Enhanced Geothermal Systems
Reservoir Creation Workshop
Houston, TX
August 21, 2007

Summary Report

Executive Summary

The reservoir creation workshop focused on creation of suitable reservoirs for exploitation of subsurface heat. The general topics of discussion were: 1) the technological state of the art for reservoir creation; 2) potential problems encountered in reservoir creation; 3) reservoir characterization; 4) site selection; 5) economics and commercialization; and 6) future research and approaches. The workshop only briefly covered the determination of suitable geologic settings for EGS development. Industry participants agreed that solutions to all challenges could be engineered if there is an economic incentive. An industry participant suggested that the business threshold for technology development is an annual market of about $100,000.

There is insufficient experience to determine how enhanced systems will behave in the long term, so development is too risky for industry. It is necessary to be able to model the effects of changes in system parameters on EGS economics to determine what is commercial.

Achievements up to now indicate that the targets can be achieved, but it is still speculative. There are no major technology gaps preventing EGS development, but there are minor technology gaps to be filled in. A demonstration project is required to show that it is economically feasible to create a reservoir that generates power.

The O&G industry does not have all the answers; they are still trying to learn about the Barnett shale, and trying to learn from geothermal technology for their own purposes. Shear is an important component of many unconventional gas stimulations.

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Introduction

A workshop on Reservoir Creation for Enhanced Geothermal Systems (EGS) was held in San Francisco, California on August 21, 2007. This was the second of a series of four workshops, the first of which evaluated the assumptions set forth in the report by the Massachusetts Institute of Technology (MIT) entitled *The Future of Geothermal Energy* (MIT, 2006), and three (on Reservoir Creation, Reservoir Management and Operations, and Wellfield Construction) focused on identifying technology gaps associated with aspects most critical to EGS development. The intent of the workshops was to motivate facilitated identification and discussion of technology gaps related to reservoir creation.

The objectives of the workshop were to identify the state of the art for reservoir creation; define technology needs, gaps, and barriers; and suggest technology development paths to meet the needs and overcome the barriers.

The discussion at the workshop covered a wide range of topics, with participants moving from one topic to another depending on the context of the presentations and the questions asked. For the purposes of this report, the results of these discussions have been categorized by topic. The general topic areas covered were:

- The state of the art for oil and gas and geothermal fracturing technology.
- Potential problems and technology gaps associated with reservoir creation.
- Technologies and methods associated with reservoir analysis.
- Site selection requirements.
- Economics and commercialization activities.
- Future research and approaches.

Workshop participants were encouraged to speak freely and discussions were allowed some latitude to encourage dialog. While notes were taken, the workshop discussions were not transcribed, again to promote frank and open discussion. Participants were also encouraged to provide written comments to the workshop organizers following the day's discussion. The workshop's agenda and a list of attendees are included at the end of this report. Key discussions and written comments from the workshop are summarized here.

1. Technology State of the Art

A major focus of the workshop was identification of the current state of the art in both geothermal resource enhancement and oil and gas stimulation. In both cases, key real-world examples (i.e., the Soultz EGS and the Barnett Shale, respectively) were used as points of reference for discussion of similarities, differences, and areas of convergence between the technologies.

1.1. Geothermal State of the Art

Geothermal reservoirs, in contrast to oil and gas reservoirs, are typically monolithic rather than layered, the rocks are often heterogeneous and fractured, and higher flow rates are required compared to O&G wells.

1.1.1. Soultz Resource Enhancement Experiment

Among EGS projects to date, the best performance achieved has been at Soultz. A four-month circulation test in 1997 produced fluid at a rate (25 l/second) approaching the theoretical requirement (80 kg/second), though at too low a temperature for economic viability (142°C). It is likely that Soultz could produce at 35 to 40 liters/second or more, but because the experiments were trying to answer specific questions other than the maximum achievable flow rate, the actual maximum is not known. The Soultz experience suggests that impedance may improve as fluid is circulated.

The key to minimizing parasitic power needed to overcome impedance is to reduce injection pressure as much as possible while maintaining power output. Efficiency can be increased by reducing injection pressure/flow rate or using production pumps, and power level can be maintained by using additional wells at the lower flow rate.

