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SUMMARY

OVERVIEW

The Department of Energy (DOE) and its predecessors have conducted research and development (R&D) in geothermal energy since 1971. To develop the technology needed to harness the Nation's vast geothermal resources, DOE's Office of Geothermal Technologies oversees a network of national laboratories, industrial contractors, universities, and their subcontractors. The following mission and goal statements guide the overall activities of the Office.

Mission

To work in partnership with U.S. industry to establish geothermal energy as an economically competitive contributor to the US energy supply.

Goal

- Reduce the levelized cost of generating geothermal power to 3-5 cents per kWh by 2007
- Double the number of States with geothermal electric power facilities to eight by 2006
- Supply the electrical power or heat energy needs of 7 million homes and businesses in the United States by 2010.

This Federal Geothermal Program Research Update reviews the accomplishments of DOE's Geothermal Program for Federal Fiscal Year (FY) 2003. The information contained in this Research Update illustrates how the mission and goals of the Office of Geothermal Technologies are reflected in each R&D activity. The Geothermal Program, from its guiding principles to the most detailed research activities, is focused on expanding the use of geothermal energy.

RESEARCH FOCUS

In accordance with the mission and goals, the Geothermal Program serves two broad purposes: 1) to assist industry in overcoming near-term barriers by conducting cost-shared research and field verification that allows geothermal energy to compete in today's aggressive energy markets; and 2) to undertake fundamental research with potentially large economic payoffs.

Since the inception of the Geothermal Program, the Federal government and private industry have worked closely together - in pursuing promising research directions, and in overcoming difficult technical barriers—to establish an extensive geothermal knowledge base. Over the past two decades, industry, in turn, has succeeded in creating an infrastructure that translates research results into marketplace applications. This DOE/industry partnership guides the DOE research program towards more cost-competitive power generation from geothermal resources. In addition, this partnership assesses the value of long-term research options. Private-sector inputs to DOE's planning process are critical to a logical, balanced strategy for the Geothermal Program.

This research update uses four categories to distinguish the research activities of the Geothermal Program during FY 2003. Reservoir Engineering, Exploration, Drilling and Energy Systems reflect the main components of real-world geothermal research projects, and are introduced briefly below. They form four of the five main sections of the project descriptions in this report. A fifth category, GeoPowering the West, fosters awareness of the availability and benefits of geothermal energy.

Reservoir Engineering Research

The geothermal industry has made progress in devising techniques for characterizing and developing hydrothermal reservoirs. Nevertheless, reservoir technology still suffers from several major uncertainties, such as those encountered in assessing reservoir productivity and sustainability, and in assessing the extent of field reserves. These uncertainties may lead to overproduction in a field and premature pressure and production declines. Reservoir Technology research combines laboratory and analytical investigations with equipment development and field testing to establish practical tools for resource development and management for both hydrothermal reservoirs and enhanced geothermal systems. Research in various reservoir analysis techniques is generating a wide range of information that facilitates development of improved reservoir management tools. Five projects are working on developing numerical and modeling tools for that will aid in reservoir characterization and management. Research on geothermal tracers is continuing and is leading to increased understanding of reservoir volume and geometry, fluid velocities and thermal sweep efficiency. Research to increase the fundamental understanding of the complex chemistry of hydrothermal systems, including scale formation, equilibria, gas breakout, pH, solid/gas/liquid interactions and heat properties has been conducted. Understanding fractures in geothermal reservoirs is key to designing new operations and enhancing existing ones. Researchers are using a combination of computer modeling, laboratory experiments and field experiments to investigate processes that enhance permeability in fractured reservoirs. In addition to theoretical and modeling activities, researchers have been upgrading conventional low temperature borehole televiewer instrumentation to operate at high temperatures, and thus provide data to enhance our understanding of fractures in geothermal systems.

Exploration Research

Most of the U.S. hydrothermal systems with obvious surface manifestations have been located and evaluated. New hydrothermal discoveries will require exploration in frontier areas where the reservoirs are either concealed or lie at greater depths. Exploration research focuses on developing instruments and techniques to discover hidden hydrothermal systems and to explore the deep portions of known systems. Research in geophysical and geochemical methods is expected to yield increased knowledge of hidden geothermal systems. Improved exploration techniques and data interpretation methods will facilitate expanding the geothermal resource base. Efforts are underway to develop better exploration models because better exploration models lead to optimization of exploration strategies, reduction in the time and cost for finding and developing new systems capable of producing electric power, and ultimately lead to an increase in the amount of geothermal power available. Exploration based research focus is to simplify, regionalize, and increase accuracy in targeting new geothermal resource development locations using tools such as hyperspectral remote sensing, magnetotellurics, geochemistry, and 3D geological modeling.

Drilling Research

Drilling and completion of wells for exploration, production, and injection accounts for 20 to 40 percent of the cost of generating electricity from geothermal resources. Current geothermal drilling and completion technology is derived primarily from the oil and gas industry. This technology is often unsuitable for the high temperatures, hard rock, and highly corrosive fluids found in the hostile geothermal environment. Drilling Technology focuses on developing improved, economic drilling and completion technology for geothermal wells. Research is continuing on developing and evaluating new high temperature components such as microprocessors, passive devices, and batteries that will combine to provide critical information from the borehole both during and after drilling. Research conducted this year furthered the understanding of drill bit design and operation, cements and cementing processes used in high temperature geothermal applications. Studies of prior geothermal drilling information have led to formation of a drilling database that will provide baseline data so that we can judge the effect of technology improvements, and ultimately reduce geothermal drilling and well maintenance costs.

Energy Systems Research

The three conversion technologies in current use for electricity generation are: 1) dry steam conversion, such as used at The Geysers since 1960; 2) flash steam plants, favored for liquid-dominated or two-phase resources when the resource temperature is over 180°C (360°F); and 3) binary cycles, for moderate resource temperatures in the range of 100°C to 180°C (212°F to 360°F). Dry steam and flashed steam plants are mature technologies generating cost-competitive electricity in some situations. Binary-cycle power plant technology is less mature, only recently coming into general use as an economic conversion alternative. Conversion technology research focuses on reducing costs and improving binary conversion cycle efficiency, to permit greater use of the more abundant moderate-temperature geothermal resource, and on the development of materials that will improve the operating characteristics of many types of geothermal energy equipment. Increased output, performance enhancement and optimization of binary cycles will result from investigations in heat cycle research. This and other research enable better understanding of geothermal power plant costing methodologies. Four projects worked on ways to fabricate cost-effective tougher geothermal plant equipment that will resist scale, fouling, and high temperatures and still maintain the desired physical and thermal properties required for geothermal applications. Materials in this research range from sprayed metallic coatings to polymeric elastomers and organometallic polymers. Nondestructive testing of these types of systems is being conducted. Biotechnology research focuses on solutions that characterize microbiological growth and changes with various processes and environments encountered in the geothermal settings. There is potential to reduce cleaning and chemical abatement cost in some plants by up to 50% using biotechnology. Projects have addressed silica production in geothermal plants from both a problem and opportunity standpoint. Research into mitigating silica scale on equipment and optimizing silica extraction techniques for high purity silica and other byproducts that can be produced and sold has been conducted. New membranes for separation of non-condensable gasses, new instrumentation for real time detection and control of abatement process parameters and new components in improve heat rejection in air-cooled condensers have been developed.

GeoPowering The West (GPW)

Geothermal energy represents a major economic opportunity for the American West. GeoPowering the West is a commitment to increase the use of geothermal energy in the western United States by promoting environmentally compatible heat and power along with industrial growth and economic development. DOE's GeoPowering the West (GPW) program works with the U.S. geothermal industry, power companies, industrial and residential consumers, and federal, state, and local officials to provide technical and institutional support and limited, cost-shared funding to state-level activities. By demonstrating the benefits of geothermal energy, GPW increases state and regional awareness of opportunities to enhance local economies and strengthen our nation's energy security while minimizing environmental impact. By identifying barriers to development and working with others to eliminate them, GPW helps a state or region create a regulatory and economic environment that is more favorable for geothermal and other renewable energy development. GPW is pursuing this opportunity by bringing together national, state and local stakeholders for state-sponsored geothermal development workshops. In addition, non-technical educational workshops and seminars are conducted throughout the west. GPW is working with American Indians to identify and develop geothermal resources on tribal land. Site visits to help state and local agencies determine if there are geothermal opportunities are being conducted.

I. RESERVOIR ENGINEERING RESEARCH

Numerical Tools for Resource Management

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
Applied Earth Sciences
PO Box 1625
Idaho Falls, ID 83415-2107

Principal Investigator: G. Michael Shook
Phone: (208) 526-6945
E-Mail: ook@inel.gov

Collaborating Researchers: Dr. John Doherty, Watermark Numerical Computing
John Pritchett, SAIC

DOE HQ Program Manager: Dr. Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $250K

Cost Share Funding: $100K

Project Objective: The objective of this project is to develop a suite of new numerical tools for use in geothermal reservoir management. In particular, we are developing numerical models and interfaces that couple the geothermal reservoir model TETRAD with SAIC's geophysical codes and the inverse model PEST. The various models' capabilities are summarized below.

- Tet^{-1} is a Parameter Estimation (aka, inverse model or automatic history match) version of TETRAD. It is designed to estimate reservoir parameters from inverse modeling of reservoir data alone.
- TetGeo is a version of TETRAD which is coupled to SAIC's geophysical models. TetGeo writes output files that are subsequently used as input to the geophysical models. The added model output adds constraints to the history match process (i.e., use production history and what geophysics surveys are available to estimate reservoir parameters).
- TetGeo-1 will be an inverse version of TetGeo, and will be developed by mid-FY04. This inverse model uses both reservoir and geophysical models in the parameter estimation process.

Because TETRAD is used by all domestic geothermal companies, it was selected for use in this project. It should be noted, however, that, as most of the software developed herein only interfaces with TETRAD (i.e., is not imbedded), adding these new tools to other geothermal models is straightforward.

Background/Approach: 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 are being written to couple TETRAD to other codes in order to enhance the effectiveness of reservoir modeling. Specific programs are discussed in more detail below.

The public domain inverse model PEST (Parameter ESTimation) was identified as the most appropriate inverse engine to couple to TETRAD. Because TETRAD is proprietary, care must be taken to preserve the developer's interest. 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. Two advantages come from this. First, the proprietary nature of the code is preserved. More importantly, however, the method is readily expanded to include numerous forward models (e.g., TETRAD followed by geophysical models). The flexibility of the PEST code, and the ability to add more model instructions, make it an ideal candidate for this project.

Interfaces are also being written to generate an output file from a TETRAD run that can subsequently be used as input to SAIC's geophysical models. Conceptually, this "post processing" is similar to plotting production histories from a reservoir model to compare the simulated history with the observed. In reality, of course, the geophysical models are appreciably more complex than simple post processing implies. The models that are being coupled to TETRAD include Microgravity, DC Resistivity, SP, and MT codes (Pritchett, 2000). This is the only task that requires modifications to TETRAD in order to generate the output file.

Given the discussion above regarding the flexibility of the inverse engine PEST and the ability to generate multiple sets of field observations by running both reservoir and geophysical models, the logical next step of this project is to create an inverse model that operates on both reservoir and geophysics data. Because of the care taken in developing Tet^{-1} (most importantly the flexibility and freedom to include multiple forward models) and the existence of a coupled reservoir + geophysics code (TetGeo), writing this model, $TetGeo^{-1}$, is expected to be a relatively straightforward matter. It will be started in late FY03, and will be completed in FY04. Should additional geophysical models become available (e.g., seismic models), further code modifications to TETRAD will be performed to include these new capabilities.

Status/Accomplishments: All software and program interfaces have been completed for creating Tet^{-1}. The goal of the coding was to maintain the flexibility of TETRAD input structure – for example, permeability can be defined in more than five different ways – while still ensuring invariant input formats required by Tet^{-1}. The method ultimately devised is summarized as follows. First, we assume that all reservoir parameters to be estimated are constant over some spatial domain, and we wish to estimate those properties in these "regions" (note there is nothing to stop the user from defining each grid block to be its own region). Three new files are created by the user that define the number of regions and their location, initial values (guesses) of the parameters to be estimated, and a template file specifying which parameters are to be estimated. The new software (i.e., the PEST-TETRAD interface) updates the properties being estimated and writes the data to an input file read by TETRAD every forward model run. This input file can be constructed manually or through the use of a GUI such as PetraSim.

The beta version of Tet^{-1} has been tested against several synthetic geothermal problems, with good success (Shook, 2002, 2003), and has been released to three domestic geothermal companies for their testing. It is currently being field tested by INEEL on the Dixie Valley geothermal field, and has shown promise in this application as well. The study is too preliminary to present results; however, an example of the utility of Tet^{-1} can be given. In the initial calibration runs, Tet^{-1} was consistently unable to match both temperature and pressure at various observation wells. Further review of the data indicated the reason: the datum for temperature and pressure were different, and no correction for elevation differences had been made. It is not likely this discrepancy would have been found without Tet-1, given the age of the error in the data.

A relatively simple example of Tet-1 application is given below. The domain is a two-dimensional inverted five-spot well configuration (a central injector with a producer at each corner). Permeability, porosity and initial steam saturation are unknown, and are to be estimated on the basis of observed production rates, a tracer test, and effluent temperature histories. The reservoir is known to be two-phase because of pressure and temperature "measurements."

The example is numerical in nature; the "real" reservoir parameters were used in a forward TETRAD run. Output files of well histories (rates, temperature, and tracer concentrations) were taken to be real field observations. The input was subsequently changed to incorrect, constant values of permeability, porosity and steam saturation and Tet-1 was run. There are four regions of different permeability and porosity, corresponding to each quadrant of the domain. Steam saturation is constant everywhere. "Correct" parameter values are given in Table 1, as are the initial guesses used in the Tet-1 run.

The steps to execute the Tet^{-1} inverse run for this case are summarized briefly. Most of the work is done "behind the scenes" and thus transparent to the user.

- Create a standard input deck for a forward TETRAD run, excluding the parameters to be estimated.
- Using either PetraSim or other GUI, create a '.IS' file containing at least the variables k, φ and S_g. See TETRAD users' manual keyword ISREAD.
- Create three "regions files." The first denotes what grid blocks belong to which region. The second defines initial values of the parameters to be estimated, and their variable names. The third identifies which of these parameters are to be estimated in which regions.
- Create parameter description files to define any variable transformations required, parameter value bounds, etc.
- Create the "problem definition file" that describes the number of observations available, their relative weight, names of forward models (currently TETRAD, but TetGeo and geophysical models soon), their addresses, etc.
- Execute the interface command Tet2Pest, which creates the final set of input decks required by PEST automatically.

For the relatively simple example given here, these steps took approximately 20 min. After 19 iterations, final parameter estimates obtained are as given in Table 1. While reservoir description is simple, the problem is still highly nonlinear. Tet-1 does an excellent job at parameter estimation for this case.

Table 1. True, initial, and final parameter estimates for Tet^{-1} example problem.

Quad.	Permeability (md)			Porosity			Initial Steam Saturation		
	True	Init Est.	Final Estimate	True	Init Est.	Final Estimate	True	Init Est	Final Estimate
I	50.	750.	50.1	.05	.1	.0498	.8	.2	.801
II	150.	750.	150.5	.025	.1	.0235	.8	.2	.758
III	250.	750.	249.	.075	.1	.075	.8	.2	.77
IV	100.	750.	99.9	.04	.1	.042	.8	.2	.814

Code modifications required for TetGeo have also been completed. The modifications included several new subroutines within TETRAD to output the appropriate variables required for the geophysical models. Validation exercises have also been complete, and results compared against a similar dataset generated by the Star geothermal reservoir model. A beta-version is available to interested parties. TetGeo is also being used in a study to evaluate its potential as an exploration tool. This project is being performed in collaboration with SAIC.

Changes internal to TETRAD for Tet-1 and TetGeo have been reviewed by the code developer and are implemented in the latest version of the code. The enhancements discussed above are provided with TETRAD gratis.

Reports & Articles Published in FY 2003:

Shook, G.M. and J.E. Doherty, 2003, "Tet-1: An Interface between PEST and TETRAD for Parameter Estimation in Thermal, Multiphase Flow Problems," INEEL report, distributed to Tet-1 users.
Shook, G.M., "New Data and File Requirements for Tet-1," Trans., 28th Stanford Workshop on Geothermal Reservoir Engineering, Jan. 2003.

Presentations Made in FY 2003:

Shook, G.M., "New Data and File Requirements for Tet-1," 28th Stanford Workshop on Geothermal Reservoir Engineering, Jan. 2003.

Planned FY 2004 Milestones:

Release of Tet-1, version 2.	Apr 04
Release of TetGeo-1 for beta testing by industry	Sept 04
Report evaluating geophysical surveys for fracture detection, with recommendations	Aug 04

Studies of Geothermal Reservoir Dynamics

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC03-76SF00098

Performing Organization: Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA 94720

Principal Investigator: Karsten Pruess
Phone: (510) 486-6732
E-Mail: K_Pruess@lbl.gov

Collaborating Researchers: Tianfu Xu, Eric Sonnenthal, Nicolas Spycher, Chao Shan

DOE HQ Program Manager: Roy Mink
Phone: (202) 586-5463
E-mail: Roy.Mink@hq.doe.gov

DOE Funding Allocation: $195K

Cost Share Funding: $150K

Project Objective: This project enhances and applies mathematical modeling techniques (numerical simulation) for the study of geothermal reservoir behavior. Issues addressed include (1) mineral dissolution and precipitation effects in geothermal reservoirs during their natural evolution and during production and injection operations, and (2) use of noble gases as tracers in boiling geothermal systems. Results from the project are expected to improve management and exploration of geothermal systems, thereby reducing costs and increasing the economically recoverable resource base.

Background/Approach: Advances in reservoir engineering are key to more economical geothermal field exploration, development, and management. Currently available reservoir simulators typically include only rudimentary capabilities for chemical transport and rock-fluid interactions. This limits model calibration to reservoir engineering-type data, such as pressures, temperatures, flow rates, flowing enthalpies, and concentrations of non-reactive solutes. The overall purpose of this project is to develop more accurate and comprehensive numerical simulation capabilities and to make these capabilities available to the geothermal industry. Our main focus is on incorporating geochemical information, in order to develop more reliable reservoir models, and to optimize field development and management, especially fluid injection for enhanced energy recovery. The approach involves applying and enhancing LBNL's simulation codes TOUGH2, TOUGHREACT and iTOUGH2 to model rock-fluid interactions and the behavior of noble gases. The codes are used to develop quantitative numerical models of chemical processes such as scale formation during production and injection, using data from operating geothermal fields. We also study injection monitoring by means of natural and artificial tracers.

Status/Accomplishments:

1. Rock-Fluid Interactions

A major emphasis of our work has been the further development of TOUGHREACT, a numerical simulator for chemically reactive flows in multiphase non-isothermal systems. Our aim is to ready the code for release to the public. This involved an overhaul of all program units and associated thermodynamic databases, development of a comprehensive suite of sample problems to serve as templates for future code applications, extensive code testing and debugging, and writing user documentation. Collaborations with industry (Unocal, ExxonMobile, Geothermex, EPDC) were an essential part of this process. A beta-version of the code and associated documentation was completed, and was transferred to several external groups for beta-testing (Xu et al., 2003). Comments received during the beta-testing period will be addressed in the final version of TOUGHREACT, which we expect to release to the public in FY04.

In collaboration with industry, TOUGHREACT was applied to several geothermal field problems. We worked with Unocal to investigate the observed loss of injectivity in well Nag-67 at the Tiwi field, Philippines. Simulation results support the view that this is caused by precipitation of amorphous silica, and have suggested ways in which scaling may be avoided through changes in field operating procedures (Ontoy et al., 2003; Xu et al., 2004). In cooperation with researchers from Electric Power Development Company (EPDC, Japan), we studied the hydrogeologic conditions that give rise to low-permeability zones in the Onikobe reservoir, Japan. TOUGHREACT simulations employed a comprehensive description of aqueous species (Table 1) and solid minerals. Results showed precipitation in a region where acidic and neutral fluids mix, in agreement with field observations (Todaka et al., 2003a, b). A systematic study of rock-fluid interactions was performed for geothermal reservoirs situated in volcanic terrains. Mineral alteration was found to be generally consistent with field observations (Kiryukhin et al., 2004).

