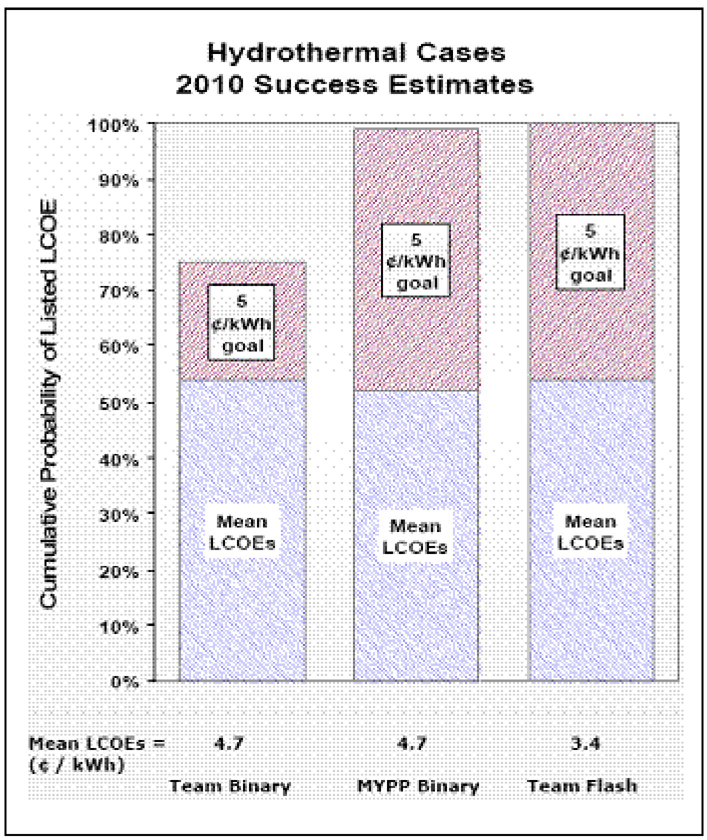
The objectives of this project are:

- Develop database information on Enhanced Geothermal Systems projects worldwide
- Make data available interactively through Google Earth. Include EGS projects worldwide, sites with EGS potential in the US and data on temperature with depth developed by Dave Blackwell and Maria Richards, SMU

Risk Analysis – Gerry Nix

The objectives of this project are to provide the EGS program with:

- Better metrics
- Better view
- Consistent evaluation



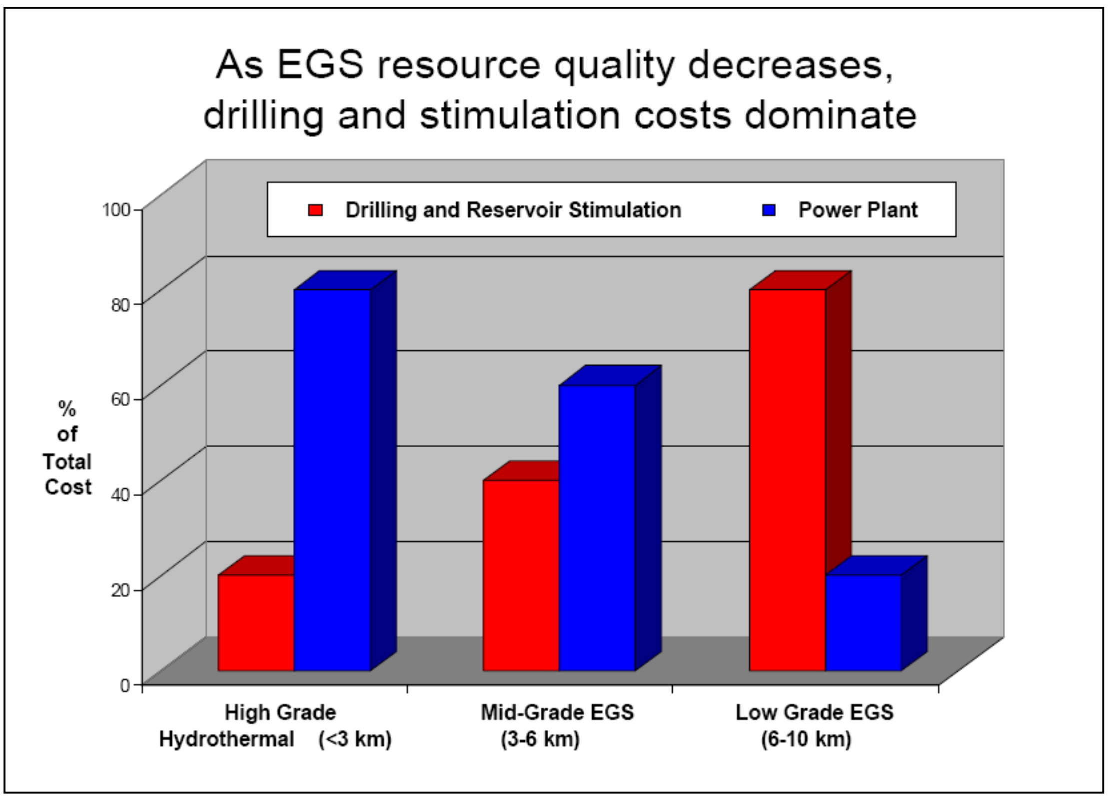
The GTP develops the tools to enable analyses to be performed to guide the Program with portfolio evaluation and impact estimates. A program, GETEM (Geothermal Electric Technology Evaluation Model) was developed to simulate cost-performance for geothermal power plants. Supply curves were developed based on conventional hydrothermal and EGS sources. Technology improvement opportunities were identified and the ranges of potential impacts of accomplishing these opportunities were quantified using panels of industrial experts. These inputs were used with GETEM coupled with a Monte Carlo sampling routine to automate probabilistic evaluation to estimate likelihood of accomplishing the goals of the GTP. This risk assessment resulted in an estimate of 74% likelihood of accomplishment of the 2010 goal of 5 ¢/kWh for a hydrothermal binary system, and an estimate of 14% accomplishment of the 5 ¢/kWh EGS goal by 2040. However, if the EGS goal was relaxed to 6.3 ¢/kWh, the probability of accomplishment went up to 58%, with the sensitivity of the results indicating additional planning and implementing of research tasks is required.