In tight gas production, flow rates can be increased by increasing pressure, but at high flow rates the fluid will not have sufficient time to transfer heat from the rock. A balance between flow rate and conductivity is required and that would be determined by site-specific conditions.

Soultz has both an open system (at shallow depth) and a deeper closed system that was created after temperatures in the shallow system were determined to be too low. Because the shallow system at Soultz is open, water loss is not a relevant consideration. In this case the far-field contribution of water was about the same as the losses, making water loss effectively zero.

The possibility of using more wells at Soultz has been rejected because the reservoir is very narrow, and additional wells would not be likely to connect. Whether additional wells will provide a benefit depends on the stress conditions that control reservoir creation. Additional wells are certain to provide a benefit only if the reservoir is isotropic.

1.2. Tight Gas Formations State of the Art

1.2.1. Reservoir Design and Methods

The general status of reservoir design capabilities is that gas reservoirs can be effectively created if enough data is available. Reservoir design techniques are available, though they are not completely reliable.

A 3-D volume of enhanced fracturing leads to enhanced permeability. Fracturing is designed to increase permeability over a scale of hundreds or thousands of feet. The natural fracture width in tight gas formations is significant (on the order of 10-100 microns). The fractures are sealed, but can be opened with pressure. Rock porosity is also meaningful in tight gas, where it is not in EGS. The injection pressure is above the parting pressure for tight gas, but it is not clear whether injection pressure should be above or below the parting pressure for EGS. The injection time is much less for tight gas, and proppant is considered critical in tight gas, but not in EGS.

The fracturing approach is to inject fluid and induce shear failure on weak planes. Models are used to predict the permeability increase and the size of the shear failure zone, and the predictions are then mapped to the microseismic cloud produced during injection.

Modeling and prediction of rock failure is becoming more sophisticated. A screening model can be used to predict the extent of failure, but the model does not predict permeability enhancement; injection permeability is a matching parameter. Multiple models are available.

Technology needs, gaps, and barriers are being addressed by the Alberta Research Council's JIP consortium, which is leveraging funding, taking advantage of geomechanics and petroleum engineering expertise, and providing core testing of technologies and models. The cost of joining the consortium is $75,000. Ten companies are participating. The DOE Geothermal Technologies Program should consider joining.

1.2.2. Barnett Shale Stimulation

The Barnett Shale was used as an example for discussion of domain stimulation in oil and gas. The critical variables for design of fracturing operations in the Barnett Shale are high stress, high rock strength, and abundant natural fractures. Shear dilation occurs when there is high deviatoric stress and high rock strengths, but shear and tensile failure both occur. Production increases as natural fractures increase and as virgin permeability decreases.

Table: Comparison of EGS (Soultz) and tight gas (Barnett shale) fracturing parameters

	EGS	Tight Gas
Natural fracture width (microns)	0.05-5	10-100
Virgin permeability(units?)	26	15-25
Porosity (%)	0.3	5
Mean depth (ft):	8000	8200
Scale of stimulated fractures (ft^3)	2500 x 4000 x 6200 (vertical well, but vertical depth is significantly	2600 x 2600 x 400 (horizontal well)

	different from tight gas)	
Injection pressure	Below parting pressure	Above parting pressure
Injection time (hours)	200	20

Barnett shale horizontal wells do not produce unless they are hydraulically fractured, probably because of skin damage due to drilling. The skin factor is large – 10 to 20 – due to fines and drilling fluid pushed into the formation. A typical single-stage horizontal frac produces a network of fractures outlined by microseismic events. The dominant natural fractures are stimulated, and shearing and tensile fractures are generated as well.

The Barnett shale may be unique in some respects. Complex fractures are required to increase permeability, and complex fractures are unusual. Shear slippage at interfaces leads to a complex fracture network. If the fracture injection pressure is high enough, both shear and tensile failure will occur. Stimulation design using domain models that could predict this behavior is in its infancy in O&G.