Table 1. Aqueous species considered for modeling precipitation processes at the Onikobe field, Japan

Primary species	**Secondary species**		
H_2O	$AlOH^{2+}$	$FeOH^+$	HSO_4^-
H^+	$Al(OH)_2^+$	$Fe(OH)_2(aq)$	$H_3SiO_4^-$
Ca^{2+}	$Al(OH)_4^-$	$Fe(OH)_3(aq)$	HS^-
Mg^{2+}	$CaCl^+$	$H_2(aq)$	$MnCO_3(aq)$
Na^+	$CaCl_2(aq)$	$KCl(aq)$	$MnOH^+$
K^+	$CaCO_3(aq)$	KSO_4^-	$ZnCl^+$
Fe^{2+}	$CaHCO_3^+$	$MgCl^+$	$ZnCl_2(aq)$
Cl^-	$CaOH^+$	$MgHCO_3^+$	$ZnCl_3^-$
$SiO_2(aq)$	$CaSO_4(aq)$	$MgOH^+$	$ZnCl_4^{2-}$
HCO_3^-	$CH_4(aq)$	$NaCl(aq)$	$ZnOH^+$
SO_4^{2-}	$HCl(aq)$	$NaCO_3^-$	$PbCl^+$
Al^{3+}	CO_3^{2-}	$NaHCO_3(aq)$	$PbCl_2(aq)$
$O_2(aq)$	$CO_2(aq)$	$NaOH(aq)$	$PbCl_3^-$
Mn^{2+}	$FeCl^+$	$NaSO_4^-$	$PbCl_4^{2-}$
Zn^{2+}	$FeCl_2(aq)$	OH^-	$PbOH^+$
Pb^{2+}	$FeCl_4^{2-}$	$H_2S(aq)$	

2. Noble Gas Tracers

Expanding on previous work with phase-partitioning tracers, a new fluid property module "EOSN" was developed for TOUGH2 to describe fluid mixtures that include noble gases (Shan and Pruess, 2003a, b).

Numerical studies of production-injection systems in fractured, vapor-dominated reservoirs demonstrated sensitivity of tracer returns to average fracture spacing, see Fig. 1 and (Shan and Pruess, 2003c). Studies are continuing to determine the feasibility of using noble gas tracers to determine reservoir processes (boiling, condensation, fracture-matrix exchange) and obtain insight into the migration of thermal fronts.

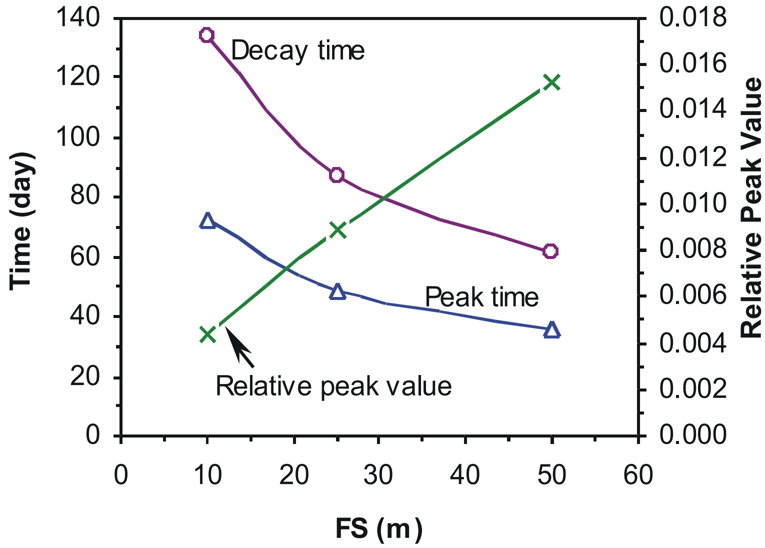


Figure 1. Effects of fracture spacing (FS) on breakthrough of neon tracer for injection into depleted zones of vapor-dominated reservoirs (from Shan and Pruess, 2003c). "Decay time" is the time required for tracer concentrations to decrease to 1/10 the peak value.

3. Coupled Mechanical Effects

With funding from research programs in nuclear waste and geologic disposal of greenhouse gases, LBNL has developed a simulation tool for multiphase non-isothermal flow and associated mechanical deformation by coupling TOUGH2 with the commercial rock mechanics code FLAC3D. Thermodynamic conditions calculated by TOUGH2 are fed into FLAC3D for stress-strain analysis (Fig. 2), and resulting changes are coupled back into TOUGH2 through dependence of porosity, permeability, and capillary pressure curve on effective stress. This has recently been applied to the Phlegrean Fields hydrothermal system, Italy, to model ground uplift in response to deep inflow and degassing of magmatic fluid (Todesco et al., 2003, 2004).

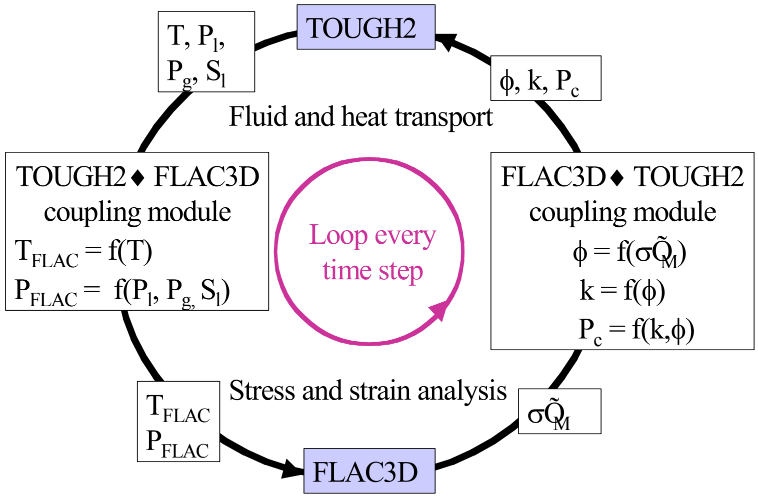


Figure 2. Schematic of the coupling between TOUGH2 and FLAC3D codes (J. Rutqvist, private communication).

Reports & Articles Published in FY 2003:

Kiryukhin, A., T. Xu, K. Pruess, J. Apps and I. Slovtsov. Thermal-Hydrodynamic-Chemical (THC) Modeling Based on Geothermal Field Data, to appear in Geothermics, 2004.

Todaka, N., C. Akasaka, T. Xu and K. Pruess. Reactive Geothermal Transport Simulation to Study the Formation Mechanism of Impermeable Barrier between Acidic and Neutral Fluid Zones in the Onikobe Geothermal Field, Japan, Lawrence Berkeley National Laboratory Report LBNL-52493, March 2003b.

Shan, C. and K. Pruess. EOSN: A TOUGH2 Module for Noble Gases, Lawrence Berkeley National Laboratory Report LBNL-52379, March 2003a.

Shan, C. and K. Pruess. EOSN - A New TOUGH2 Module for Simulating Transport of Noble Gases in the Subsurface, to appear in Geothermics, May 2003b.

Todesco, J. Rutqvist, G. Chiodini, K. Pruess and C. Oldenburg. Modeling of Recent Volcanic Episodes at Phlegrean Fields (Italy): Geochemical Variations and Ground Deformation, to appear in Geothermics, 2004.

Xu, T., Y. Ontoy, P. Molling, N. Spycher, M. Parini and K. Pruess. Reactive Transport Modeling of Injection Well Scaling and Acidizing at Tiwi Field, Philippines, to appear in *Geothermics,* 2004.

Presentations Made in FY 2003:

Dobson, P., S. Salah, N. Spycher and E. Sonnenthal. Simulation of Water-Rock Interaction in the Yellowstone Geothermal System Using TOUGHREACT, Proceedings, TOUGH Symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, CA, May 2003.

Finsterle, S., G. Moridis, C. Oldenburg and Y.S. Wu (eds.) Proceedings, TOUGH Symposium 2003, Lawrence Berkeley National Laboratory Report LBNL-52494, Berkeley, CA, May 2003.

Ontoy, Y., P. Molling, N. Spycher, T. Xu, M. Parini and K. Pruess. Scaling of Hot Brine Injection Wells: Supplementing Field Studies with Reactive Transport Modeling, Proceedings, TOUGH Symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, CA, May 2003.

Shan, C. and K. Pruess. Numerical Simulation of Noble Gases as Natural Tracers for Injection Returns and Reservoir Processes in Vapor-Dominated Systems, Proceedings, 28th Workshop on Geothermal Reservoir Engineering, report SGP-TR-173, Stanford University, Stanford, CA, January 2003c.

Todaka, N., C. Akasaka, T. Xu and K. Pruess. Modeling of Geochemical Interactions between Acidic and Neutral Fluids in the Onikobe Geothermal Reservoir, Japan, Proceedings, 28th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, January 2003a.

Todesco, M., J. Rutqvist, K. Pruess and C. Oldenburg. Multi-Phase Fluid Circulation and Ground Deformation: A new Perspective on Bradyseismic Activity at the Phlegrean Fields (Italy), Proceedings, 28th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, January 2003.

Xu, T., E. Sonnenthal, N. Spycher and K. Pruess. TOUGHREACT: A New Code of the TOUGH Family for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media, *Proceedings,* TOUGH Symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, CA, May 2003.

Planned FY 2004 Milestones:

Complete coding and documentation of TOUGHREACT, and release code to the public through DOE's Energy Science and Technology Software Center	Mar 04
Report on benchmarking of mechanically coupled simulation codes	Apr 04
Report on applications of TOUGHREACT to geothermal field problems	May 04
Report on feasibility of characterizing thermal parameters of production-injection systems, including EGS, through "active" tracers	Sep 04

Technology for Increasing Geothermal Energy Productivity

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)	
DOE Grant/Contract No.:	DE-FG07-99ID13745/DE-FG36-99ID13745
Performing Organization:	University of California, San Diego
Principal Investigator:	Dr. Nancy Moller
Phone:	(858) 534-6374
E-Mail:	nweare@ucsd.edu
Collaborating Researchers:	Professor John H. Weare, Dr. Christomir Christov, Dr. Zhenhao Duan, and Mr. Philippe Lamoise
DOE HQ Program Manager:	Allan Jelacic
Phone:	(202) 586-6054
E-mail:	Allan.Jelacic@hq.doe.gov

DOE Funding Allocation:	$300K
Cost Share Funding:	$17,229 (UCSD) Equipment match cancelled due to DOE budget cut for equipment. We presently use a large Beowolf parallel cluster computer funded by NSF, The Department of Chemistry computer facilities and personal computers funded by DOE and other agencies.

Project Objective(s):

- Develop thermodynamic models that predict scale formation, phase equilibria, gas breakout, pH, solid/gas/liquid interactions and heat properties for present-day geothermal energy operations.
- Develop equation of state (EOS) representations and molecular simulations of the thermodynamics of near critical and supercritical geothermal fluids for predictions of energy extraction chemistry, reservoir engineering studies and fluid inclusion analyses of the history and evolution of deep high TP reservoirs.
- Develop user interfaces and software application packages that allow easy access and use of our modeling technologies via the Internet. Develop and maintain a high level user interactive web site.
- Increase the fundamental understanding of the complex chemistry of energy extraction operations.
- Train students in earth science with expertise in hydrothermal resources.

Background/Approach: Our research program provides advanced modeling technologies that describe the complex chemistry of present and future energy production operations. They thereby help expand geothermal operations and reduce the financial risk involved in developing the resource. Our modeling approach describes the thermodynamics of mixed brine-gas-solid systems via their free energies and allows the construction of solubility, phase equilibria and heat models for geothermal fluids and their associated solid and gas phases for wide ranges of composition, temperature and pressure. Present near-surface operations face chemical problems (e.g., scaling or corrosion of wells and plant equipment, reservoir permeability losses and toxic gas emission) that can significantly increase energy production costs. Below about 300°C and P ≈1 atm, where the main variation of the liquid free energy is due to solute concentration changes, we use our solubility modeling approach, based on the Pitzer electrolyte equations. Future operations that exploit uncharacterized, deeper heat sources and low permeability reservoirs face new problems involving very high temperature and pressure rock/water interactions and unknown injection effects. To treat problems involving density variation (e.g., fluid inclusion, miscibility, flashing calculations) expected to be encountered in future deeper crustal and/or low fluid resources, we have developed EOS frameworks and molecular simulation technologies that can handle the large changes in density and high solute mole fractions encountered under these conditions. Our molecular level simulation methods can supply needed thermodynamic information when experimental data are not available. We develop user interfaces so that our models (bundled into application packages: TEQUIL, GEOFLUIDS, GEOHEAT) can be easily accessed on our interactive web site (geotherm.uscd.edu).

Status/Accomplishments: *TEQUIL, Model for the H-Na-K-Ca-OH-Cl-HSO_4-SO_4-HCO_3-CO_3-$H_4SiO_4^o$-$H_3SiO_4^-$-H_2O-CO_2(g)-SiO_2 System:* This year we completed several project goals using our methodology for describing solid-liquid-gas equilibria in complex geothermal brines at near surface conditions (T < 300°C). Our variable temperature model of acid-base reactions and solid-liquid equilibria in the Na-K-H-Cl-OH-HSO_4-SO_4-H_2O system is now complete (manuscript in press: *Geochimica Cosmochimica Acta*), and has been expanded to include calcium acid-base interactions and calcium hydroxide solid phases (manuscript submitted to *Geochimica Cosmochimica Acta*). Carbonate interactions (HCO_3^-, CO_3^{2-}) and carbonate solid phases have been added to the Na-K-Ca-H-Cl-OH-HSO_4-SO_4-H_2O model (preliminary version). We also have a preliminary model of silica-silicate interactions in brines. Now pH effects as well as temperature and brine composition effects on comprehensive brine-solid equilibria, including dominant salts, carbonate and acid/base reactions, can be assessed and used to aid the prediction of scale formation and the behavior of hydrothermal fluid and formation minerals under varied resource and production conditions.

TEQUIL, Model of Aluminum Interactions and Solubility: The major rock forming minerals in the earth's crust are aluminosilicates. An accurate thermodynamic model of the aqueous chemistry of aluminum, including interactions of Al^{3+} and aluminum hydrolysis species, forms an essential foundation for modeling aluminosilicate mineral solubilities and describing brine and injection fluid interactions with the important reservoir aluminum-silicate minerals as a function of temperature and fluid composition over wide pH ranges. For example, the hydrothermal mineral, wairakite ($CaAl_2Si_4O_{12}$●(H_2O)), undergoes dissolution via the reaction:

CaAl2Si4O12●(H2O)(s) + 8H+(aq) + 3H2O = Ca2+(aq) + 2Al3+(aq) + 4H4SiO4(aq).

In order to interpret the effects of injection or formation water interactions with this mineral, we need to be able to estimate the activities of all the species in this reaction. The chemistry of Al^{3+} is very complex and involves a number of hydrolysis species. This year, using our recently completed acid/base model, we constructed a variable temperature model of aluminum interactions and $AlCl_3.6H_2O$(s) solubility in the H-Na-K-Al-Cl-H_2O system and began adding aluminum hydrolysis species and other solid phases to this model. Figure 1 shows the predicted concentration product of one important hydrolysis reaction vs. temperature. With our preliminary model of silica-silicate/brine interactions, we are making good progress towards developing a model for formation aluminosilicate rock/water interactions.

GEOFLUIDS, EOS Models of Salt-H_2O Systems for High T,P Conditions: High temperature behaviors of reservoir rock/fluid interactions are well approximated by the thermodynamic behavior of the CO_2-CH_4-N_2-H_2O-salt system. Using perturbation theory plus additional empirical corrections, we previously developed accurate high TP (573 –1300K; 1bar - 5 kbar) EOS for the NaCl-H_2O, KCl-H_2O, $CaCl_2$-H_2O and $MgCl_2$-H_2O salt-water binaries, the NaCl-KCl-H_2O ternary and the NaCl-H_2O-CO_2-CH_4 quaternary.

However, there are very few high TP data to expand our model descriptions to treat other salt mixtures, such as $MgCl_2$-$CaCl_2$-H_2O solutions. This year we developed a mixing model for the $MgCl_2$-$CaCl_2$-H_2O system using an empirical approach based on classical mixing rules. Very non-ideal behavior is predicted, but the lack of data for this system, makes it impossible to tell whether the predicted non-ideal behavior is accurate. Therefore, we temporarily suspended the EOS approach and concentrated on direct molecular simulation to gain useful information about the behavior of important geothermal systems under high TP conditions.

GEOFLUIDS, Molecular Simulations of CH_4-CO_2-H_2O Phase Equilibria at High T,P Conditions: The CH_4-CO_2-H_2O system is an important component of many hydrothermal systems. Understanding the vapor/liquid phase relationships of this system at temperatures near and above critical the point of H_2O is essential to predict the flow and chemical behavior of deep geothermal energy resources. There are very few data for these systems in the high TP region. We performed high TP simulations of CO_2-H_2O and CH_4-H_2O mixtures using our water-water interaction model (manuscript submitted to *J. Phys. Chem.*) that represents well the H-bonding structure and critical behavior of the pure water system and our spherical models for the CH_4-H_2O and CO_2-H_2O interactions. Simulations of the CO_2-H_2O system at 653 K (just above the critical point of water) at 500 and 800 bar show that the system homogenized (no phase separation) consistent with the observation of an upper critical line moving from the critical point of water to lower temperatures. To check our results, we simulated the CO_2-H_2O phase behavior at temperatures below critical point of water. For these conditions, we were able to find both immiscibility for pressures just above the liquid/vapor transition pressure of pure water and homogenization at higher pressure (the upper critical line). Since there are no data very near or above the critical point of water for the CH_4-H_2O binary, present interpretations of CH_4-H_2O phase behavior have assumed that it is like the behavior of the CO_2-H_2O system. Our CH_4-H_2O mixture simulations show quite different behavior. There is a lower critical line extending from the critical point of water to higher temperatures (vs. an upper critical line going to lower temperatures for CO_2-H_2O). An example of these results is given in Figure 2 below. For pressures above 400 bar, the fluid separates into H_2O-rich and CH_4-rich fluids. Our simulations for temperatures below the critical temperature of water show immiscibility down to the liquid vapour transition line for pure water. The coexisting fluid compositions for this region are in good agreement

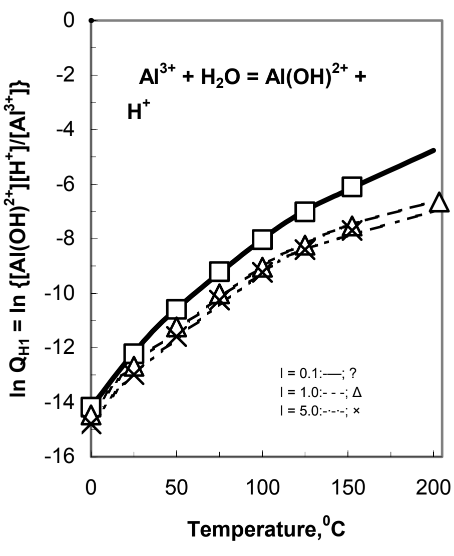


Figure 1. $Al(OH)^{2+}$ formation vs. temperature.