5.7. Looking Forward

EGS Feasibility Study – Jeff Tester

The objectives of this project are:

- Provide an in-depth evaluation of EGS as a major US primary energy supplier
- Provide a framework for informing policy makers of what R&D support and policies are needed for EGS to have a major impact



EGS Roadmap – Clay Nichols

Technology Roadmapping, a powerful tool for determining how to allocate resources, has been chosen by the GTP as a way to set priorities among numerous technology research options. Expert groups identified technology pathways to achieve Program goals, highlighted expected technological barriers, and listed and characterized the technologies required to address those barriers. The groups ranked these technologies along six dimensions (critical path, technology impact, risk, cost, urgency, and value to industry) to enable prioritization of research.

Critical path technologies were selected, and the associated research and development activities were prioritized. Critical path technologies are technologies or processes that must be completed on a schedule or in sequence in order for the goal to be achieved in a given time frame. The roadmap includes more detail for activities to be undertaken in the next 10 years, but achievement of GTP goals may take longer, depending on funding. Technologies are grouped into five major categories, with evaluations of needs and opportunities make for each, with recommendations consistent with the critical path consist rations. The road map stresses the importance of a rational path to the accomplishment of EGS technology development.

Appendix A. General Breakout Session

After the review of the EGS research program, the attendees broke into three working groups to discuss future direction for the EGS program. Group membership was selected to provide homogeneity of inputs. Technical experts in certain areas were spread around to create balanced groups.

A	B	C
Stu Johnson	Ted DeRocher	Mitch Stark
Frank Monastero	Sue Petty	Bill Livesay
Peter Van Dyke	Ann Robertson-Tait	John Pritchett
Jeff Tester	Jose Rial	Steve Hickman
Russ Detwiler	Derek Elsworth	Ahmad Ghassemi
Karsten Pruess	Herbert Einstein	John Weare
Lori Dilley	Mack Kennedy	Brian Anderson
Cliff Carwile	Teresa Nealon	Gerry Nix
Jay Nathwani	Richard Price	Pete Rose

Each group appointed a group leader (facilitator), a scribe and a reporter for the large group meeting. The following questions were discussed by each group.

What are realistic goals for the EGS program? What goals would you support?

- Provide year and measurability

What are the barriers (technical and institutional) to making EGS work on a large scale in the U.S.?

What strategies need to be pursued to overcome the barriers?

- Consider uncertainty and risk in the above two questions.

What should the EGS program do through January 2009? And in the longer term?

How can DOE gain support of the geothermal community at large for EGS?

Appendix B. Technical Breakout Session

Meeting attendees also participated in technical breakout groups to discuss specific research needs for the program. Group membership was selected by technical expertise so that each group contained the appropriate knowledge base.

A	**B**	**C**
Site Characterization	**Productivity Enhancement (Res. Design & Development)**	**Resource Mgmt (Reservoir O&M)**
Steve Hickman	Bill Livesay	Karsten Pruess
Stu Johnson	John Pritchett	Peter Rose
Lori Dilley	Ann Robertson-Tait	Jose Rial
Mack Kennedy	Russ Detwiler	Ahmad Ghassemi
Ted DeRocher	Jeff Tester	John Weare
Frank Monastero	Herbert Einstein	Sue Petty
Brian Anderson	Derek Elsworth	Mitch Stark
Cliff Carwile	Peter Van Dyke	Richard Price
Joel Renner	Jay Nathwani	Gerry Nix

Each group appointed a group leader (facilitator), a scribe and a reporter for the large group meeting. Each group prepared responses to the following items for their respective technical area.

- Specific and measurable goals with completion dates
- Barriers and challenges
- List of key tasks
- Critical Path (with completion dates)

Appendix C. EGS Program Review Participants

July 18 and 19, 2006
Marriott Denver West
Golden, CO

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