1.3. Comparison of O&G and EGS Environments and Stimulation Approaches

The O&G and geothermal industries have different philosophies of fracture generation that may be related to differing tensile strengths of rock and differing porosities. The O&G industry tries to take advantage of porosity, while geothermal rocks tend to shear and have little or no matrix permeability. Comparison of techniques and results will be valuable, but there is a fundamental difference in approach.

The O&G industry is seeking to develop more shear fractures and fewer tensile fractures. The optimum balance between shear and tensile failure is a major unresolved question for which the O&G industry is trying to identify solutions based on geothermal/EGS experience. The key completion issues are predictive fracture propagation in naturally fractured media; open hole fracture initiation; maximizing reservoir surface area; and interwell connectivity.

The conditions that favor complex fracturing are very low matrix permeability; large-scale regional fracturing; and low-permeability anisotropy. The goal is to maximize rock area exposure. Factors unfavorable for complex fracturing are higher permeability; high permeability anisotropy; closely spaced tectonic natural fractures; and thin fluvial intervals and weak barriers that inhibit massive fairway fracturing.

Fracture geometry is related to the scale of the stress field (regional fractures like that found in the Barnett shale vs. tectonic natural fractures.)

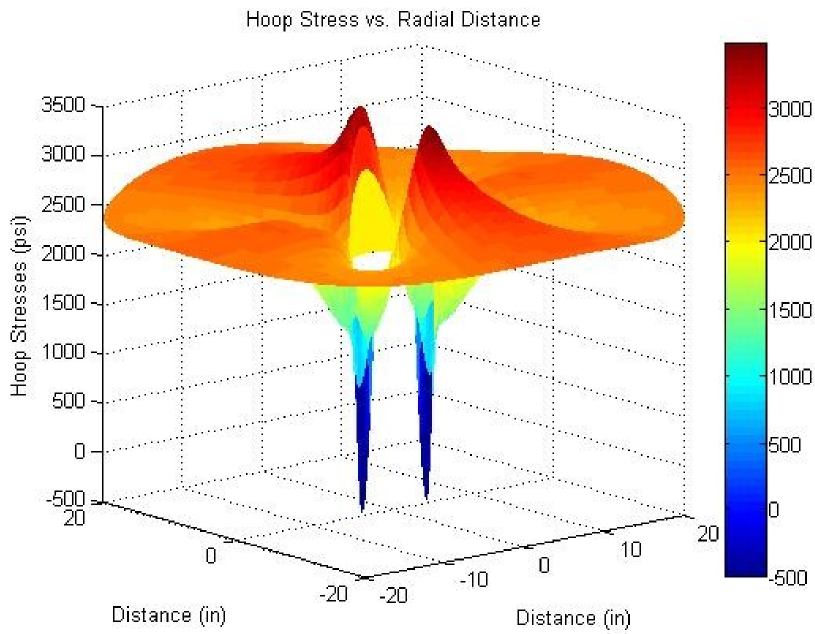

Figure 4: Stress distribution during fracturing.

The orientation of natural fractures with respect to stress orientation and stress anisotropy affects the results of stimulation, including the fracture intersection angle; the density of intersections with natural fractures, the pressure at which natural fractures dilate, and completion efficiency.

Fracture dilation can be manipulated by relatively small changes in pressure. Even moderate reductions in natural fracturing pressure with respect to induced fracturing pressure can effectively shut down natural fracture involvement and eliminate fracture complexity. Because EGS is a high shear environment, injection of less fluid will produce less stress, but permeability will still be created. EGS shear failure usually occurs well below dilational pressure; self-propping shear fractures are being created instead of fractures dilated by pressure. Because EGS is a very high shear stress environment, it is possible to inject at less than the least principal stress and still increase permeability.

The solution to good fracture design is to use FMI (a Formation Micro-Imager) to determine natural fracture azimuth, width, and spacing, and use sonic logs and a mechanical earth model (MEM) to determine induced fracture azimuth, fracture permeability, natural dilation pressure, and stress profile. These data can be used to design a customized completion.