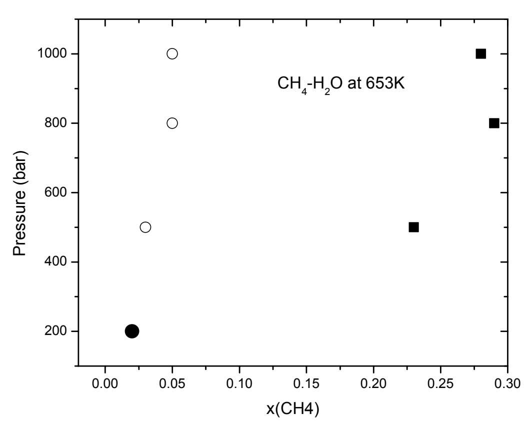


Figure 2. Simulated phase compositions vs. pressure.
○: H2O-rich fluid; ■: CH4-rich fluid; ●: homogeneous fluid.

with experimental data. If these results are correct, we would expect to encounter immiscible supercritical fluids at moderate pressures in geothermal reservoirs. We believe that this is the first time fluid-fluid coexistence has been simulated using realistic molecular interaction models.

GEOFLUIDS, Molecular Simulations of CH_4-CO_2-N_2 Phase Equilibria at High T,P Conditions: Fluid inclusions in minerals contain small relics of the formation and alteration fluids. Therefore, their observation, typically via spectroscopic and thermal methods, provides an important means of analyzing the thermal and chemical history of hydrothermal systems. On cooling, the fluids in inclusions separate into CH_4-CO_2-N_2 (MCN) rich phases and a water-salt phase. The correlation of the observed MCN phase behavior as a function of temperature with the dependence of phase coexistence on composition allows good estimation of the composition, pressure and temperature of formation and alteration processes. Therefore, to effectively carry out such an analysis, it is necessary to know as much as possible about the phase relations in the hydrothermal fluid as a function of composition. We have demonstrated that the Gibbs ensemble Monte Carlo (GEMC) method can simulate phase relationships even in the MCN ternary where there are very few data with accuracies close to the available experimental data. Simulation results show liquid/vapor immiscibility between 220 K and 304 K, from below 220 bar to 1000 bar. Initial results indicate that there may be additional phase separation at very high pressures (> 5000 bar). As far as we know, this is the first observation of this behavior. Below the critical temperature for N_2 (126.7 K), metastable liquid-liquid separation in the N_2-CO_2 system is possible and has been observed in our calculation. This behavior, which should also be present in the CO_2-containing binaries and ternaries, could help in the interpretation of fluid inclusion data.

Technology Transfer: We made substantial progress improving our web site (geotherm.ucsd.edu). The navigation, visual appearance and flexibility of the site have been substantially improved. In addition, we implemented new computational options and updated modeling codes for GEOFLUIDS.

Reports & Articles Published in FY 2003:

"Gibbs Ensemble Simulations of Vapor/Liquid Equilibrium Using the Non-Rigid RWK2 Water Potential." Revised and submitted: *J Phys. Chem. B*.

"A Chemical Model of Solution Behavior and Solubility in the H-Na-K-Ca-OH-Cl-HSO_4-SO_4-H_2O System to High Concentration and Temperature." In press: *Geochimica Cosmochimica Acta*.

"A Chemical Model of Solution Behavior and Solubility in the H-Na-K-Ca-OH-Cl-HSO_4-SO_4-H_2O System to High Concentration and Temperature." Submitted: *Geochimica Cosmochimica Acta*.

FY02 Federal Geothermal Research Program Update

Presentations Made in FY 2003:

Planned FY 2004 Milestones (grant terminates on 3/17/04):

- Complete and validate temperature (T < 300ºC) and pH dependent model of solid-liquid 3/17/04
- Equilibria in the carbonate H-Na-K-Ca-OH-Cl-HSO4-SO4-HCO3-CO3-H2O-CO2(g) system.
- Complete aluminum-brine interaction model of the H-Na-K-Al-OH-Cl-H2O system (T<150°C). 3/17/04
- Complete parameterization of a variable temperature silicate/brine model
- (H4SiO4o-H3SiO4--NaCl-KCl-CaCl2-H2O)
- Using molecular dynamics simulation methods explore the behavior of important hydrothermal vapor-liquid equilibria at high TP conditions. 3/17/04

- Using simulations and scaling EOS initiate predicting properties of thermodynamic functions, such as enthalpy, in gas-water CH_4-CO_2-H_2O systems at high and intermediate TP and in the critical region. 3/17/04
- Maintain and continue to improve our web site by updating user communication and documentation. 3/17/04

Reservoir Characterization for EGS and Hydrothermal Systems

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
Applied Earth Sciences
PO Box 1625
Idaho Falls, ID 83415-2107

Principal Investigator: G. Michael Shook
Phone: (208) 526-6945
E-Mail: ook@inel.gov

Collaborating Researchers: Dr. Gary A. Pope, gpope@mail.utexas.edu

DOE HQ Program Manager: Dr. Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $164K

Cost Share Funding:

Project Objective: 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. Geothermal tracer test analysis is currently handicapped by insufficient tracer selection criteria and poor understanding of the information available from tracer test analysis. This project will improve the utility of tracer testing by addressing the following needs:

- Develop a complete list of tracer candidate selection criteria to enable quantitative analysis of tracer tests, including necessary tracer selection protocol.
- Demonstrate reservoir properties that can be estimated from a well-designed tracer test.
- Develop the analytical and numerical tools to estimate reservoir properties.

These project objectives directly address the Geoscience Program goals in several ways. First, tracer test analysis can provide estimates of reservoir geometry, flow paths, fluid and thermal velocities, etc. These parameters are critical for improving reservoir management, thereby reducing the levelized cost of geothermal power. The interpretation methods being developed in this project also have direct application in EGS characterization. For example, we are working on methods to estimate heat transfer areas (matrix-fracture surface areas) from tracer tests. This task will be conducted in FY04. Improved characterization methods for EGS also supports the Geothermal Program goals by enhancing the regional distribution of geothermal power generation.

Background/Approach: A large number of tracer tests have been conducted in the geothermal industry in the last decade; however, analysis of such tests remains largely qualitative. Interpretation methods developed previously at INEEL show that reservoir volume and fluid and temperature velocities can be estimated in heterogeneous (but porous) media. That work needs to be extended to more complex cases of fractured media. Two-phase or vapor phase tracer tests have proven much more difficult to analyze, in large part due to the complexities of phase partitioning, variable heats of vaporization, and adsorption. These difficulties must be overcome in order to develop methods for interpreting tracer tests in two-phase or superheated, fractured geothermal reservoirs. New methods for estimating geothermal reservoir geometry, including fracture geometry and surface area, are also required to improve reservoir management.

These tracer test interpretation methods have particular importance in engineered or fluid-starved geothermal systems. In these cases an accurate assessment of connected pore volume and reservoir geometry, leak-off rates, and predictions of thermal velocities can be used in real time to optimize use of available fluid for injection, as well as identify and mitigate thermal breakthrough potential.

Status/Accomplishments: An INEEL external report has been completed on tracer testing and test analysis. That document is in final review, and will be distributed in early 2004. The report summarizes steps that are required to successfully implement and interpret a tracer test in the field. The report includes discussions of appropriate tracer test goals, laboratory tests required to ensure the tracer has the required properties, field deployment, and an extensive discussion of test analysis methods. This report will also be submitted to *Geothermics* in the coming year.

Analytical studies have focused on methods to estimate reservoir properties from tracer tests in fractured media. This work is an extension of methods previously developed for porous media (Shook, 2001). In particular, we are developing means of estimating reservoir geometry from tracer tests. These results will be used in extending methods of estimating thermal velocities and heat transfer surface areas, and will help constrain numerical reservoir models. One such method, a “flow-storage” diagram is discussed below.

The concept of flow vs. storage was developed originally in the petroleum literature to determine injection sweep efficiency in layered media. The method relates the relative velocity of a given layer to its associated pore volume. It can be used semi-quantitatively to describe reservoir geometry (e.g., “40% of the flow coming from only 10% of the pore volume” indicates a few fast flow paths). Such a description of reservoir geometry gives the operator a means of visualizing the reservoir, and is also useful as constraints in any subsequent reservoir modeling. The method can be generalized to fractured reservoirs in the following manner (Shook, 2003). Noting that tracer velocity is a function of porosity, permeability, and flow lengths, we define the following terms for Storage Capacity, C, and Flow Capacity, F.

$$C_i = \frac{\sum_{i=1,}^{\#frac} \varphi_i \ell_i}{\overline{\varphi}\overline{L}}; \qquad F_i = \frac{\sum_{i=1,}^{\#frac} k_i / \ell_i}{\overline{k} / \overline{L}}$$

A conservative tracer flows with the same velocity as bulk fluid flow. The cumulative pore volume of a fracture network is proportional to the mean residence time of the tracer (e.g., Shook, 1999). How much of the tracer flows in any given fracture is likewise proportional to the flow impedance of the fracture as in the equations above. Using these concepts, we can define a proxy to true F-C calculations as:

$$C(t)=\frac{\int_0^t c\tau d\tau}{\int_0^\infty ctdt}\;; \qquad F(t)=\frac{\int_0^t cd\tau}{\int_0^\infty cdt}$$

C(t) is simply the time-weighted reservoir volume "seen" by the tracer at time t. F(t) is the fractional cumulative amount of tracer "delivered" to the production well via the pore volume, C(t). For a given tracer effluent history, these calculations are very simple and fast on an Excel spreadsheet. The equations given above assume constant flow rates; however, variable flow rates can be handled easily as well. As an added bonus, the total pore volume follows directly from calculating C. The single limitation to the method is that it does not describe the spatial distribution of the flow and storage.

The method has been tested numerically on several relatively simple, fractured geothermal reservoirs. One example is given below. The test is numerical in nature because we must have some idea of the true reservoir F-C characteristics to compare against estimates obtained from tracer tests. A rectangular domain was set up, and three fractures connecting the injection well with a single extraction well were explicitly modeled. Information on the fracture properties is given in Table 1. Tracer was injected (along with water) at t=0 for 5 days, followed by pure water. Production was constrained by a pressure constraint (i.e., production rate varied). Figure 1 shows the tracer effluent history at the production well. A simple Excel spreadsheet application was created to calculate the F-C data from the tracer data. True reservoir F-C calculations were made from the reservoir description given to compare against the tracer analysis estimates. F-C analysis also gives an estimate of total swept pore volume, which is compared against the known volume in Figure 2.

Table 1. Summary of fracture properties for F-C example problem.

Fracture Length	Fracture Porosity	Fracture Permeability	$\varphi_i \cdot \ell_i$	k_i/ℓ_i	C_i	F_i
					0	0
340 m	0.2	600 md	68	1.765	0.456	0.722
390 m	0.15	200 md	58.5	0.513	0.849	0.932
300 m	.075	50 md	22.5	0.1667	1.	1.

A comparison between the two reservoir descriptions (in terms of F-C) is shown in Figure 2. The tracer analysis gives a good approximation to the true reservoir F-C data. Differences between the two are attributable to viscous effects; the injected fluid is appreciably more viscous than the in-situ fluid. Other examples further support the conclusion that reservoir geometries are obtainable from tracer test analysis. Effects of open boundaries and multiple production wells have been investigated; the F-C description obtainable from tracer tests is insensitive to such conditions.

The spreadsheet applications have been distributed to geothermal companies worldwide. Feedback from the companies will be used to make the application more user-friendly and robust. INEEL will continue to distribute and support tracer test interpretation applications for the geothermal community.

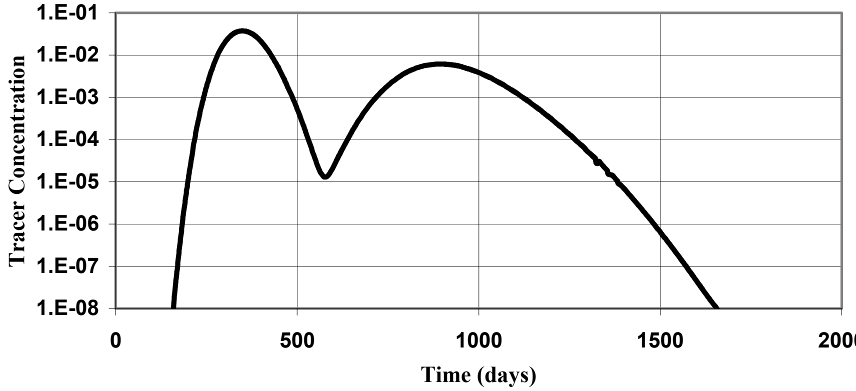


Figure 1. Tracer effluent history for the F-C example. Note that only two of the known three fractures are apparent from the tracer history. This is also manifest in the pore volume estimate.

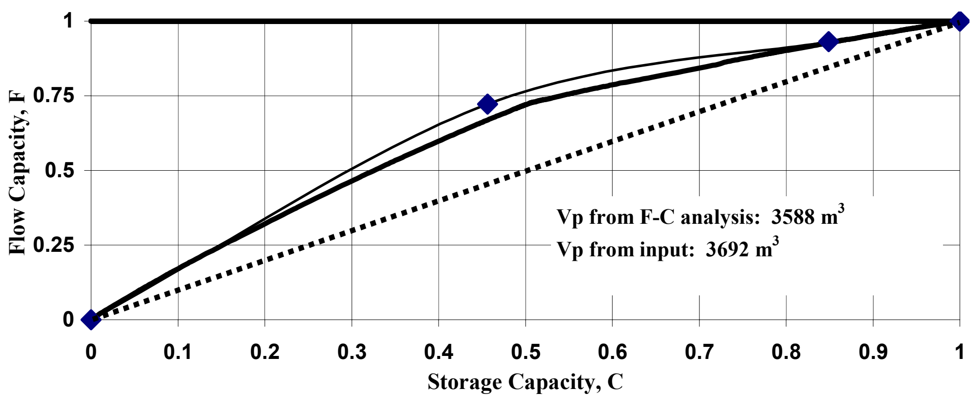


Figure 2. Comparison in F-C diagrams for a simple fractured reservoir. The upper line (with data points) is the F-C relationship calculated from the true fracture properties. The bold line is that calculated from the tracer test. Differences are due to viscous effects in injecting cold water. The dotted line is a theoretical minimum curve, and represents a homogeneous reservoir.

Reports & Articles Published in FY 2003:

Shook, G.M., "A Simple, Fast Method of Estimating Fractured Reservoir Geometry from Tracer Tests," Trans., Geothermal Resources Council, Vol. 27, Sept. 2003.

Shook, G.M., S.L. Ansley, and A. Wylie, "Tracer Testing Methods: Test Design Implementation and Interpretation Methods," INEEL report 03-01466, 33 pp.

Maxfield, B.T., D.M. Ginosaur, and G.M. Shook, "Evaluation of Perfluorocarbons as Geothermal Tracers," submitted to *Geothermics*, in review.

Presentations Made in FY 2003:

Shook, G.M., "A Simple, Fast Method of Estimating Fractured Reservoir Geometry from Tracer Tests," 27th annual meeting of the Geothermal Resources Council, Sept. 2003.

Shook, G.M., G. Nalla, K. Kit Bloomfield, and J.L. Renner, "Tracer Test Capabilities at the INEEL," 27th annual meeting of the Geothermal Resources Council, Sept. 2003.

Planned FY 2004 Milestones:

Develop tracer methods to estimate fracture surface area	May 04
Publish Tracer Test Protocol and Interpretation article in reviewed journal	Jun 04
Extend tracer methods for thermal velocity estimates to superheat conditions	Aug 04

Analysis of Injection in Fluid Starved (EGS) Environments

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3830

Principal Investigator: K. Kit Bloomfield
Phone: (208) 526-5250
E-Mail: blookk@inel.gov

Collaborating Researchers: Gopi Nalla, INEEL
Calpine (industry cost share and technical oversight)

DOE HQ Program Manager: Alan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $130K

Cost Share Funding: $30K Industry cost share

Project Objective: A controlling economic factor in geothermal power generation is the efficient use of the working fluid: injected water. In either hydrothermal or engineered geothermal systems, water is injected to increase energy extraction via improved thermal sweep efficiency. The processes of heat transfer from reservoir to fluid or wellbore, multi-phase flow effects, and effects of contaminants on generation efficiency, are complex and coupled processes. The level of complexity generally requires numerical simulation as a tool to evaluate optimizing injection usage. This project uses numerical modeling to evaluate energy recovery and power generation efficiency for various hydrothermal and engineered geothermal systems.

Background/Approach: The objective of this project at its most basic level is to use numerical modeling to evaluate optimal methods of energy extraction and power generation efficiency for various reservoir descriptions. By evaluating a variety of injection conditions in hydrothermal systems, we expect to identify relationships between power generation efficiency and location and volume of injectate used. We emphasize that under consideration here is generation efficiency, not production per se. A number of studies have considered injection effects on production rates; others have considered the effect of geochemical effects on generation efficiency. These studies have been artificially separated into “reservoir” and “plant” studies. Given the coupled nature of production and generation efficiency, we argue the need to combine these into a single study.

Other operational targets addressed in this project include energy recovery in enhanced, or engineered, geothermal systems (EGS). At the request of DOE, we have undertaken studies of an end member of EGS: extracting energy in a dry EGS reservoir by circulating water in a wellbore (i.e., heat transfer by conduction only; no communication between the well and the reservoir rock). A number of variables influence this process, including well design parameters, residence time of the working fluids, local heat flux, and thermal properties of the rock.

These objectives support the Geothermal Program objectives in a number of ways. Evaluating means of increasing generation efficiency via injection optimization reduces the levelized cost of geothermal power. Heat transfer studies in dry EGS environments can lead to an increase in the regional distribution of geothermal power production.

Status/Accomplishments: The NW Geysers injection study extends the work of Truesdell and Shook (1997) and Stark and Koenig (2001). The reservoir description is representative of NW Geysers: A "normal, vapor-dominated reservoir" (NVDR) is underlain by a "high temperature reservoir" (HTR). Pressures are vapor-static, and temperature gradients are as reported in the literature (Walters et al., 1988): negligible in the NVDR, but approaching 0.25º C/m in the HTR. Non-condensable gas (NCG) content of the reservoir fluid is also markedly different in the two zones, with the gas content in the NVDR averaging 2 %wt and 10 wt% in the HTR. Initial liquid saturation in the HTR remains unknown. Estimates range from zero (Truesdell, 1991) to intermediate values (Shook, 1995). For the cases presented here, a liquid saturation of zero was assumed, similar to Truesdell and Shook (1997). The reservoir was modeled as a dual continuum, with properties taken from the literature. Various simulations have been performed examining such issues as injection rate, injection depth, rock matrix saturations, petrophysical properties, etc.

The effect of non-condensable gas on a surface condenser can be considerable. If the backpressure is higher than the design pressure, expansion in the turbine is incomplete and the thermal efficiency decreases. The calculations of the off-design operation can be done with basic heat transfer equations from Heat Exchange Institute (1995). Assuming a typical Geysers condensing unit power plant, power generation for the two injection cases of injecting just above the HTR and injecting into the HTR would reduce the NCG production by ~0.5 wt%. The relatively small reduction in NCG production corresponded to a two MWe increase in power generation. The increase in power generation was a result of a decreased condensing pressure. NCG impedes the condensation process in the condenser. As steam proceeds through the condenser, water vapor condenses as it is drawn to the cold tube wall. The NCG present in the steam tends to accumulate at the vapor liquid interface. This lowers the partial pressure of the water vapor in this region, requiring a lower temperature for condensation to proceed. A driving potential for the condensation process is the temperature difference between the cold fluid and the condensing temperature. With the presence of the NCG and the associated reduction in the water partial pressure adjacent to the tube surface, this driving potential is reduced. When this lower potential for heat transfer occurs, the total condenser pressure increases in order to condense all of the steam flow. This rise in the partial pressure of the water restores the driving potential for heat transfer. This effect has been described as apparent sub-cooling, where the calculated saturation temperature at the total condenser pressure is higher than the condensate temperature.

The second task within this project involves analysis of heat gain to working fluid circulating in a dry EGS environment. The wellbore heat exchanger consists of a 12 ¼ " wellbore to a depth of 6000 ft., casing cemented to a depth of 2500 ft and a 6000 ft. insulated tubing string. The bottom 3500 ft. is uncased. Cold water is circulated at 80^{o} F down the annulus and the heated water is produced through the tubing that is hung just above the bottom of the well. Heat transfer from the formation to the fluid takes place due to conduction through the formation rock and wellbore. Numerical modeling of a wellbore heat exchanger was conducted to investigate the effects of the various operating and design parameters on its performance and to evaluate the best set of conditions for optimal thermal energy extraction from a wellbore heat exchanger system. The variables undertaken for the sensitivity study include the circulation rates, well depths (based on varying basal heat flux for fixed bottom hole temperatures), wellbore diameter, tubing size, formation thermal diffusivity, formation natural convection effects, and working fluid properties (volumetric specific heats).

The major controlling parameters of the heat transfer process is the thermal conductivity properties of the formation rock and the short residence times the working fluid has in contact with surface area of the wellbore. The major limitation of the wellbore heat exchanger ability to produce enough heat for commercial power generation is the poor thermal conductivity properties of formation rock.

Reports & Articles Published in FY 2003:

An article was published in the Geothermal Resource Councils Annual meeting transactions volume 27 pages 383-386 “Injection Studies Into the High Temperature Reservoir In the Northwest Geysers”

Presentations Made in FY 2003:

Presentations were made at the peer review in July and at the Geothermal Resource Councils Annual meeting

Planned FY 2004 Milestones:

Final report of wellbore heat exchanger study	Feb 04
Establish reservoir model for NW Geysers margin.	Jul 04
Publish ‘Relative Response to Injection in Reservoir Margins’ at conference	Sept 04
Report on strength and means of propagating fractures in margins or EGS	Sept 04

Prediction and Detection of the Attributes of Induced Fractures in EGS

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory
7000 East Avenue
P.O. Box 808
Livermore, CA 94551

Principal Investigator: Jeffery J. Roberts
Phone: (925) 422-7108
E-Mail: roberts17@llnl.gov

Collaborating Researchers: Russell Detwiler, detwiler1@llnl.gov
Paul Kasameyer, kasameyer1@llnl.gov
Barry Kirkendall, kirkendall1@llnl.gov

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $300K

Cost Share Funding: In-kind: EMI/Schlumberger GeoBILT tool development;
Ormat—Desert Peak Core

Project Objective: During FY03, the primary objectives of this project have been twofold: 1) develop enhanced approaches for identifying and characterizing fractures in geothermal reservoirs using electrical techniques through a combination of laboratory and field experiments and 2) investigate processes that enhance and degrade the permeability of fractures in enhanced geothermal systems through a combination of laboratory experiments and computational modeling. This work supports two Geoscience objectives of the DOE Geothermal Program: 1) Enhance our understanding of the mechanical, thermal and chemical evolution of natural and induced fractures, and 2) Improve methods of fracture detection and characterization. This project addresses the Geothermal Program goal of increasing the supply of geothermal generated electrical energy.

Background/Approach: Fractures provide the dominant pathway for fluid flow in geothermal reservoirs, and thus our ability to design effective enhanced geothermal systems depends critically on our ability to locate and characterize fractured zones, and to create and maintain hydraulic connection between injection/production wells and permeable fractures. Borehole logging techniques can be used to characterize fractures that intersect the borehole, but these methods provide little information on the presence or nature of non-intersecting fractures. Locating and characterizing nearby fractures can greatly improve our ability to design hydraulic or propellant fracture schemes to maximize the performance of enhanced geothermal systems. Through the concurrent development and deployment of field scale geophysical tools (GeoBILT) and laboratory investigations of the transport properties (mass and electrical) of fractured rocks, we have developed enhanced techniques for characterizing near borehole conditions. In addition to providing data in support of the development of EGS reservoirs, these techniques are potentially useful for tracking injectate in steam/water reservoirs. We have recently initiated computational modeling studies aimed at evaluating the potential efficacy of propellant fracturing techniques, widely used in the petroleum industry, for EGS applications. We have also initiated laboratory experiments focused on the influence of rock and fluid properties on the permeability evolution of fractures under geothermal conditions.

During FY03, this project consisted of three concurrent elements, discussed below: 1) Complete laboratory and modeling studies of the electrical response of fractured rocks to flow and phase change under geothermal conditions, 2) deploy the GeoBILT tool in an active geothermal field, and 3) begin investigating the properties of EGS induced fractures.

Status/Accomplishments: Although this project is considered to be in its first year, this is actually a transition year for work performed by our group as we focus our research efforts on fracture propagation and permeability evolution in Enhanced Geothermal Systems. We concluded our prior study of the transport properties of fractured geothermal reservoir rocks under mixed water/vapor conditions which included laboratory experiments and modeling of fracture/matrix interactions in geothermal reservoir rocks, and deployment of the EMI/Schlumberger EM induction tool (GeoBILT). We have also initiated an investigation of how the physical and chemical properties of rocks and fluids control the attributes of induced fractures in geothermal reservoirs.

1) Laboratory *experiments and modeling of mass and electrical transport in fractured rocks ($100k).*

The electrical resistivity of rock cores under conditions representative of geothermal reservoirs is strongly influenced by the phase (liquid/vapor) of the pore fluid. In fractured samples, phase change (boiling/condensing) can result in resistivity changes that are more than an order of magnitude greater than those measured in intact samples. These results suggest that electrical resistivity monitoring of geothermal reservoirs may provide a useful tool for remotely detecting the movement of water and steam within fractures, the development and evolution of fracture systems, and the formation of a steam cap. We measured the electrical resistivity of cores of welded tuff containing fractures of various geometries to investigate the resistivity contrast caused by active boiling and to determine the effects of variable fracture dimensions and surface area on water extraction from the matrix. We then used the Nonisothermal Unsaturated Flow and Transport model (NUFT) (Nitao, 1998) to simulate the propagation of boiling fronts through the samples. The simulated saturation profiles combined with previously reported resistivity-saturation curves allow us to estimate the evolution of the sample resistivity as the boiling front propagates into the rock matrix. These simulations provide qualitative agreement with experimental measurements, suggesting that our modeling approach may be used to estimate resistivity changes induced by boiling in more complex systems.

A paper on the electrical conductivity signatures of fractured geothermal reservoir rocks was published in the 2003 GRC Transactions. This work has led to an increased understanding of fracture/matrix fluid interaction in two-phase reservoirs and is applicable to fluid dominated reservoirs where a steam cap can develop. Modeling of laboratory results has resulted in a flow and transport modeling tool that has incorporated prediction of changing electrical properties during phase change and fracture evolution that is easily adaptable for fluid dominated EGS systems. An additional benefit of this research has been the development of enhanced laboratory capabilities for measuring the permeability and electrical properties of fractured reservoir rocks at reservoir conditions, which we are utilizing in our ongoing research.

2) GeoBILT *Deployment ($100k).*

A second area covered by this project is the field deployment of the GeoBILT long spacing induction tool. This work was done in collaboration with Electromagnetic Instruments (EMI), who developed and built the tool. The GeoBILT tool is an inductive EM system that has multiple transmitter-receiver spacing of 2, 5, and 10 meters. The system was designed to operate at the high temperatures of geothermal fields with the goal of mapping fractures and tracking injectate. This single hole, multi-frequency tool can yield 3D information surrounding the borehole to distances of about 5 meters. There have been two deployments of the tool in geothermal areas. Despite significant difficulties, due primarily to the high temperatures of geothermal wells, reasonable quality data were obtained. The first was in the Dixie Valley, Nevada geothermal field in 2001 and 2002. Two sections were logged in well DV2, 4200 to 5000 ft, and 8300 to 7000 ft. Anomalies in the apparent resistivity plots and null coupled logs were recorded that may correlate to the presence of dipping fracture zones and logged steam entry zones. A deployment at The Geysers was performed in March, 2003.

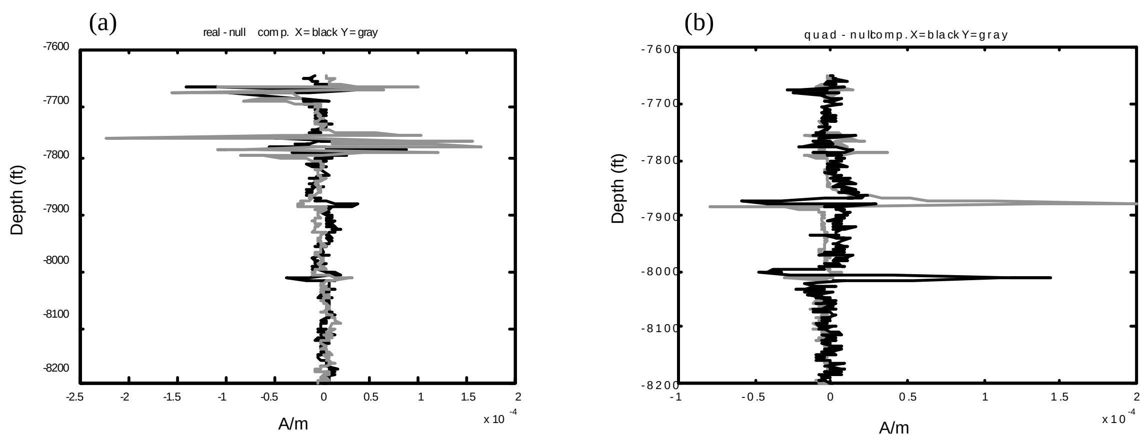


Figure 1a. Real part of the null component signal from Dixie Valley, Nevada, 6.0 kHz. The transmitter component was vertical, and both horizontal receiver components are shown (north = black, east=gray). 1b. Imaginary, or quadrature, part of the null component.

LLNL has developed a code that can locate, at a specific depth, the maximum azimuth of the null-component signal. In EM induction, the null component describes a transmitter placed on an axis perpendicular to the receiver. Energy received in this configuration can be indicative of inhomogeneity or anisotropy. Fig. 1a shows the two horizontal (X and Y) real null components from Dixie Valley, while Fig. 1b shows the imaginary, or quadrature, component. The geophysical parameters and the geologic setting constrain the quadrature component to predominantly contain the energy scattered, or induced, into the formation. A null signal anomaly of interest is seen at approximately 7880 feet depth in Fig. 1b, which correlates with well-logs taken from the area. Fig. 2 shows the maximum azimuthal response of this anomaly to be ~100 degrees from north. Borehole acoustic televiewer image logs acquired from Caithness also indicate fracture zones at these depths. Results indicate that the GeoBILT tool, combined with modeling, may be useful in locating permeable fracture regions not intercepted by EGS boreholes.

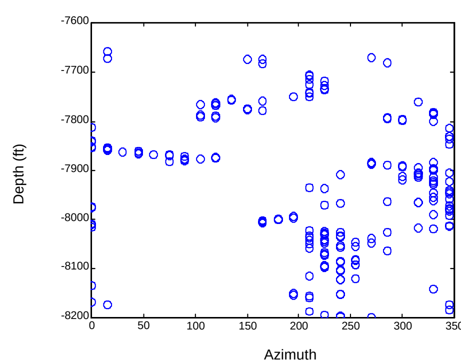


Figure 2. Azimuth of dominant null-component response calculated from the data in figures 1a and 1b above.

Attributes of induced fractures in Enhanced Geothermal Systems ($100k).

Propellant fracturing is frequently used in petroleum reservoirs to create hydraulic connection between the well bore and the undamaged formation. We have begun to explore the applicability of this approach to EGS where the formation consists of low porosity, crystalline rocks rather than the high porosity, relatively weak sedimentary rocks encountered in petroleum reservoirs. We subcontracted with JFSRC, the developers of PulsFrac, a computational model developed to predict propellant fracturing in petroleum reservoirs, to explore the potential for using propellant fracturing in EGS to create hydraulic connection between well bores and nearby fractures. During a meeting with JFSRC at LLNL in June we explored areas of research critical to the development of EGS and outlined future research topics, such as identification of critical differences between propellant fracturing in sedimentary rocks typical of petroleum reservoirs and the crystalline rocks encountered at EGS sites. Critical issues include the magnitude and orientation of fractures and the degree of self propping of fractures induced under non-hydrostatic conditions.

In addition to enhancing hydraulic connection through induced fractures, maintaining the enhanced permeability during production of geothermal energy is critical to the success of EGS. In conjunction with our computational investigations of fracturing procedures, we have planned laboratory experiments to investigate the role of rock and fluid properties on the evolution of fracture aperture and permeability under geothermal conditions. We contacted GeothermEx, Inc. (Ann Robertson-Tait) and ORMAT (Christy Morris), who are now sharing information with us. GeothermEx is a participant in ORMAT's EGS project at Desert Peak. ORMAT contributed core from DP-35-13 to LLNL for use in our experimental research.

Reports & Articles Published in FY 2003:

Detwiler, R. L., J. Roberts, W. Ralph, and B. P. Bonner, Modeling fluid flow and electrical resistivity in fractured geothermal reservoir rocks, *28th Stanford Workshop on Geothermal Reservoir Engineering*, Stanford, CA, Jan. 27 –29, 2003.

Detwiler, R. L., and J.J. Roberts, Electrical resistivity as an indicator of saturation in fractured geothermal reservoir rocks: Experimental data and modeling, Geothermal Resources Council Trans., 27, 2003, Annual Meeting, Morelia, Mexico, Oct. 13-15, 2003.

Presentations Made in FY 2003:

Detwiler, R. L., J. Roberts, W. Ralph, and B. P. Bonner, Modeling fluid flow and electrical resistivity in fractured geothermal reservoir rocks, 28th Stanford Workshop on Geothermal Reservoir Engineering, Stanford, CA, Jan. 27–29, 2003.

Planned FY 2004 Milestones:

Complete initial design of experiments of permeability changes in fractured rock based on FY03 findings	Nov 03
Complete assessment of first experiments and begin modeling of results	Feb 04
Discuss results with industry partners	May 04
GRC paper reporting results or an internal report	Aug 04

Reinjection of Chemically Modified Geothermal Brines

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA, 94550-9234

Principal Investigator: Carol J. Bruton
Phone: (925) 423-1936
E-Mail: bruton1@llnl.gov

Collaborating Researchers: Brian E. Viani
Lawrence Livermore National Laboratory
viani1@llnl.gov

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $15K

Cost Share Funding: None

Project Objective: The objective of this project is to evaluate the chemical and mechanical effects of injection of chemically modified fluids on the geothermal reservoir, and on injectivity and permeability over time. Injected fluids can be modified by various additives that reduce or delay mineral precipitation and modify rock strength. Better control of fluid chemistry and rock-water interactions accompanying injection will help to reduce the cost of geothermal power by improving resource management and by reducing operations and maintenance costs associated with workover, re-drilling and abandonment of reinjection wells. Better fluid chemistry control may also ensure that fracture permeability generated during enhanced geothermal system (EGS) development will be sustained over the long term, thus increasing the viability of EGS. Chemical modification of drilling fluids may also increase drilling efficiency and extend bit life by altering the strength and fracture properties of rocks.

Background/Approach: This project addresses a number of issues regarding the effect of injection of chemically modified fluids on the geothermal reservoir. The term injection, as used here, includes reinjection of spent geothermal brines as a disposal and reservoir pressure support mechanism, hydrofracturing during EGS development, and the use of drilling fluids during drilling. The chemistry of injected fluids not only affects the injected zone through the precipitation and dissolution of solids which alter the permeability of the injected zone, but through the dependence of the mechanical properties of rocks on their chemical environment.

pH modification technology is increasingly being used to delay silica precipitation and avoid scaling in surface facilities and the wellbore during reinjection of spent geothermal brine. Despite the delay, silica will eventually precipitate and the aquifer rock will dissolve to buffer the pH when pH-modified fluid is reinjected. The degree to which the reduction in porosity/permeability from silica precipitation balances the potential increases from mineral dissolution requires evaluation, as do issues related to the sites of precipitation (e.g. in the wellbore or the formation), and the potential release of toxic elements leached from the rock into future production fluids. Given the variability of host rock mineralogy and fluid chemistry in geothermal fields, efficient field management depends on knowing the effect of long-term reinjection of brines, especially chemically modified brines, on injectivity and the resource over time, on a field or well by well basis.

The issue of permeability changes due to introduction of chemically incompatible fluids is of importance to EGS operations in which the intended reservoir is fractured to increase its permeability. It must be determined how long these fractures will remain "open" before they are closed by mineral precipitation (e.g. silica) or by pressure solution-type dissolution of asperities that hold the induced fractures open. Because fluid chemistry affects rock strength and can be used to influence subcritical cracking, it may also be possible to control the chemical composition of the fluids used to induce fracturing to enhance the rate, type and direction of fracturing. Similar chemical-mechanical dependencies may be exploited to increase drilling penetration rates and reduce drill bit wear by modifying the composition of drilling fluids.

Status/Accomplishments: Work was directed towards developing an experimental plan aimed at determining if chemical modification of drilling fluids can significantly enhance drilling efficiency. Despite several decades of recognition that fluid chemistry affects the strength and fracture properties of rocks and minerals, this knowledge has not been applied to drilling. Application of this largely laboratory-based data to drilling has been difficult because of the complexity of drilling, the limited ability to control fluid chemistry during drilling, data/model limitations, and uncertainty regarding the factor that exerts the major control on fracturing. Some consider surface tension to be the controlling variable, while others point to the electric charge of the surface. Our analysis points towards surface tension as a major governing parameter in fracture propagation, although the data are less clear on the governing parameter for drilling efficiency.

To address these issues, we devised an integrated series of tests using DOE geothermal program capabilities to correlate chemical controls on fracture propagation with chemical controls on drilling efficiency. Data from these tests would hopefully result in a more basic understanding of the operative phenomena, aid in the design of drilling-enhancing fluids, and increase the likelihood of identifying chemical treatments that are compatible with current drilling fluid technologies.

A model for the rates of silica precipitation from supersaturated geothermal fluids as a function of temperature and pH was being developed with LLNL task 3.1.13 (Burton, Silica Scale Inhibition). This model can be used to predict decreases in injectivity resulting from injection of spent geothermal brines during EGS operations.

Reports & Articles Published in FY 2003:

Presentations Made in FY 2003:

Planned FY 2004 Milestones:

Laboratory Measurements of Properties for Steam/Water Flow in Geothermal Rock

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG36-02ID14418

Performing Organization: Stanford Geothermal Program
Department of Petroleum Engineering
367 Panama Street
Stanford University, CA 94305-2220

Principal Investigator: Roland N. Horne
Phone: (650) 723-9595
E-Mail: horne@stanford.edu

Collaborating Researchers: None

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $175K

Cost Share Funding: None

Project Objective: Steam/water relative permeability and capillary pressure are important properties for geothermal reservoir engineering, in that they have a major influence on the performance of geothermal reservoirs under development. All numerical simulations of geothermal reservoir performance require the input of relative permeability and capillary pressure values, yet actual data on these parameters has not been available. The Stanford Geothermal Program (SGP) has succeeded in making fundamental measurements of steam/water flow in porous media and thereby made significant contribution to the industry by providing both understanding of the phenomena as well as actual parameter value measurements. Two of the important problems left to undertake is the measurement of steam/water relative permeability and capillary pressure in geothermal rock (most of the previous study was conducted in high permeability sandstone as well-controlled test material), as well as the understanding of how steam-water boiling mixtures flow in fractures.

Background/Approach: The main objective is to improve the ability of engineers and scientists to forecast the future performance of geothermal reservoirs. By understanding the production characteristics, development decisions can be made sooner and with greater certainty. This will result in more efficient utilization of the geothermal energy resource. Another objective is to provide engineers and scientists direct methods to estimate the energy production rate of geothermal reservoirs and practical models of steam-water flow properties, including steam-water relative permeability and capillary pressure models.

The Stanford Geothermal Program uses both theoretical and experimental approaches to conduct the research. We use numerical simulation for modeling work and we use an X-ray CT scanner as one of our main experimental tools to measure in-situ water saturation and its distribution. We also design and construct purpose-built apparatus to conduct the experiments needed.