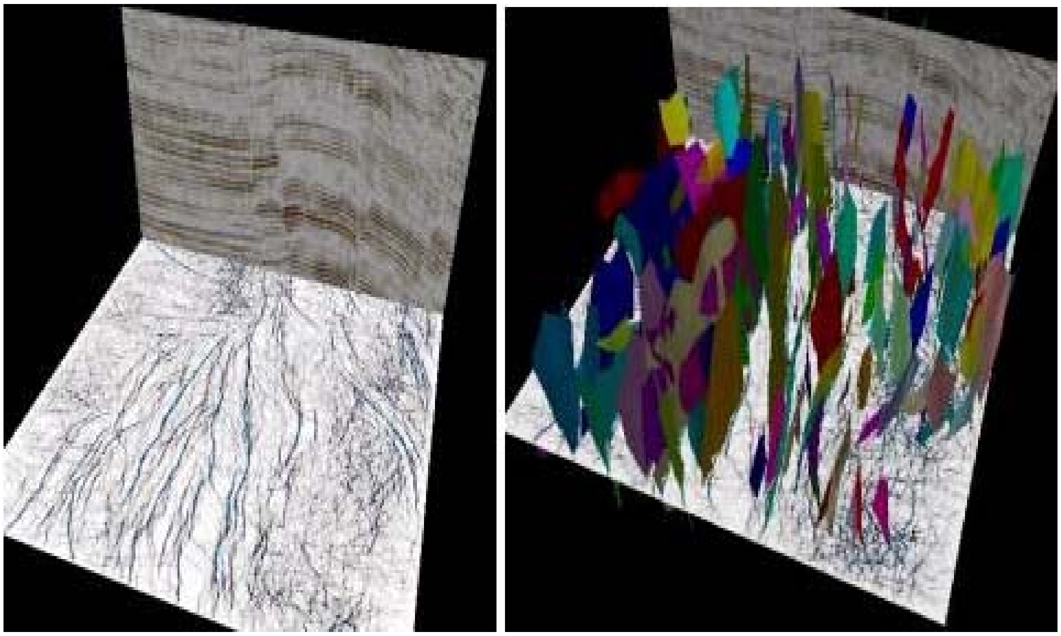

Figure 5: Fracture imaging using logs and models.

Since the O&G industry is already doing volumetric fracturing, this could be extended to deeper and hotter environments.

Pressure transient effects were not discussed during the workshop. The O&G industry has many methods for calculating these effects, which are important in O&G reservoir development.

Proppants were recommended for use by the geothermal industry in reservoir creation. The failure of proppant in geothermal conditions may be because the proppant has not been used properly and fails to reach inflated fractures.

Halliburton and BJ Services did not attend the meeting, and reservoir creation may not have been covered as thoroughly as some of the other topics. However, the O&G representatives that did attend seemed secure about reservoir creation capabilities. The issue of whether proppant is useful remains a question.

Forward modeling is required to describe how to develop a reservoir given a certain set of conditions. Data are required to feed a model and predict what will happen when a certain stimulation design is used. Data from earlier projects can be used to ensure that models are able to successfully predict the results of past experiments. Both data and data processing capabilities are currently inadequate.

2. Potential Problems

2.1. Short Circuiting

An EGS stimulation designer must balance reduced impedance against the risk of thermal breakthrough. The threat of short circuiting is reservoir specific, since it is dependent on relative permeabilities along different flow paths. Some hydrothermal reservoirs short circuit rapidly because the majority of flow is directly between the wells.

The worst case is a large flow path directly between the two wells, rather than small pathways throughout the stimulated mass. The rate of drawdown increases as the cube of the crack thickness. This problem is not as severe as it appears, because, as heat is drawn from the rock around the short circuit, thermal stress opens concentric flow paths around the cooling area, in a feedback effect which mitigates the effects of thermal drawdown due to channeling, allowing removal of additional heat. The flow short circuit will not always be equivalent to a thermal short circuit; thermal drawdown is slower than the breakthrough.

Whether short circuiting is a critical threat to EGS economics is partly a question of semantics. Rapid breakthrough of tracer is not the same thing as channelization/short circuiting. In the modeled example, there was no short circuit even though tracer indicated rapid communication between wells. Rapid breakthrough of tracer is not necessarily equivalent to development of a preferential flow path between wells.