Status/Accomplishments: In this research, an experimental apparatus has been built to capture the unstable nature of the two-phase flow in a smooth-walled fracture and display the flow patterns in different flow configurations real time. Air-water relative permeabilities were obtained from experiments at both room temperature and high temperature. These results showed deviation from the X-curve suggested by earlier studies. Through this work the relationship between phase-channel morphology and relative permeability in fractures was determined. A physical channel-oriented model, which could replicate experimental results in both room- and high-temperature cases, was proposed. Other relative permeability models (viscous-coupling model, X-curve model and Corey-curve model) were also investigated. These models could not, however, represent the experimental relative permeabilities as well as the proposed channel-oriented model, as shown in Figure 1. Hence, we concluded that the two-phase relative permeability in fractures depends not only on liquid type and fracture geometry but also on the two-phase flow patterns.

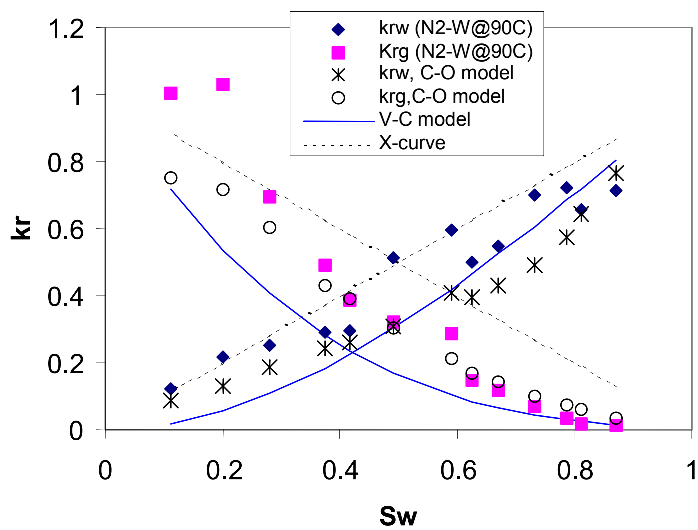


Figure 1: Comparison of the experimental relative permeability with the channel-oriented model, viscous-coupling model and X-curve for the nitrogen-water experiment at 90ºC.

Capillary pressure is an important parameter in reservoir engineering. It is essential to represent capillary pressure curves mathematically in an appropriate way. The Brooks-Corey capillary pressure model has been accepted widely, however it has been found that the Brooks-Corey model can not represent capillary pressure curves of The Geysers rock samples, as shown in Figure 2. In fact, few existing models work for these rock samples. To this end, we modeled porous media using fractal geometry and derived a universal capillary pressure model theoretically, as shown in Figure 3. It was found that the universal capillary pressure model could be reduced to the frequently-used Brooks-Corey capillary pressure model when the fractal dimension of the porous media takes a limiting value. We also developed a relative permeability model from the universal capillary pressure model.

In another facet of the project, we calculated the steam and water relative permeabilities at The Geysers and Salton Sea geothermal reservoirs from available production data. A method was developed to estimate the relative permeability curves using Darcy's Law from mass production rates of steam and water that is available from the California Division of Oil, Gas and Geothermal Resources (DOGGR) database. Results show The Geysers behavior approaches the X-curve behavior and Salton Sea behavior approaches Corey curve behavior, as seen in Figure 4.

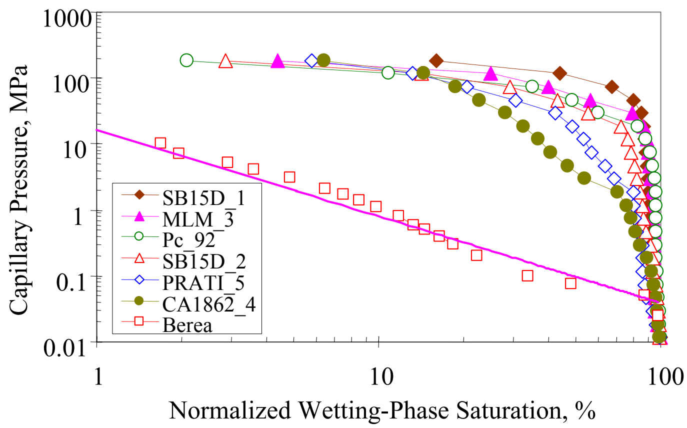


Figure 2: Capillary pressure curves of The Geysers rock and Berea sandstone.

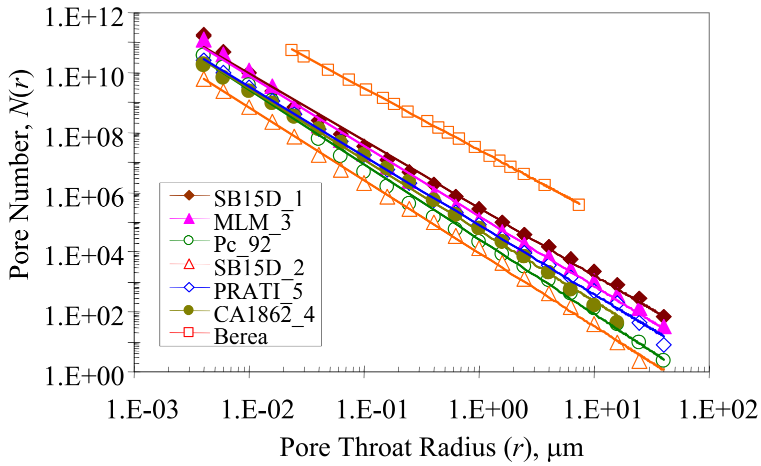


Figure 3: Relationships between N(r) and r of The Geysers rock and Berea sandstone.

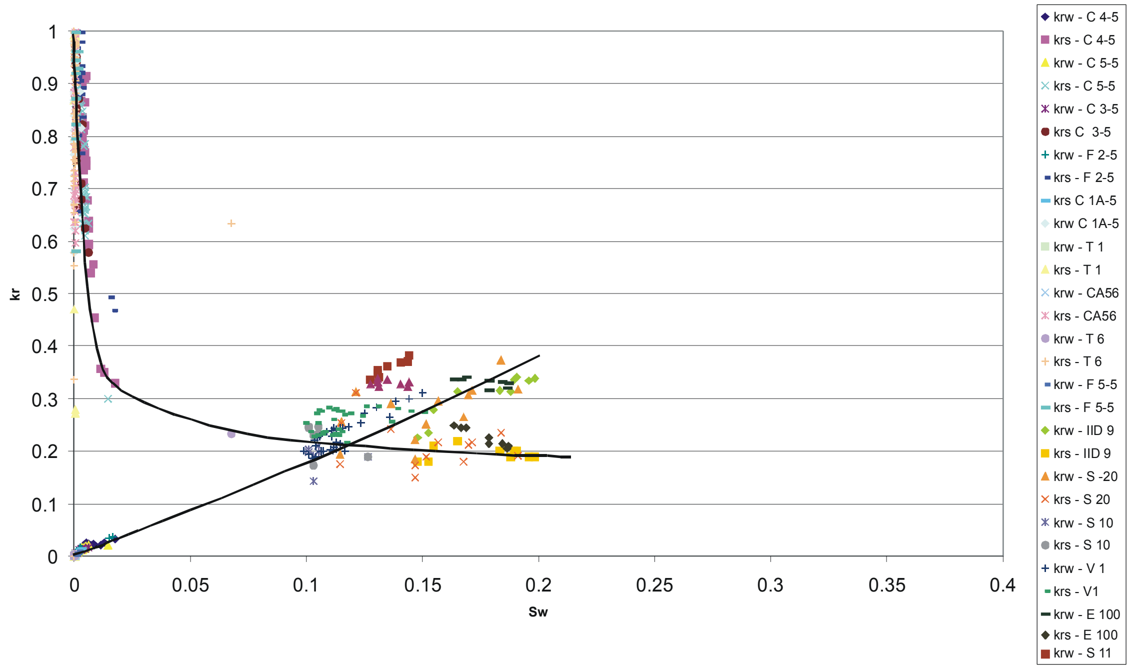


Figure 4: Plot of relative permeability curves against water saturation for The Geysers and Salton Sea Geothermal Fields.

Reports & Articles Published in FY 2003:

Li, K., and Horne, R.N.: "Fractal Characterization of The Geysers Rock", Geothermal Resources Council *Transactions* 27 (2003).

Powell, T. and Li, K.: "A Depletion Mechanism for the Behavior of Noncondensable Gases at The Geysers", Geothermal Resources Council *Transactions* 27 (2003).

Chen, C.Y., Li, K., and Horne, R.N.: " Difference Between Steam-Water And Air-Water Relative Permeabilities In Fractures", Geothermal Resources Council *Transactions* 27 (2003).

Reyes, J.L.P., Li, K., and Horne, R.N.: "Estimating Water Saturation at The Geysers Based on Historical Pressure and Temperature Production Data and By Direct Measurement ", Geothermal Resources Council *Transactions* 27 (2003).

"Estimating Water Saturation at The Geysers Based on Historical Pressure and Temperature Production Data", Jericho L.P. Reyes, June 2003

"Relative Permeability of Fractured Rock", Mark D. Habana, June 2002

Presentations Made in FY 2003:

Li, K. and Horne, R.N.: “A General Scaling Method for Spontaneous Imbibition,” SPE 77544, Proceedings of the 2002 SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, September 29 to October 02, 2002.

Li, K. and Horne, R.N.: "Direct Measurement of In-Situ Water Saturation in The Geysers Rock", *Proceedings*, Twenty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, 2003

Reyes, J.L.P., and Horne, R.N.: "Inferred Water Saturation in The Geysers Based on Well Performance Data" *Proceedings*, Twenty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, 2003

Planned FY 2004 Milestones:

Completion of steam/water relative permeability experiments in fractures.	Sept 04
Completion of steam/water relative permeability experiments in geothermal rock.	Sept 04

High Temperature Borehole Televiewer

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: Scott S. Kuszmaul
Phone: (505) 844-5401
E-Mail: sskuszm@sandia.gov

Collaborating Researchers: Steve Bjornstad, stevenbjornstad@navy.mil
Steve Hickman, hickman@usgs.gov

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $285K

Cost Share Funding: Note: $200K direct funding received from Naval Air Warfare CTR Weapons for next fiscal year (FY2004).

Project Objective: This project is funded jointly by DOE's Geothermal Technology Program and Naval Air Weapons Geothermal Program Office. The geothermal industry has a critical need for the type of formation and fracture information available from low temperature borehole imaging televiewers. Unfortunately, these tools will not survive in the high temperature environments typically encountered in geothermal wells. The goal of the High Temperature Borehole Televiewer project is to upgrade an existing conventional low temperature televiewer to operate at high temperature in order to provide data to enhance the understanding of underground fractures.

The system will initially be deployed by the U.S. Geological Survey (USGS) to perform fracture imaging at the Coso Geothermal field as part of the Enhanced Geothermal System (EGS) technology demonstration. The purpose of the EGS project is to develop and demonstrate new EGS techniques to improve the productivity of the Coso Geothermal field.

Background/Approach: A feasibility study was initiated to investigate the viability of developing a +300 °C High Temperature Borehole Televiewer that could be deployed by the USGS at the Coso Geothermal field to perform fracture imaging in order to demonstrate the required techniques for improving productivity.

Early project emphasis consisted of conducting a market survey to identify and evaluate the technology utilized in existing low temperature borehole televiewers with the expectation that one of these commercially available systems could be readily upgraded to operate at high temperature. Our preference was for a system that was domestically available from a manufacturer that also provides field services to the geothermal industry and was willing to market the new borehole televiewer system.

The design approach used was based on selecting a system that could be configured such that all the electronics and software can be used without modifications. This would be achieved by inserting the printed circuit boards with embedded software in a Dewar to prevent exposure to high temperatures. Also, we required that the surface system functionality not need modification due to the limited budget. The majority of the design effort will consist of mechanically redesigning the tool nose and related components that are exposed to the +300 °C well-bore fluids. A new motor, transducer, mirror, and associated components rated at +300 °C will need to be developed.

An evaluation matrix was developed to aid our selection process of potential suppliers. The template contained categories chosen to permit comparison of the three leading companies that offer borehole televiewers. We believe the results of the assessment clearly indicated that Mount Sopris Instrument Company was best suited to upgrade their borehole televiewer to high temperature.

Status/Accomplishments: Negotiations were successfully completed and the High Temperature Borehole Televiewer contract was issued to Mount Sopris on June 11th, 2003. Major contract tasks scheduled include delivery of a prototype tool version to support USGS deployment to perform fracture imaging at the Coso Geothermal field now scheduled for March 2004 and the delivery of two final tools by June 2004.

A System Conceptual Design Review was held July 8th at Sandia during which a review panel with expertise in high temperature borehole televiewer design challenges offered suggestion for success. A transmission test to verify the ability of the system to communicate over 15,000 feet of cable at room temperature using the latest surface acquisition system was successfully completed using the USGS's high temperature cable.

Design progress through the end of September 2003 includes redesign of the stepper motor electronic driver to implement a Pulse Width Modulated constant current driving technique instead of a linear constant voltage. This modification was needed in order to deliver more torque at high speed and make this torque independent of motor coil resistance, which is the major temperature related performance factor.

Also, a problem with bearing friction that was causing the motor to stall at high temperatures was overcome. The difficulty was resolved by using the proper angular contact bearings so that the required axial force is applied thus preventing an increase in friction as the temperature increases. Design work continues on the prototype system acoustic head with an anticipated full-scale system test at Coso in January 2004.

Reports & Articles Published in FY 2003:

Mount Sopris Instrument Company detailed the results of their data transmission test in “Transmission Test Report High Temperature Borehole Televiewer Contract 160697 Section IV-2”, July 9, 2003.

Presentations Made in FY 2003:

No presentations were given at external open meetings since the start of the High Temperature Borehole Televiewer project in July 2003.

Planned FY 2004 Milestones:

Complete initial lab checkout of 300°C tools	Mar 04
Field test 300°C tools	Apr 04
Final signoff of two 300°C tools	May 04
Report commercial results to geothermal industry	Jun 04

Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FC07-01ID14186

Performing Organization: Energy and Geoscience Institute at the University of Utah
423 Wakara Way Suite 300
Salt Lake City, UT 84108

Principal Investigator: Peter E. Rose
Phone: (801) 585-7785
E-Mail: prose@egi.utah.edu

Collaborating Researchers: Jess McCulloch, Paul Spielman, and Brian Berard, Coso Operating Company; Frank Monastero and Kieth Richards Dinger, Geothermal Program Office of the China Lake Naval Weapons Center; Steve Hickman, Gillian Foulger, and Bruce Julian, USGS; Ralph Weidler and Stefan Baisch, Q-con; Colleen Barton and Judith Sheridan, Geomechanics International; Dan Swenson, Kansas State University; Tony Singh, Pinnacle Technologies; Phil Wannamaker, Joe Moore, Katie Kovac, Mike Adams, Christian Kasteler and Doug Ekart, EGI

DOE HQ Program Manager: Jay Nathwani
Phone: (303) 275-4756
E-mail: Jay.Nathwani@go.doe.gov

DOE Funding Allocation: $2,445,927

Cost Share Funding: $5,779,652 (in kind)

Project Objective: The objective of this project is to design and create an Engineered Geothermal System within the east flank of the Coso geothermal field through hydraulic stimulation. Our objective is not only to create an EGS but also to understand that creative process. We will realize our objective through the development of a predictive model that will be calibrated and verified by field experiments. As a final product, we will have created and tested an EGS, complete with an injector/producer doublet, on the edge of the Coso geothermal field. In addition, we will have understood and articulated the underlying principles for the creation of an EGS wherever appropriate tectonic conditions exist.

By engineering a geothermal system, we will greatly increase the geothermal reserves beyond the relatively limited resource available through conventional geothermal approaches. At Coso alone, this project will increase the electrical power output by 20 MWe, helping to reduce the cost per MWe and thus helping to reduce overall cost of generating geothermal power to 3-5 cents/kWh by 2007. But, the technologies that we are developing and demonstrating at Coso can be applied to any resource where appropriate thermal and tectonic conditions apply. Thus, if successful, this Coso EGS project will help supply the electrical power needs of 7 million homes and businesses in the United States by 2010. It will also help to increase the number of states with geothermal electrical power facilities to eight by 2006.

Background/Approach: An Engineered Geothermal System (EGS) is defined as an accessible region of the earth's crust that possesses higher than average heat flow but where the natural permeability and/or fluid content are limited. With measured formation temperatures exceeding 300^{o}C at depths less than 9,000 ft, but where the natural permeability is low, regions within the eastern margin of the Coso geothermal system constitute an excellent laboratory for the evaluation of EGS concepts. Preliminary studies indicate that such tectonic conditions exist at Coso such that reservoir stimulation techniques would create permanent permeable fractures. In addition, this candidate setting is at the edge of what is one of the largest and most productive liquid-dominated geothermal systems in the U.S., with the entire appropriate infrastructure in place for testing EGS concepts.

Key to the creation of an EGS is an understanding of the relationship between natural fracture distribution, fluid flow, and the ambient tectonic stresses that exist within the resource. Once these relationships were understood, we would proceed to design and conduct a hydraulic stimulation of an east-flank injection well as the first step in the creation of a heat exchanger at depth. We would quantify the success of our experiment through hydraulic, microseismic, geomechanical, and geochemical measurements. Finally, we would conduct interference testing and a circulation test complete with tracer testing in order to confirm and to characterize the newly created heat-exchanger-at-depth that will comprise the heart of the EGS.

Last year (FY2002), we conducted a number of experiments and studies that lead to the approach taken during FY2003. During FY2002, we analyzed all available FMS and EMI wellbore data in order to characterize the fracturing and stress state within the east flank EGS study area. This was necessary in order to understand the orientation and magnitude of the maximum and minimum horizontal stresses that would in turn indicate which of the existing fractures would become hydraulically conductive as well as the hydraulic pressures and flow rates needed to induce fracturing. We analyzed cuttings available from the wells studied in the fracture analysis in order to create a petrographic/petrologic model of the EGS study area. We conducted an injection study of a promising east flank injector, complete with microseismic monitoring, in order to characterize thermal and chemical effects under 'soft' stimulation conditions.

From insights gained in these studies, a plan emerged for FY2003. We would continue with completing the characterization of the entire Coso/EGS study area (e.g., through an MT survey to discover the resistivity structure of the east flank and through a 3D Vp/Vs analysis to determine the structure of the seismogenic volume), while beginning to narrow our focus on the design and creation of the EGS doublet. We would drill a new well, 38C-9, that would ultimately constitute the production leg of the EGS doublet. The injection leg would be created through the redrilling and stimulation of the neighboring injector 34-9RD2.

Status/Accomplishments: During FY2003, we completed the drilling of 38C-9, the production leg of the EGS doublet to a total depth of 9412 ft. During the drilling we conducted a 'mini-hydrofrac' experiment in order to determine the magnitude of the minimum horizontal stress. This is the stress at which the formation will fail in tension and initiate tensile fracturing. The minimum horizontal stress at 1132 m was determined to be 18.2 Mpa. We also conducted a suite of wellbore logs including PTS and EMI.

The preliminary analysis of the 38C-9 EMI data indicated that SHmax azimuth measurements of 14° ±16°. This is in general agreement with stress orientations measured at other east-flank wells. Temperature data from temperature-pressure-spinner (TPS) logs were used to calculate temperature gradients (Δ°F/Δft) and to identify the depths of flow anomalies for well 38C-9, in addition to wells 38A-9, 38B-9, 83-16, and 86-17. The corresponding image logs were inspected at these depths and the likely causal fractures were selected and tabulated. One of the most useful findings from these analyses is that the orientations of fractures associated with temperature gradient anomalies closely resemble the orientations of fractures with significant apparent aperture, and they both show much less scatter than the fracture orientations of all observed fractures. This correlation suggests apparent fracture apertures may be useful in identifying fluid flow horizons in wells where high-resolution TPS data do not exist.

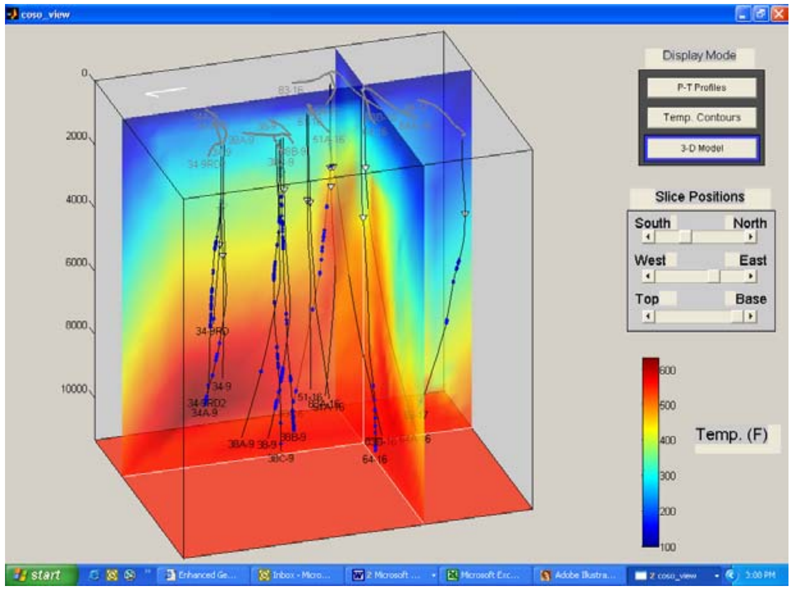
We completed petrographic and petrologic studies using drill cuttings from production wells 38A-9, 38B-9, 38C-9 and initiated similar analyses for injection wells 34A-9 and 34-9RD2. We also conducted fluid inclusion studies from those same cuttings in an effort to better characterize a thermal history and vein mineral paragenesis within the EGS study area. One of the significant findings from the drill cuttings analyses is that open space crystals found within the cuttings seem to correlate with regions of lost circulation zones and drill breaks. Thus, open space crystals may serve to indicate regions where subsequent hydraulic stimulation of tight injection wells may yield highly permeable fluid entry zones.

In anticipation of the pending hydraulic stimulation experiments of the candidate EGS injector 34-9RD2, we have developed an approach for the thermal-hydraulic-mechanical modeling of this stimulation process. The goal is to identify the conditions under which thermal stimulation is significant and to predict the magnitude of the change resulting from such stimulation. In order to meet this goal, we have proceeded to incorporate a coupled stress capability into the geothermal numerical simulation code TOUGH2. Initial studies using examples relevant to hydraulic stimulation processes indicate that we are ready to model the upcoming EGS injection experiment.

The objective of the magnetotelluric (MT) monitoring task is to provide for imaging of the subsurface electrical resistivity properties that will provide us with an improved understanding of the geometry, bounds, and controlling structures within the Coso EGS study area. Production data suggest abrupt northern and southern bounds to the entire system plus a compartmentalization of the east flank reservoir from the main west-central field. This can be verified through a detailed magnetotelluric (MT) survey with moderately dense coverage and a 3D analysis. In addition, the upcoming 34-9RD2 hydraulic stimulation experiment will change the underground resistivity properties in the vicinity of the injection well due to fracture porosity enhancement. Recording of MT data during the injection experiment may provide an image of bulk porosity change and orientation. We have completed data collection for the MT background survey and are in the process of analyzing these data.

With important contributions from the Navy's Geothermal Program Office and the USGS, we have made significant progress in microseismic monitoring of the Coso EGS study area. We designed a temporary network of surface seismometers to supplement the permanent network during injection tests. We successfully deployed this network during injection testing at EGS-study-area well 51B-16. We have also completed a time-dependent seismic tomography study of the Coso area, based upon data collected over the past decade using the Navy's permanent seismometer network. Using this approach, we have succeeded in detecting temporal changes in seismic-wave speeds, which reflect variations in pore-fluid compressibility and rock-matrix elasticity. With these background data in hand, we are ready to observe velocity changes resulting from the hydraulic stimulation experiments of 34-9RD2. This will provide a valuable tool for monitoring the development of an EGS.

We have completed a beta version of a Matlab-based 3D visualization program that will allow a variety of Coso EGS-project-data (thermal, structural, geophysical, geochemical) to be displayed. Shown below is an image of the EGS study area showing a thermal model and the east-flank wellbores. The viewer allows the user to rotate the shown volume in any orientation and to zoom in or out as desired.



We have also designed and constructed a website (http://egs.egi.utah.edu) that describes the Coso EGS project and includes quarterly reports.

Reports & Articles Published in FY 2003:

DOE Technical Report for Quarter Ending December 31, 2002: Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation.

Sheridan, J., Kovac, K., Rose, P.E., Barton, C., McCulloch, J., Berard, B., Moore, J.M., Petty, S., and Spielman, P. (2003) In situ stress, fracture and fluid flow analysis—East Flank of the Coso Geothermal Field: Proc. Twenty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-173, pp. 34-49.

Petty, S. and Gastineau, J. (2003) Life Cycle Modeling of Wellbore Cement Systems Used for Enhanced Geothermal System Development: Proc. Twenty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-173, pp. 205-215.

DOE Technical Report for Quarter Ending March 31, 2003: Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation.

DOE Technical Report for Quarter Ending June 30, 2003: Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation.

DOE Technical Report for Quarter Ending September 30, 2003: Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation.

Rose, P.E., Barton, C., McCulloch, J., Moore, J.M., Kovac, K., Sheridan, J., Spielman, P., and Berard, B. (2003) The Coso EGS Project—Recent Developments: GRC Transactions, 27, pp. 879-883.

Presentations Made in FY 2003:

Rose, P.E., Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation, (2003) U.S. DOE Geothermal Technologies Peer Review, Golden Field Office, July 29-August 1.

Rose, P.E., Barton, C., McCulloch, J., Moore, J.M., Kovac, K., Sheridan, J., Spielman, P., and Berard, B. (2003) The Coso EGS Project—Recent Developments: GRC Transactions, 27, pp. 879-883.

Planned FY 2004 Milestones:

Complete MT survey of Coso east flank	Dec 03
Present five papers at Stanford Workshop	Jan 04
Redrill 34-9RD2 and conduct borehole image logging, minihydrofrac experiment, FMS and PTS logging, cuttings collection	Mar 04
Conduct massive hydrofracture experiment complete with microseismics, MT, and tiltmeter monitoring	Apr 04
Evaluate reservoir steam development near test well using (Cl/B) method	May 04
Initiate circulation testing of newly stimulated injector	Jun 04
Complete fracture/stress analysis of 34-9RD2 and update east flank geomechanical model	Aug 04
Complete petrographic/petrologic analysis of cuttings from 34-9RD2 and update geologic model	Sep 04
Complete microseismics, MT, and tiltmeter analyses of hydrofrac	Sep 04
Use geochemical modeling to evaluate changes due to permeability increase	Sep 04

Desert Peak East Enhanced Geothermal Project

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FC36-02ID14406

Performing Organization: Ormat Nevada, Inc.

Principal Investigator: Christy L. Morris
Phone: (775) 356-9029
E-Mail: cmorris@ormat.com

Collaborating Researchers: GeothermEx, Inc.

DOE HQ Program Manager: Jay Nathwani
Phone: (303) 275-4756
E-mail: Jay.Nathwani@go.doe.gov

DOE Funding Allocation: $449K

Cost Share Funding: $131K

Project Objective: This project is being undertaken to evaluate the feasibility of creating Enhanced Geothermal Systems (EGS) by artificially increasing permeability in basement rocks in the favorable geologic/tectonic environment of the Basin and Range province. Analyses are directed toward developing a hydraulic stimulation program for an existing non-productive well (DP 23-1) with high temperature (>400°F), completed in intrusive rock at a total depth of 9,641 feet. If these analyses suggest a favorable outcome, stimulation and additional drilling will be undertaken in Phase II to create a sufficiently large and complex underground heat exchanger to support a 2-5 MWe stand-alone binary geothermal power plant. This would be the first of its kind in the United States and possibly the world (if the European HDR project at Soultz does not begin operating first). The completed project would be an unequivocal demonstration of the feasibility, techniques and costs to develop EGS-derived power in the western United States.

Background/Approach: The approach of Phase I is to assess the technical and economic feasibility of developing an EGS at Desert Peak East. This is being accomplished by undertaking a series of evaluations to: 1) determine the petrologic and physical characteristics to define the appropriate EGS reservoir at Desert Peak East; 2) characterize the geologic structure of the area as defined by geologic, drilling and geophysical data; 3) evaluate the overall stress field and the nature of specific fractures in the target EGS reservoir rocks; and 4) estimate (through numerical simulation) the size and complexity of enhancements required to support long-term EGS production from a well couplet (1 injector and 1 producer), triplet (1 injector and 2 producers), or pair of couplets (2 injectors and 2 producers).
Should feasibility be demonstrated in Phase I, the objectives of later phases of this project will be to produce 2-5 MW of geothermal power from an EGS at Desert Peak. This would be accomplished through

various geological, geophysical, drilling, stimulation, monitoring, numerical modeling, and reservoir testing activities.

While the current project is located within a state (Nevada) that already has geothermal power on-line, it is an important step in evaluating the feasibility of developing the vast EGS resource base in the United States. Only through field experimentation can such feasibility be demonstrated.

Status/Accomplishments: Petrology/Core Studies: Petrology studies were completed in early 2003 (*Petrographic and X-Ray Diffraction Analyses of Samples from Corehole 35-13 TCH and Drillhole DP B23-1, Desert Peak Geothermal Field, Nevada* by Susan Juch Lutz, Energy & Geoscience Institute – University of Utah, April 2003; and *Mechanical Properties of Desert Peak Granite*, by New England Research, Inc. May 2003).

The first work undertaken in this task was to log, box and photograph core samples from TCH35-13. A core log was made, including lithology, alteration, fracture density and fracture orientation. Several cores in the pre-Tertiary granitic section were chosen for further analyses.

The second major part of the petrology task was the preparation of an updated lithologic log for well DP23-1 with an emphasis on the pre-Tertiary section, and correlation with the lithologies noted in TCH35-13. The pre-Tertiary section in DP23-1 is formed of two distinct subgroups with a sharp contact between them. The upper (pT1), which covers a depth range of 3,260 to 5,100 feet in well DP23-1, is dominated by marine metasediments that have undergone regional greenschist facies metamorphism. The lower (pT2) extends to TD (9,641 feet). Its upper part, which extends to ~7,100 feet, is composed of a series of Jurassic/Triassic phyllite, schist and mafic-to-intermediate granitic rocks, all more strongly metamorphosed than the pT1 section. This is underlain and intruded by a two-mica granodiorite that is similar to Cretaceous intrusive rocks typical of the Sierra Nevada batholith found to the west in Nevada and California.

Since no core samples were available from well DP23-1, core samples were selected from the granitic section in TCH 35-13 for analysis of petrophysical properties. Two cores were selected: a quartz monzodiorite from 3,484 feet and a granodiorite from 3,833 feet. Grain density and dry bulk density were determined and used to estimate porosity. Single stage triaxial tests were conducted at four confining pressures to the point of failure and beyond. Young's Modulus and Poisson's Ratio were computed for each test using the linear portion of the (axial) stress versus strain curve for each sample.

As summarized in NER (2003), the results show that the two core samples are moderately strong, fractured intrusive rocks with low porosity. The deeper sample was slightly stronger than the shallower sample. Post-failure strength increase was observed in several samples and indicates heterogeneity, the initial failure point probably representing slippage along pre-existing veins or fractures. The Mohr-Coulomb analysis (Table 1) provides useful information to be used in conjunction with the analysis of the wellbore imaging log (see below) for constraining the stress tensor at Desert Peak and will provide input for the design of the hydraulic stimulation program planned for Phase II of the project.

A preliminary study of core from well 35-13 has been completed by Lawrence Livermore Labs, California with interesting results in terms of facture and chemical reactions to injection.

A cooperative effort has been initiated with the University of Nevada, Reno where the Great Basin Center for Energy Studies has several investigations, funded in part by DOE, which relate directly to the Desert Peak East EGS project area.

Table 1: Mohr-Coulomb Analysis Results (NER, 2003)

Sample depth (feet) and lithology	Sample ID	Max. Diff. Stress (psi)	Max. Axial Stress (psi)	Cohesion (S_0) (psi)	Friction Angle (Φ) (deg.)	Failure Angle (β) (deg.)	Unconfined Compressive Strength (psi)
3,484 quartz monzodiorite	A	35,560	35,860	9,129.5	34.8	62.4	34,852
	B	36,940	37,670				
	C	38,960	40,410				
	D	42,540	45,440				
3,833 granodiorite	A	39,130	39,430	9,327.7	37.6	63.8	37,913
	B	35,270	35,990				
	C	23,650	25,100				
	D	49,920	52,820				

Geophysical Review: Various geophysical surveys have been conducted in the Desert Peak area, mostly in connection with the geothermal exploration and development carried out by Phillips Petroleum and subsequent field operators. These reports and materials have been collected and reviewed and will be incorporated as appropriate into the project.

Fracture/Structure Analysis: On 3 December 2002, a sinker bar and temperature/pressure log were run to 9,600 feet in well 23-1, allowing the project to pass its single Go/No-Go decision point, and to confirm earlier temperature data. The next step evaluated available wellbore imaging tools. Although the latest generation tools (either Schlumberger's FMI tool or Halliburton's EMI tool) were preferred, particularly for better coverage of the 12-1/4-inch section of open hole (being 8-pad as opposed to 4-pad tools), both have a temperature limitation of 350°F, whereas a maximum downhole temperature of 421°F has been measured.

An injection test was designed. It was to be conducted as part of the cooling operations for evaluation of pre-stimulation hydraulic characteristics of DP 23-1. On 1 April 2003, injection into DP 23-1 began at a rate of ~100 gallons per minute (gpm). After about 24 hours of injection, a detailed (logging speed 30 feet per minute) temperature survey was run. The injection rate was increased to ~ 200 gpm, a second detailed temperature survey was run, and a step-rate injection test began on 3 April with pressure monitoring at 6,000 feet. Three rate steps (100, 70 and 40 gpm) were run for 2 hours each, after which time the injection rate was increased back to ~200 gpm. A maximum reading thermometer on the FMS tool indicated 408°F. After rigging down the logging tool, the injection rate was increased to ~200 gpm, and the pressure monitoring equipment was run in to 4,201 feet. Pressures were monitored during the last phase of injection and during a fall-off period for 4.5 hours after shut-in. Operations were completed late on 4 April 2003.

The injection rate and pressure data collected during the wellbore cooling period were analyzed using transient pressure analysis techniques. This analysis confirmed that the reservoir around the well has very low flow capacity (4,000 md-ft) and storage capacity (0.001 ft/psi), and the well does not intersect any major fractures. The well has very low injectivity (0.69 gpm/psi). The average porosity of the reservoir is very low (on the order of 2%). The radius of investigation of the test was estimated at 1,440 feet. The

flow and storage capacities at this well are far lower than encountered within the hydrothermal reservoir at Desert Peak.
The digital data for the FMS log were obtained from Schlumberger and provided to GeoMechanics International (GMI) for analysis, along with supporting data from the well, including previously collected geophysical logs, temperature logs, drilling data and well test data. Wellbore failure data were analyzed to determine stress field orientation and (in conjunction with other data) constrain the local stress tensor, and the fracture population was analyzed in a portion of the logged interval (6,730 to 9,228 feet).

52 valid breakouts were identified between 5,922 and 7,594 feet using the caliper data. Breakouts show a dominant direction of N128°E (39 breakouts) and a subordinate direction of N68°E (13 breakouts). As breakouts form at right angles to the direction of the maximum horizontal stress (SHmax), the dominant trend suggests an SHmax direction of N38°E. A total of 65 breakouts were identified between 6,418 and 9,241 feet using the image data; these suggest an SHmax direction of N27°E. A total of 170 tensile cracks were identified between 6,000 and 8,949 feet; these also suggest an SHmax direction of N27°E.

Conceptual modeling: The goal of conceptual modeling is to integrate the results of the geologic mapping, petrologic work and gravity modeling described above to refine stratigraphic and structural concepts of the EGS area. Emphasis is being placed on the structure of the basement rock, the nature of faulting within and at the edges of the EGS area, lateral and vertical temperature variations, and the nature of the separation between the EGS area and the main production field. Subsurface temperature data are being used to make an estimate of the heat reserves.

Numerical modeling: The focus of numerical modeling is the prediction of heat extraction rates from the EGS system based on reasonably conservative estimates of the permeability enhancements that will result from hydraulic stimulation operations, and various well placement options. The subsurface temperatures and hydraulic properties used in the model are those previously reported and/or collected during the course of this project. The numerical model is being used to study the sensitivity of the net generation (a function of flow rate, temperature decline rate, and pumping power requirements for the given scenario) to variations in the characteristics of matrix and fractures, and in well spacing.

Reports & Articles Published in FY 2003:

Faulds, J.E. and L.G. Garside, 2003. Preliminary geologic map of the Desert Peak-Brady geothermal fields, Churchill County, Nevada. Nevada Bureau of Mines and Geology Open-File Report 03-27.

Faulds, J.E., L.G. Garside and G. Oppliger, 2003. Structural analysis of the Desert Peak-Brady geothermal field, western Nevada: implications for understanding linkages between NE-trending structures and geothermal anomalies in the Humboldt Structural Zone. Transactions, Geothermal Resources Council, Vol. 27, pp. 859 – 864.

Lutz, S.J., 2003. Petrographic and X-ray diffraction analyses of samples from corehole 35-13 TCH and drillhole DP B23-1, Desert Peak Geothermal Field, Nevada. Report prepared for Ormat Nevada, Inc., 84 pp. plus appendices.

NER, 2003. Mechanical properties of Desert Peak granite. Report prepared for ORMAT Nevada, Inc. by New England Research, Inc., 28 pp. plus figures and tables.

Presentations Made in FY 2003:

July 29-August 1: Golden Field Office EGS Peer Review. Results to date and future plans were presented by Ann Robertson-Tait.

Planned FY 2004 Milestones:

Complete Numeric and Conceptual Models	July 04
Complete NEPA analysis for continuation of Phase 1	Aug 04
Well 23-1 recompleted and mini-frac and injection testing	Oct 04

II. EXPLORATION RESEARCH

Application of Thermal Techniques for Exploration, Evaluation, and Assessment of Basin and Range Geothermal Systems

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG07-02ID14414

Performing Organization: Southern Methodist University

Principal Investigator: David D. Blackwell
Phone: (214) 768-2745
E-Mail: blackwel@mail.smu.edu

Collaborating Researchers: None

DOE HQ Program Manager: Jay Nathwani
Phone: (303) 275-4756
E-mail: Jay.Nathwani@go.doe.gov

DOE Funding Allocation: $144K

Cost Share Funding: Industry Data Donation and PI Academic Year Salary Component

Project Objective: The first objective of the project is to develop exploration oriented models of the structure (i. e. the reservoir) of normal fault related geothermal systems. The uncertainty in this structure is demonstrated by the interpretation of the Dixie Valley fault as a single low angle listric fault only a few kilometers from the geothermal field where the drilling requires several steep structures.

The second objective of this reservoir characterization activity is to model the transient fluid and heat flow in extensional systems by developing a 4-dimensional understanding of these systems in their natural state. We will also use these results to demonstrate techniques for steering the wells during drilling to the desired target using thermal information. These activities will decrease the cost of geothermal energy because the exploration and development phase will require fewer wells.
The third objective is to develop new resource information to enlarge the known resource base and to more accurately evaluate the potential of extensional geothermal systems. Bottom Hole Temperature (BHT) information from hydrocarbon exploration wells in northeastern Nevada, northwestern Utah, and southeast Idaho will be complied and interpreted in terms of the thermal regimes of these areas. We will also prepare regional and national maps focusing on various aspects of Geothermal Energy, Hot Dry Rock (HDR) for a specific example, that convey the information in easily accessible forms.