Whether there is a limit to the flow rate that can be achieved without causing thermal breakthrough cannot be answered at this time, since not enough resources have been devoted to the issue to answer the question. The rate achieved in experiments at Soultz was 25 liters/second, where the MIT report recommended 80 kg/second for economic operation. The question is what can help achieve an economic flow rate? The transit time for the fluid can be adjusted to whatever is desired by regulating the water pressure; it is not possible to have too much conductivity. However, if a certain flow rate is required, it is not possible to simultaneously control transit time.

2.2. Water Loss

Water losses constitute a potentially serious technical problem, but it can be managed. It is unlikely that any unsaturated pores or fractures are present. (However, water can leak off in an open system, and a closed system has to be pressurized, which entails permanent addition of water.) Balanced circulation can be achieved by active management of pressure sinks and sources. An open system may lose injected water, but it will also gain water from other sources. Injected water can be trapped in fractures once pressure is reduced, which is another source of water loss.

2.3. Induced Seismicity

Analysis and experience indicates that EGS stimulation will not cause major earthquakes. Large quakes have to come from large, deep faults because small fractures don’t contain enough energy. Drilling may increase stress on faults, but that stress is unlikely to cause a major earthquake. The threat is that EGS activities could release pre-existing energy.

However, even if drilling a hole into an earthquake fault does not cause a major earthquake, society may believe that it has. It may be necessary to find areas of the fault that will not set off an earthquake. Even though researchers and industry can explain scientifically that EGS will not cause major earthquakes, the public may not accept that explanation; any quake that stops the project has to be considered catastrophic. Limiting seismicity should be a focus of program efforts.

3. Reservoir Characterization

The state of the art in petroleum reservoir characterization relies heavily on rock properties and other data obtained from multiple drill holes. Extrapolation of oil and gas stimulation technology to EGS is based on an assumption that more downhole data will be available than in typical hydrothermal development. The need for data will drive the development of effective reservoir characterization tools.

3.1. Permeability and Fracture Detection

Permeability is the key parameter for EGS development because while power is the product of both heat content and flow rate, natural permeability varies up to four orders of magnitude; in contrast, temperature only varies between 100°C and 300°C. The subsurface temperature is expected to be acceptable at any site proposed for EGS development, but the flow rate is insufficient without stimulation (otherwise it would be a hydrothermal system.)

Optimization of production in fractured reservoirs is a problem, since small fractures can control permeability over a large area. Methods are needed to sort out different effects of anisotropy and identify fractures controlling flow and transport. There is no easy way to measure permeability.

It is not known whether it is possible to stimulate a well and expect to get a flow rate of 80 kg/second. The best existing EGS well produces only 1/3 of that flow rate; but hydrothermal wells produce at this rate and more.

3.2. Microseismicity and Fluid Flow

Existing EGS reservoirs are not complex volumetric fracture networks. While seismic clouds may give the impression of a volumetric rock mass as at Cooper Basin, careful analysis shows a more planar structure. The volumetric appearance is the result of errors in measurements of the locations of seismic events. A more sophisticated method of analysis (keying of event locations to a few events that can be localized with relatively high accuracy) shrinks the seismic cloud and flattens it.

Experiments show that seismic results from surface reflection show a negative relationship: reservoirs with the highest production had the lowest anisotropy, which is counterintuitive. Vertical Seismic Profiling (VSP) shows that anisotropy is not consistent with a single direction of vertical fractures.

New techniques that may be of value in reservoir design and characterization include wave scattering and coda analysis. An AE reflection method can be used to delineate structures.

Higher resolution is needed in MEQ (microearthquake) studies to be able to understand the fracture system. There is a range of mechanisms producing seismic energy, but shear is easiest to detect. Fault plane solutions determined from MEQs can indicate good targets for new wells.

While it is theoretically possible to determine the type of seismicity from the seismic signature of the event, some signals will not be distinguishable, so it might not be possible to clearly identify every event. While some types of events have the same signature, there might be different signatures related to chemical operations.