Background/Approach: The objective of this project is to decrease the cost of exploration and development of geothermal systems in an extensional setting such as the Basin and Range province in the Western United States by several activities related to understanding the thermal regime and structural setting in these geothermal systems. The positive results of recent resource developments and resource evidence have shown the extensional geothermal systems to both have much greater potential than realized and to be larger and more numerous than anticipated. However, the costs of exploration and development of geothermal systems in the Basin and Range are difficult to amortize given the present price structure for electrical power production.

Status/Accomplishments:

Prepared 6 km temperature map for US for DOE Headquarters, Nov, 2003

Papers/Abstracts prepared or revised in 2003 and accepted or in press:

McKenna, J.R., and D.D. Blackwell, Transient thermal conditions in Basin and Range extensional geothermal systems, Geothermal Resources Council Trans., 27, 21-26, 2003.

McKenna, J.R. and D.D. Blackwell, Numerical modeling of transient Basin and Range extensional geothermal systems, *Geothermics*, in press, 2004.

Waibel, Al, David Blackwell, and Richard Ellis, The Humboldt House – Rye Patch geothermal district: An interim view, Geothermal Resources Council Trans., 27, 33-36, 2003.

Wisian, Ken, and D. D. Blackwell, Numerical modeling of Basin and Range Geothermal Systems, returned to Geothermics with revisions, December, 2003.

Blackwell, D. D., and M. Richards, Equilibrium Temperature Calibration of the AAPG GSNA BHT data base (abstract), AAPG 2004 Annual Meeting, submitted September, 2003

Negraru, P. and D. D. Blackwell, New Heat Flow Measurements in Texas (abstract), AAPG 2004 Annual Meeting, submitted September, 2003

McKenna, J., D. Merriam, and D. D. Blackwell, Thermal Regime in a Large Midcontinent Oil Field,-El Dorado, Kansas (abstract), AAPG 2004 Annual Meeting, submitted September, 2003.

Reports & Articles Published in FY 2003:

Kelley, S., and D. D. Blackwell, Temperatures in the Southern Denver Basin, Colorado, Rocky Mountain Geology, 37, 215-227, 2002.

McKenna, J. R., and D. D. Blackwell, Thermal Regime of a large midcontinent oil field (El Dorado) from high resolution temperature logs, in Petroleum Systems of Sedimentary Basins in the Southern Midcontinent, Oklahoma Geol. Surv. Circ. 106, 149-159, 2002.

Smith, R.P., V.J.S. Grauch, and D.D. Blackwell, Preliminary results of a high-resolution aeromagnetic survey to identify buried faults at Dixie Valley, Nevada, Geothermal Resources Council Trans., 26, 543-546, 2002.

McKenna, J.R., and D.D. Blackwell, Transient thermal conditions in Basin and Range extensional geothermal systems, *Geothermal Resources Council Trans*., 27, 21-26, 2003.

Richards, Maria and David Blackwell, Montana, waiting to be discovered, Geothermal Resources Bulletin, 32(1), 35-37, 2003.

Richards, Maria and David Blackwell, The heat is on, SMU 2002 Geothermal Resources Potential Map, *Geothermal Resources Bulletin*, 32(3), 117-119, 2003.

Presentations Made in FY 2003:

GRC September 2003 (not listed) October 2003, 2 see above

National Annual Meeting of Desk and Derrick Clubs, in Dallas, Texas, September 25, 2003, Panel participant representing geothermal Energy

Planned FY 2004 Milestones:

AAPG Publishes "2004" Geothermal Map of North America in March, debuted with publicity at the Annual meeting in April (review copies have been circulated since June, 2003)	Apr 04
Publish paper at 2004 GRC annual meeting on Basin and Range resources with new BHT data;	
Present 2 posters at 2004 AAPG Annual meeting re 2004 NA Geothermal Map	Apr 04
Prepare paper for 2004 GRC annual Meeting on phase 2 thermal modeling results	May 04
Prepare presentation and publish paper at 2004 GRC annual Meeting on phase 2 thermal modeling	Aug 04
Complete BHT heat flow calculation for Nevada (300 points) and inclusion in geothermal database	Mar 04
Prepare paper(s) about geothermal map, explanation, BHT calibration, etc.	Mar-Aug 04
Prepare HDR resource map based on North America Geothermal Map	May 04
Update website geothermal data bases	July 04
Prepare Contract Final Report	Aug 04

Expanding Geothermal Resource Utilization in Nevada

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG36-02ID14311

Performing Organization: University of Nevada, Reno
MS 178
Reno, NV 89557-0088

Principal Investigator: Lisa Shevenell
Phone: (775) 784-1779
E-Mail: lisaas@unr.edu

Collaborating Researchers: Greg Arehart (arehart@mines.unr.edu),
Geoffrey Blewitt (gblewitt@unr.edu),
Wendy Calvin (wcalvin@mines.unr.edu),
Mark Coolbaugh (mfc@unr.nevada.edu),
James Faulds (jfaulds@unr.edu),
Paul Lechler (plechler@unr.edu),
John Louie (louie@seismo.unr.edu),
Gary Oppliger (oppliger@mines.unr.edu)

DOE HQ Program Manager: Jay Nathwani
Phone: (303) 275-4756
E-mail: Jay.Nathwani@go.doe.gov

DOE Funding Allocation: $936K/yr till 6/30/03; $963K/yr after 6/30/03

Cost Share Funding: None

Project Objective: The Great Basin Center for Geothermal Energy is conducting work encompassing two main tasks. We are (1) producing a web-based, stakeholder geothermal information system for Nevada geothermal data relevant to assessing and developing geothermal resources, and (2) we are conducting an applied research program of peer reviewed, geothermal research addressing the goal of increasing applications of geothermal energy in the Great Basin. Approximately 10% of the granted funds will be used to accomplish the goals of task (1), another 10% will be used to provide partial administrative and management support. Approximately 80% of the granted funds are being used to fund research proposals. The objectives of both the research and outreach components of this work are to increase the amount of energy produced with geothermal resources in the Great Basin by evaluating existing, new and developing scientific methods to improve exploration and assessment of these resources.

Background/Approach: The Great Basin Center for Geothermal Energy was established at the University of Nevada, Reno in May 2000 to promote research on and utilization of geothermal resources in the Great Basin of the Western United States. The Center received funding through this grant to promote increased geothermal development in the Great Basin. Most of this funding is used to fund peer-reviewed research to improve exploration for and assessment of geothermal resources. The Center awarded seven research grants that were competitively selected with the assistance of external reviewers, and research on these projects was initiated in FY02. Three additional research grants were awarded in June, 2003 using a similar external review process.

Status/Accomplishments: A list of the ten research projects follows:

Geochemical characterization of magmatic-related vs. extension-related geothermal systems in the Great Basin: Implications for exploration, exploitation, and environmental issues, $71,128 (Greg Arehart, Mark Coolbaugh, Simon Poulson)

Dating of young igneous rocks associated with geothermal systems in the Great Basin, $34,502 (Greg Arehart, Mark Coolbaugh)

Targeting of potential geothermal resources in the Great Basin from regional to basin-scale relationships between geodetic strain and geological structures, $149,975 (Geoff Blewitt)

Remote sensing for exploration and mapping of geothermal resources, $85,407 (Wendy Calvin, Mark Coolbaugh)
Regional assessment of exploration potential for geothermal systems in the Great Basin using a geographic information system (GIS) – Part II, $ 93,023 (Mark Coolbaugh, Gary Raines, Lisa Shevenell, Tim Minor, Don Sawatzky, Gary Oppliger)

Geologic and geophysical analysis of the Desert Peak-Brady geothermal fields: Structural controls on geothermal reservoirs in the Humboldt Structural Zone, $97,760 (James Faulds, Larry Garside, Gary Johnson, Gary Oppliger, Rasool Anooshehpoor)

Exploration for concealed structures at Desert Peak using mercury soil gas detectors, $33,984 (Paul Lechler, Mark Coolbaugh, Chris Sladek)

Assembling crustal geophysical data for geothermal exploration in the western Great Basin, $74,833 (John Louie)

Investigating the relation between geothermal reservoir compaction, geometry and production rates from a ten-year InSAR ground displacement history at the Brady's and Desert Peak fields: Assessing the potential of retrospective InSAR monitoring to assist reservoir management and expansion over fields without previously documented subsidence, $43,056 (Gary Oppliger, Mark Coolbaugh)

Geochemical sampling of thermal and nonthermal waters in Nevada: Continued evaluation of geothermal resources for electrical power generation and direct-use applications, $63,933 (Lisa Shevenell, Larry Garside)

Work is proceeding on each of these projects, and preliminary results were presented at the annual GRC meeting in October 2003. Accomplishments on these research projects are summarized here.

- Sampling and trace element analytical work was completed on 64 geothermal fluid samples, which were evaluated and compared with approximately 250 analyzed geothermal samples from around the world taken from the literature and other researchers (Note: funding for this project ended in late 2002) (Arehart).

- Twelve samples of young volcanic rocks located near geothermal systems in Nevada were collected and evaluated for their suitability for radiometric dating (Arehart).
- GPS data have been used to derive a map of strain accumulation across the Basin and Range, leading to identification of regions promising for geothermal exploration (Blewitt).
- Mapping of sinter outcrops around Brady's Hot Springs continued, and relevant space imagery over Buffalo/Jersey and Fish Lake Valleys was obtained (Calvin).
- A compilation of hot spring occurrences and geothermal systems in the entire Great Basin was completed, and the Geo-Heat Center's geothermal fluid data for the Great Basin was added, and a database of strike orientations of faults controlling geothermal fluid flow in Nevada was created (Coolbaugh).
- Completion of a transect of detailed geologic mapping, stratigraphic and structural analyses, a new gravity survey, and GIS compilation of well logs and down-hole temperature data have elucidated the controls on the Desert Peak and Brady geothermal fields in the Hot Springs Mountains of northwestern Nevada (Faulds).
- Approximately 400 Hg soil gas samples have been collected, analyzed, and entered into a database for the Desert Peak geothermal area, at about 50% sampling density (Lechler).
- A database of previous seismic geophysical characterizations of the western Great Basin has been compiled, and an analysis of a 450-km-long crustal seismic survey was completed; in addition, revisions were made to a peer reviewed technical paper describing the surprising degree of lateral heterogeneity in the crust. (Louie).
- InSAR-related research included the completion of an initial Brady's/Desert Peak InSAR web site, collection of a significant fraction of the needed well production data, creation of a digital terrain model, and processing of four ERS-1/2 radar scenes to preliminary format (Oppliger).
- Over 200 hot springs were visited and temperatures measured, and selected springs (>80) were sampled and analyzed, geothermometers were calculated, and sites visited thus far were ranked for their geothermal potential (Shevenell).

Outreach activities have focused on the development of web pages to deliver databases, reports, presentations, and maps to stakeholders and the public at large. The main web site of the Great Basin Center for Geothermal Energy (www.unr.edu/geothermal/) now includes 40 digital maps of geological, geochemical, and geophysical data, as well as an ArcView-compatible project file of 23 integrated map layers, and an interactive map site where user-designed maps can be combined, composed, and printed. In conjunction with this effort, a comprehensive database of known geothermal resources and geochemical compositions of thermal waters, including an interactive map, has been built at the Nevada Bureau of Mines and Geology (http://www.nbmg.unr.edu/geothermal/gthome.htm).

Reports & Articles Published in FY 2003:

(For brevity, 7 abstracts and 16 internal DOE reports are omitted):

Arehart, G., Coolbaugh, M., and Poulson, S., 2003. *Evidence for a Magmatic Source of Heat for the Steamboat Springs Geothermal System Using Trace Elements and Gas Geochemistry.* Transactions Geothermal Resources Council 27: 269-274.

Blewitt, G., Coolbaugh, M., Sawatzky, D., Holt, W., Davis, J., and Bennett, R., 2003. *Targeting of Potential Geothermal Resources in the Great Basin from Regional to Basin-Scale Relationships Between Geodetic Strain and Geological Structures.* Transactions Geothermal Resources Council 27: 3-7.

Coolbaugh, M., 2003, *Regional Geologic Controls, Geochemical Characteristics, and Thermal Infrared Signatures of Geothermal Systems of the Great Basin*. GSN Newsletter (Geological Society of Nevada), v. 17, n. 1, p. 3.

Coolbaugh, M., and Bedell, R., 2003. *A Simplification of weights of evidence using a density function and fuzzy distributions: a comparison of probability modeling techniques in the designation of geothermal systems in Nevada*. Geological Association Canada Special Volume "GIS applications in the Earth Sciences", in press.

Coolbaugh, M.F., Kratt, C., Fallacaro, A., Calvin, W.M., and Taranik, J.V., 2003. *Enhancement of geothermal anomalies using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) thermal infrared images at Brady's Hot Springs, Nevada, USA*. Submitted to Remote Sensing of Environment.

Coolbaugh, M., Kratt, C., Fallacaro, A., Mahoney, S., Muehlberg, J., Calvin, W., and Taranik, J.V., 2002. *Enhancement of geothermal anomalies using ASTER thermal infrared images at Brady's Hot Springs, Nevada,* USA. 2002 annual meeting of the Geologic Remote Sensing Group, London, England. Published on CD.

Coolbaugh M., Sawatzky, D., Oppliger, G., Minor, T., Raines, G., Shevenell, L., Blewitt, G., and Louie, J., 2003. *Geothermal GIS coverage of the Great Basin, USA: Defining regional controls and favorable exploration Terrains*. Transactions Geothermal Resources Council 27: 9-11.

Faulds, J., Garside, L., and Oppliger, G., 2003. *Structural Analysis of the Desert Peak-Brady Geothermal Fields, Northwestern Nevada: Implications for Understanding Linkages between Northeast-Trending Structures and Geothermal Reservoirs in the Humboldt Structural Zone*. Transactions Geothermal Resources Council 27: 859-864.

Faulds, J.E., Garside, L.J., and Oppliger, G.L., 2003, *Stratigraphic and structural framework of the northern Hot Springs Mountains, Desert Peak and Brady geothermal fields, northwestern Nevada, in Foster, S., ed., Oil, gas, and geothermal occurrences in northwestern Nevada*: Nevada Petroleum Society 2003 Field Trip Guidebook, p. 31-38.

Kratt, C., Coolbaugh, M., and Calvin, W., 2003, *Possible Extension of Brady's Fault Identified Using Remote Mapping Techniques.* Transactions Geothermal Resources Council 27: 653-656.

Louie, J.N., Thelen, W., Smith, S.B., Scott, J.B., and Clark, M., 2003. *The northern Walker Lane refraction experiment: Pn arrivals and the northern Sierra Nevada root*. Submitted to Tectonophysics, July 2. (Available on line at www.seismo.unr.edu/geothermal/walker.pdf)

Shevenell, L., and Garside, L., 2003. *Nevada Geothermal Resources*. Nevada Bureau of Mines and Geology Map 141.

Shevenell, L., and Garside, L., 2003. *Geochemical sampling of thermal waters in Nevada.* Transactions Geothermal Resources Council 27: 27-31.

Shevenell, L., and Garside, L., 2003. *Thermal Waters of Nevada: Update of Bulletin 91*. Nevada Bureau of Mines and Geology CD-ROM containing interactive maps, site descriptions, detailed maps, photos, bibliography, and databases.

Skalbeck, J.D., Karlin, R.E., Shevenell, L., and Widmer, MC., in review. *Gravity and aeromagnetic modeling of alluvial basins in the southern Truckee Meadows adjacent to the Steamboat Hills geothermal area, Washoe County, Nevada*. Submitted to Geophysics.

Vaughan, R.G., Hook, S.J., Calvin, W.M., and Taranik, J.V., Feb. 2003. *Surface mineral detection with multi-wavelength thermal infrared images.* Submitted to J. Geophys. Research-Solid Earth.

Presentations Made in FY 2003:

Not including DOE meetings, 20 presentations were made at conferences, meetings, and short courses. For purposes of brevity, they are not listed here, but are available on request.

Planned FY 2004 Milestones:

Arehart: Presentation of final results of magmatic-extensional fluid geochemistry research at 2003 annual GRC meeting	Oct 03
Arehart: Completion of age date measurements on 24 samples of young volcanic rocks	Sep 04
Blewitt: A new GPS station network will be installed in regions of the northwestern Great Basin that have been identified by FY03's investigation as having high strain rates and styles of strain that are characteristic of non-magmatic geothermal regions	Sep 04
Calvin: Pursue analysis of new data in Buffalo/Jersey and Fish Lake in collaboration with industry and begin mapping basement rock textures of surface outcrops related to hydrofracturing at Desert Peak, and conduct a pilot study of spectral analysis of drill chips boards from Desert Peak site.	Sep 04
Coolbaugh: Completion of predictive maps of geothermal potential for the Great Basin and continued updates and improvements to an interactive geothermal GIS web site	Sep 04
Faulds: Future work includes 1) expansion of detailed mapping to include remaining parts of the northern Hot Springs Mountains, 2) conducting more thorough stratigraphic and structural analyses, 3) acquisition of additional gravity data, 4) running a micro-earthquake study, and 5) continuing the GIS compilation	Sep 04
Lechler: Infill sampling of every other grid line of the Hg gas survey will be completed, the samples will be analyzed, and statistics, graphics, and interpretation will be completed	Sep 04
Louie: An additional 450-km-long seismic characterization survey is planned, using 200 recorders scheduled with the PASSCAL Instrument Center to supplement the 21 bought for the project	Sep 04
Oppliger: Acquisition and processing of radar scenes, GPS control acquisition and processing, compilation of well production data, and a preliminary technical report	Sep 04
Shevenell: Complete sampling and analysis of the second phase of hot springs selected for evaluation, and calculate and evaluate geothermometers and any mixing of thermal and non-thermal waters	Sep 04

Regional Analysis of Deep Circulation Geothermal Fields

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415

Principal Investigator: Richard P. Smith (under contract to INEEL Geothermal Program)
Phone: (719) 395-8114
E-Mail: rps3@realwest.com

Collaborating Researchers: David Blackwell, Southern Methodist University
Catie Helm-Clark, INEEL
Mark Coolbaugh, UNR – Great Basin Center for Geothermal Research

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $150K

Cost Share Funding: None

Project Objective: The objective of this project is to improve the exploration models ("conceptual models", "deposit models") used in the search for undiscovered geothermal resources in the Basin and Range Province. Better exploration models lead to optimization of exploration strategies, reduction in the time and cost for finding and developing new systems capable of producing electric power, and ultimately lead to an increase in the amount of geothermal power available. Hence, this project supports all three DOE Geothermal programmatic goals.

Background/Approach: This project addresses a significant obstacle to development of an optimum exploration model for Basin and Range deep-circulation geothermal systems: the lack of a detailed synthesis of available information for each system. A variable amount of spatially-referenced information from diverse sources is available for each system. The information includes published literature, university theses and dissertations, unpublished reports, company files, internet sites, publicly available remote sensing imagery, and aerial photographs from various agencies. Even though some areas have abundant available information, there is no comprehensive compilation at the same scale on maps, nor is it organized in a way that allows efficient comparisons of the various characteristics of the different systems. Both map compilations and systematic organization of characteristics greatly facilitate the synthesis of diverse data and the development of optimum exploration models.

The approach is to compile available geologic, geophysical, geochemical, and hydrologic information for selected geothermal systems, and to display and summarize the data in ways that allow comparison and discovery of previously unrecognized relationships that bolster exploration models used to search for additional geothermal systems. Spatially referenced information is compiled from published literature, from unpublished reports, from industry files, from original mapping and geophysical surveys, and from analysis of aerial photography and remote sensing images. The compilations cover areas considerably larger than the geothermal fields in question, typically an entire basin and its adjacent ranges. The information is compiled and summarized in two ways. First, overlays (thematic layers) are made on high-resolution topographic base maps for each data set (e.g. gravity, high-resolution aeromagnetics, Quaternary faults, etc.) so that it can be compared and analyzed with respect to all the other data sets. Second, the data are tabulated so that the specific characteristics of each system (say tectonic setting, fault trends, maximum temperature, fluid composition, interaction with aquifers, etc.) can be easily compared to the characteristics of other systems.