What is needed is something equivalent to the Direct Hydrocarbon Indicators (DHI) approach used in O&G, which uses passive seismicity to detect fluid flow in a reservoir and identify zones where hydrocarbons are left behind.

3.3. Stress

The type of stress (tensile, shear, vertical) needed for optimal reservoir development is not known. Insufficient data are available to perform the analyses required to identify optimum stress and other conditions. Technology requirements include the ability to model and predict reservoir creation in a given stress environment, based on available data regarding stresses and fractures.

Given the right stress regime, it should be possible to create the required permeability. However, there is currently no method to determine stress from the surface without drilling wells. A method to determine stress fields remotely would be very helpful. If there are local earthquakes, local stress state can be identified to verify that it is possible to create permeability.

3.4. Reservoir Characterization Methods (other than seismic)

Optimization and implementation of EGS will require cost effective characterization and monitoring of static properties, including fractures and faults, fluid content, and the heat source, and also dynamic properties including the stress field, fluid flow, and fracture creation and evolution. Granite is more homogeneous than typical oil and gas and hydrothermal environments, and this may make identifying fracture properties easier.

Issues driving research include fracture characterization (location, density, etc.), permeability mapping (permeability creation and sustaining permeability over the long term), and fluid imaging. Potential reservoir characterization and modeling methods include potential field, logging, joint geophysical methods, and well testing. It may be possible to use tracer tests to collect important reservoir information such as the surface area available for heat exchange.

EM imaging is increasingly being used in oil and gas due to new instrumentation and increased computing power. Magnetotelluric (MT) data sets are used for identifying subsurface structures.

Challenges and needs for future work include improved imaging and data acquisition technology; rock physics and coupled dynamics (pore-scale imaging on a micro- to nanoscale); computational methods (joint inversion and modeling); and computational geomechanics.

4. Site Selection

Workshop participants concluded that Demonstration projects are needed. An experimental site (or sites) will be necessary in creating a pathway to commercialization for EGS. The site selection process must be defined, and the next steps for the DOE program should be identified.

Site selection capability is a technology gap since there is no defined system for efficiently narrowing down sites and selecting one. The way to proceed is to find a spot with acceptable parameters and then make sure the tools are available to manipulate the system created there, particularly technologies to identify and manipulate both closed and open fractures.

Stress is considered to be the most critical variable in selecting a site (after the presence of heat). One approach to site selection is to proceed by identifying and eliminating types of stress fields that are not good for reservoir creation, rather than trying to find ideal sites.

The oil and gas industry is interested in collaborating on EGS research, because there is a lot of overlap between their research and the subjects discussed at the workshop.

5. Economics and Commercialization

The technology for creating a reservoir is available, but researchers must be able to run a project over the time frame required in order to create a viable business. The science is available to produce an economic model, although data will be required to validate it. Industry does not have access to such a model.

The MIT EGS report set a target of 80 l/second based on an economic model that allowed determination of the parameter values required to achieve competitive costs. However, if a higher temperature resource is available, a lower flow rate will be economically viable.

There is insufficient experience to determine how systems will behave in the long term, so development is too risky for industry. It is necessary to be able to model the effects of changes in system parameters on the economics of an EGS, to determine what is commercial.

Previous EGS achievements indicate that the targets can probably be achieved,. A demonstration project is required to show that it is economically feasible to create a reservoir that generates power.

6. Future Research and Approaches

The challenges for EGS development are:

- generating confidence in investors and public by developing four or five successful operating systems;
- developing experience with long-term circulation to enable prediction of reservoir evolution;
- determining the lifetime of a reservoir based on a successful stimulation design through use of tracers or seismic to assess the surface area;

- management of geochemical problems (precipitation and dissolution); management of reservoir issues such as corrosion, short-circuiting, and the interpretation of tracer results;
- evaluation of primary economic and technical areas, and
- reducing or eliminating large seismic events.

Much of the new O&G technology is proprietary, and what oil company representatives will discuss and what they can do are very different.

Reservoir creation models should have hydromechanical coupling and thermal coupling added to their capabilities. Requirements for further progress also include sufficient data to run the models, and testing of these models (the existing models have not yet been used to create reservoirs.) Meeting these needs will require additional modeling work, data collection, and field testing.

Table: Data requirements, gaps, and approaches

Technology Area	Status	Requirements	Approach
Site Selection	Inability to define site requirements Gap in hydromechanical stress type models. What do we know about stress fields to determine the best EGS regime?	Exploration program to identify site selection criteria – select sites, drill slim holes, and collect data. Tools are required to collect data. Numerical models can be used to identify areas to avoid.	Literature search
Reservoir Design	If the stress regime and prior existing fractures are known, it is possible to design a fracturing job. Drilling will be required, and the site history must be known to enable stimulation design. Models may not be adequate – a model exists, but 2 or 3 different models are required. The current model has insufficient detail.	Additional model development is required. The model must be able to use available data to project how the fracture system will develop. Adaptive meshing may not be available today. It must be possible to identify zones for sites.	
Reservoir Creation	The necessary technology is available (proppants, etc.)	The required stress regime must be determined (shearing vs.	Technology research

	Some tools do not operate above 200 degrees. Other tools exist, but they are very expensive.	tensile.) Commercially available PTS tools.	
Reservoir Character ization	Seeking to maintain resolution of well logs. Interpretation of micro earthquakes is unclear.	Interpretation of micro earthquakes should be improved to enable correlation of seismicity with fluid flow. Interpretation of tracer tests should be improved. Methods should be developed for determining reservoir surface area. Data should be collected on stress fields, etc. Mitigation of seismicity should be a priority.	Identify existing tools and determine if they are adequate Compile results of previous strategic planning exercises: 1998 meeting at LBL, GRC meeting in Reno, 2 American Rock Mechanics meetings, MIT study, and roadmap.

ENHANCED GEOTHERMAL SYSTEMS: RESERVOIR CREATION WORKSHOP

HOUSTON, TEXAS AUGUST 21, 2007

The objectives of the workshop are to understand the status and experiences within reservoir creation and characterization; define the technology needs, gaps and barriers; and, define the technology development paths to meet those needs.

Invited speakers will provide a framework for open discussion by the audience, with the session chair acting as facilitator. Audience members will be permitted to expand, rebut, or make their own point with an impromptu mini-presentation of less than 5 minutes. A lap top computer with PowerPoint will be available, as well as an overhead projector with transparencies and markers.

Topic	Session Chair	Speaker	Time
Sign-In and Continental Breakfast			8:00-8:30 am
Welcome		Allan Jelacic, U.S. Department of Energy	8:30-8:40 am
EGS Reservoir Requirements and Challenges	Gerry Nix, National Renewable Energy Laboratory	Roy Baria, Mil-Tek UK	8:40-9:00 am
		Group Discussion	9:00-9:40 am
Reservoir Design	Joel Renner, Idaho National Laboratory	Ralph Weidler, Q-con GmbH	9:40-10:00 am
		Group Discussion	10:00-10:40 am
		Break	10:40-11:00 am
		Ian Palmer, Higgs-Palmer	11:00-11:20 am
		Group Discussion	11:20 am -12:00 pm
Buffet Lunch			12:00 -1:00 pm
Reservoir Formation	Doug Blankenship, Sandia National Laboratory	Halliburton (TBD)	1:00-1:20 pm
		Group Discussion	1:20-2:00 pm
Reservoir Characterization	Mack Kennedy, Lawrence Berkeley National Laboratory	Ernie Majer, Lawrence Berkeley National Laboratory	2:00-2:20 pm
		Group Discussion	2:20-3:00 pm
	Break		3:00-3:20 pm
Technical Gaps and Barriers, and Technology Development Paths	Clay Nichols, Consultant	Group Discussion	3:20-4:30 pm
Workshop Summary		Gerry Nix	4:30-4:45 pm
Closing		Allan Jelacic	4:45-4:50 pm

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Firms Represented:

Mil-Tek UK
Sentech, Inc
Exxon Mobil
Ormat Technologies, Inc.
Schlumberger
Higgs-Palmer
GeothermEx Inc.
Glitnir
GEA
Q-con GmbH
Chevron

Academic:

University of Texas at Austin