Because much of the information compiled is not available in geo-referenced digital form (it usually is found in drafted maps used as illustrations in reports, publications, theses, photographic images) it is being compiled as overlays on best available topographic base maps using Adobe Illustrator. Those layers are being converted to shape files so that the information can be analyzed using GIS technology. This step will provide for digital cross-registration and analysis by computer, allowing discovery of relationships beyond those that can be recognized by visual comparison of various thematic layers. This step is particularly important for maps with many overlays of diverse types of data.

The tabulation of characteristics and features of the different geothermal systems will augment and incorporate, rather than duplicate, databases maintained by other organizations (Great Basin Center for Geothermal Research, EGI, SMU, and others). The organization of the tabulated data is important for easy comparisons, and will evolve as more data are entered. At present, it is divided into several sections: lithology of host rocks, tectonic and structural features (fault characteristics, seismicity, in-situ stress), characteristics of geothermal fluids, and thermal characteristics. This organization and subdivision may need modification and adjustment as the tables get populated with specific data from the various systems.

This project is being done in collaboration with that of a UNR team (PI: Mark Coolbaugh) which uses GIS analysis of regional data for the entire Great Basin to identify particularly promising areas for geothermal exploration. For one such identified area, Buffalo Valley-Jersey Valley, we have compiled detailed data layers to compare to those of known geothermal systems. Other detailed compilations will be, or are being, done for other identified areas. The GIS project of the UNR team identifies promising areas (basins) within the Great Basin, and this project provides site-specific data that will focus exploration activities (detailed geophysics, geochemical sampling, and ultimately, drilling) within the identified basins.

Status/Accomplishments: Several accomplishments have been made in this project.

1. Discovery of a recurring relationship among gravity gradient maxima, intra-basin faults, hot/warm spring locations, and geothermal fields for basins in the basin and range province (Figure 1). There is a tendency for intra-basin fault systems to be coincident with gravity gradient maxima (position of major structural offset in the basin), and for both to occur several kilometers basin-ward of the range fronts. Springs (hot, warm, cold) also commonly occur along these intra-basin fault systems, and, in Dixie Valley and Railroad Valley, major geothermal systems and petroleum reservoirs occur at these locations.

2. In several basins, springs and geothermal systems are located at or near the intersections of the gravity gradient maxima (corresponding to major structural offset and often coincident with intra-basin faults) with regional lineaments identified in satellite or other remotely sensed imagery.
3. Tested high-resolution aeromagnetic techniques as an aid in exploration for geothermal resources in the basin and range province (see presentations and publications sections). The remarkable results obtained for Dixie Valley, corroboration of mapped intra-basin faults and definition of the complete intra-basin fault system, can be used effectively in basins where geothermal exploration is on-going. Areas where the method would provide particularly valuable results include Rye Patch/Humboldt House, Soda Lake, Stillwater, other prospective areas in the Carson Sink, Railroad Valley, and Black Rock Desert.

4. An organization is developed for tabulation of system characteristics. At present, it is divided into several sections: lithology of host rocks, fault and structural characteristics, fluid characteristics, and thermal characteristics.

5. Tested the translation procedure for converting Adobe Illustrator files (.ai) to GIS files (.shp) with satisfactory results. The procedure involves import of AI files into GIS software (ArcInfo or ArcView) and converting each layer to shape files with specific attributes. Selection of several common registration points for the conversion eliminates location errors in the translation process. Resulting maps plotted from the GIS software are identical to the original Adobe Illustrator maps, but can be analyzed by GIS software to reveal relationships that are not revealed by visual comparison of layers.

Reports & Articles Published in FY 2003:

Smith, R.P. and Grauch, V.J.S. (2002) High-resolution aeromagnetic survey reveals distribution of faults in Dixie Valley, Nevada (abst.); Geological Society of America, Proceedings of the 2002 Annual Meeting, Denver, Colorado, October 27-29.

Smith, R.P. (2003) A geothermal exploration strategy using high-resolution aeromagnetic surveys for the basin and range province; Proceedings, 28th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29, SGP-TR-173.

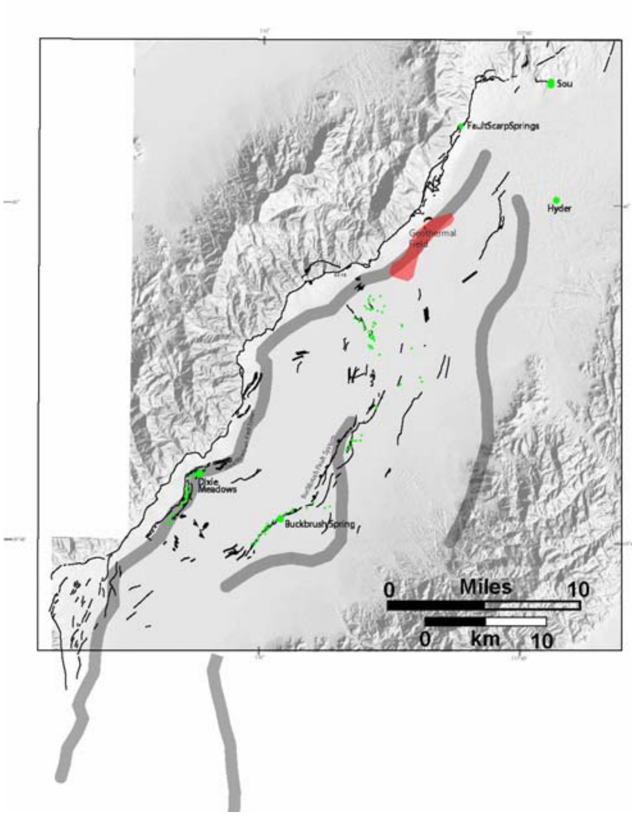
Presentations Made in FY 2003:

Smith, R.P. and Grauch, V.J.S. (2002) High-resolution aeromagnetic survey reveals distribution of faults in Dixie Valley, Nevada; Geological Society of America, 2002 Annual Meeting, Denver, Colorado, October 27, Theme session on New Views of Extensional Basins and Related Volcanic Fields Using Geophysics and Remote Sensing.

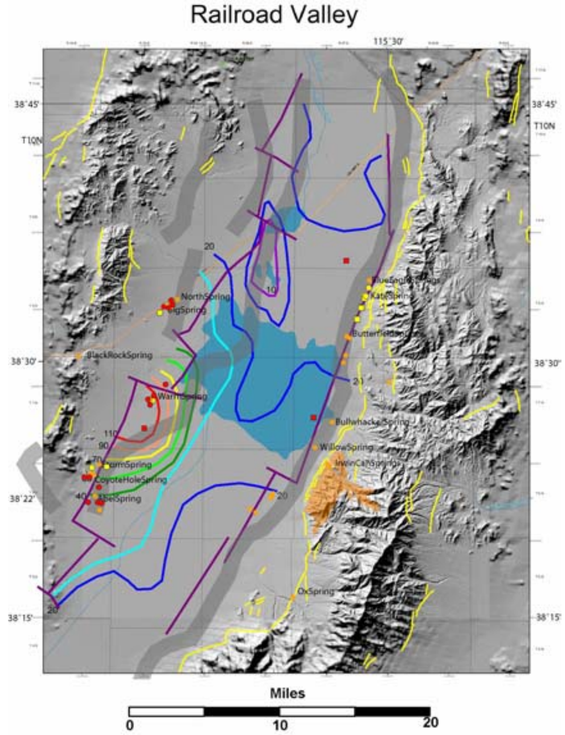
Smith, R.P. (2003) A geothermal exploration strategy using high-resolution aeromagnetic surveys for the basin and range province; Proceedings, 28th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 27-29.

Planned FY 2004 Milestones:

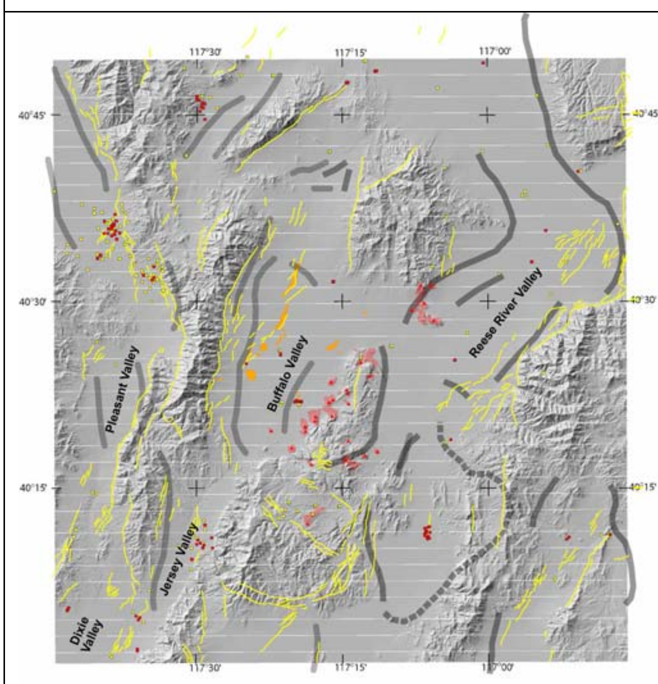
Generate maps of additional areas (Stillwater, Cove Fort/Roosevelt, Carson Sink)	Jun 04
Convert .ai files to .shp files	Jun 04
Check .shp files against original .ai files for accuracy	Aug 04
Post files on web site for public use	Sep 04
Tabulation of major characteristics of known geothermal systems	Sep 04



A. Dixie Valley



B. Railroad Valley



C. Buffalo and Reese River Valleys

Figure 1. Summary of relationships for:

A. Dixie Valley – Green = springs. Black lines = range front and intra-basin faults

B. Railroad Valley – Red and yellow dots and squares = hot and warm springs and wells. Yellow lines = Quaternary faults. Purple lines = intra-basin faults identified by deep drilling and seismic reflection. Colored contours = thermal gradients determined from deep drilling.

C. Buffalo and Reese River Valleys - Red and yellow dots and squares = hot and warm springs and wells. Yellow lines = Quaternary faults. Orange areas = springs identified on ASTER image. Red triangles and pink areas = Quaternary volcanic vents and basalt lava flows.

In all cases, the broad gray lines are gravity gradient maxima. There is a strong tendency for intra-basin faults and springs to be associated with gravity gradient maxima, and for gravity gradient maxima to lie several kilometers basin-ward of the range-fronts.

Characterization and Conceptual Modeling of Plutonically-Heated and Deep-Circulation, High-Temperature Hydrothermal Systems in the Western United States

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG07-00ID13891

Performing Organization: Energy & Geoscience Institute (EGI)
University of Utah
423 Wakara Way, Suite 300
Salt Lake City, UT 84108

Principal Investigator: Jeffrey B. Hulen
Phone: (801) 581-8497
E-Mail: jhulen@egi.utah.edu

Collaborating Researchers: Michael C. Adams, Joseph N. Moore, Gregory D. Nash, Peter E. Rose, and Susan J. Lutz (all EGI); Denis L. Norton, Geologist/Geochemist, Stanley, ID

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $1,200K

Cost Share Funding: None

Project Objective: (1) Refine existing and develop new geological, geochemical, geophysical, and numerical models for western U.S. moderate- to high-temperature hydrothermal systems. During the last six months of FY 2004, begin the process of applying knowledge gained during the first 4.5 years of the project to better understand, initially, affiliated Class 1 and Class 2 EGS hydrothermal resources, then wholly detached (i.e., not hydrologically linked to a geothermal field) Class 3 and Class 4 targets. (2)Assist domestic geothermal companies in the application of these models for risk-reduced and more cost-effective exploration and development. (3) Improve remote sensing and GIS methods for geothermal resource evaluation. (4) Develop refined electrical models and electromagnetic (EM) modeling algorithms for the geothermal environment; incorporate independent geological data in cooperative interpretations for EM data. (5) Find and test tracers capable of tagging both steam and water in vapor-phase and two-phase geothermal systems; promote research on the use of these tracers to quantify the properties of these systems; (6) Identify thermally stable tracers and develop new on-line tracer detection methods for the management and efficient testing of injection strategies in commercial and EGS hydrothermal reservoirs. (7) Maintain and augment the world-class EGI Geothermal Sample Library as a national repository and study center for geothermal cores, cuttings, and information, and as a vital research resource for the entire geothermal community.

Background/Approach: The western U.S. – in particular the Basin and Range, Cascade Range, and California Coast Range – is one of the world's richest moderate- to high-temperature geothermal provinces. The region has an estimated viable commercial geothermal power production resource of ~25,000 megawatts (MWe), and an installed capacity of 2800 MWe. The Department of Energy wants to increase the viable resource to 40,000 MWe within the foreseeable future, and realization of this ambitious goal will clearly require the routine application of Engineered Geothermal Systems (EGS) technology. Natural-hydrothermal and EGS resources form a commercial spectrum, with the former at the now-economically-viable end, and the latter becoming progressively more challenging toward the other end (conduction-dominated, or so-called "hot dry rock" resources. Class 1, 2, and 3 EGS resources (in decreasing order of modern financial viability) are really just subcommercial hydrothermal systems, sharing a large number of attributes with their commercial counterparts. Whether system is commercial or subcommercial, bringing it to full production will depend upon having the clearest possible understanding of its configuration and physical-chemical attributes, especially the density, paragenesis, orientation, and mineralization of fractures, the principal thermal fluid conduits in all systems. Stated another way: Whether EGS or commercial-hydrothermal, the more that we know about a geothermal resource, the more readily and cost-effectively it will be found and developed. The best place to obtain and expand this knowledge is in producing geothermal fields and their surroundings. For all but conduction-dominated targets, only these fields have the drill coverage and wealth of subsurface information needed for meaningful three-dimensional characterization.

For the first four years of this project, and in close collaboration with long-time geothermal-industry partners (principally Calpine, Caithness, and CalEnergy Corporations), we have undertaken to obtain significantly greater insight into the intricate and interlinked geological, geochemical, and hydrologic controls on the inception, evolution, and three-dimensional configurations of the two distinct types of moderate- to high-temperature systems prevalent in the American West; (1) those demonstrably heated by shallow, cooling igneous intrusions (e.g., the Salton Sea system, California; and (2) those ostensibly heated entirely in response to circulation along deeply-penetrating faults and fractures in regions of thinned crust and consequent elevated heat flow (e.g., Dixie Valley, Nevada). We will continue this effort in the ensuing fiscal year, while incrementally increasing our focus on the allied hydrothermal systems (or portions thereof) that are presently subcommercial but ideal targets for EGS research.

The project is organized into six Tasks, each led by a specialist in that particular discipline. The research focus of the Tasks is coordinated and integrated to yield a significantly improved understanding of how these complex hydrothermal resources really work. The Tasks and Task Leaders are as follows; Task 1 – Refined conceptual models for deep-circulation and magmatically heated hydrothermal systems in the Great Basin and Cordilleran U.S., Jeff Hulen; Task 2 – Improving exploration models of andesite-hosted geothermal systems, Joe Moore; Task 3 – Improved technologies for geothermal resource evaluations, Greg Nash; Task 4 – Enhanced data acquisition and inversion for electrical resistivity structure in geothermal exploration and reservoir assessment, Phil Wannamaker; Task 5 – Tracing geothermal fluids, Mike Adams; Task 6 – The development of tools for managing injection in geothermal reservoirs, Pete Rose.

Status/Accomplishments: Task 1 (see above): Prepared coincident, stratigraphic, structural, temperature, thermal gradient, and mineralogic cross sections for the southwestern part of the Salton Sea geothermal field. Discovered that major thermal-fluid entries are associated with tectonic-hydrothermal breccias developed at dilatational jogs along strike-slip faults. Documented permeability-specific secondary-mineral assemblages and textures for reducing the risk in locating the most productive thermal-fluid entries at depth. Discovered (1) that much of the permeability in the Salton Sea field and elsewhere in the “Greater Salton Sea geothermal cluster” has been created hydrothermally by dissolution of diagenetic calcite; (2) that natural hydraulic fractures formed in a prograding thermal field account for much of the permeability and porosity at greater depths; (3) that a shallow major fluid conduit in the southwestern part of the field is actually a high-grade lead zinc orebody (too hot to mine now); (4) that subvertical, sulfate-depleted zones in the evaporitic mudstone cap on the system may be due to fault-controlled dissolution, and may point the way to the most permeable reservoir regions at depth.

Task 2: (1) Developed an exploration model of the Karaha-Telaga Bodas hydrothermal system, West Java, Indonesia. The model documents the distribution of vapor- and liquid-dominated regimes, temperature and pressure distributions; directions of fluid flow; and time-temperature-composition history of the field. (2) Described how vapor-dominated geothermal systems develop in volcanic terrains and provided new insight into their evolution. (3) Documented the characteristics, kinematics, and distributions of the fractures in two core holes. Evaluated image logs from production wells. (4) Demonstrated fundamental differences in the structural characteristics and evolutions of the cap rock and reservoir sections. (5) Developed methods for predicting the orientations and characteristics of productive fractures

Task 3: (1) Completed vegetation health anomaly mapping at Cove Fort-Sulfurdale, UT. (2) Completed thermal anomaly mapping, including spatial correlation of faults, at Dixie Valley, NV. (3) Completed soil-mineral anomaly mapping at Dixie Valley. (4) Completed initial processing and interpretation of 18 HyMap hyperspectral flight lines for mineralogy and soil-mineral anomalies at Dixie Meadows, NV. (4) Completed initial TIR data processing for a thermal-inertia model on an image covering Railroad Valley, NV. (5) Tested high-spatial resolution remotely sensed data, coupled with a digital elevation model in a GIS for visualization. Deployed a web site for data and publication sharing including the addition of state-of-the-art web-based GIS for geospatial searching and map visualization.

Task 4: (1) Developed multidimensional inversion algorithms with unique capabilities for MT and finite-source methods. Applied these algorithms to yield a clearer picture of the subsurface in the Dixie Valley geothermal area, NV, and in the Karaha-Telaga Bodas system in West Java, Indonesia. (2) Made progress toward 3D inversion with a unique regularization technique by deriving and testing prototype fast-parameter sensitivities combining an FD forward solver with an integral equations sensitivity approach. (3) Moved closer to completing a commercial surveying capability utilizing a multi-station MT system with unique modes of acquisition and processing.

Task 5: (1) Decision made to return to the testing and usage of aliphatic, strictly hydrocarbon alcohols as two-phase (vapor-liquid) tracers. Conducted a study in which solid-phase microextraction was used to lower the detection limit down to at least 1 ppb. (2) Began developing a new method that uses the ratio of chloride to boron to monitor the expansion and contraction of two-phase zones in geothermal reservoirs. (3) Applied GIS to enhance tracer tests, utilizing a suite of tools automating several common calculations used in tracer analysis.

Task 6: (1) Identified a new tracer suitable for use in liquid-dominated geothermal systems having temperatures in excess of 300°C. (2) Designee and fabricated an electronics package for a resistivity-based, two-phase flow detector. (3) Identified a viable approach towards the development of a two-phase flow detector based upon tracer dilution. (4) Developed a method of analysis for two-phase tracer candidates (short-chain aliphatic alcohols). (5) Identified a family of polymers that may serve as effective tracers for characterizing fracture surface areas in EGS reservoirs.

Reports & Articles Published in FY 2003:

Adams, M.C., 2003, Use of naturally-occurring tracers to monitor two-phase conditions in the Coso reservoir: Davis, CA, Coso Research Symposium

Hulen, J.B., Norton, D.L., Moore, J.N., Osborn, W., van de Putte, T., and Kaspereit, D., 2003, The role of sudden dilational fracturing in evolution and mineralization of the southwestern Salton Sea geothermal system, Imperial Valley, California: Stanford University, 28th Workshop on Geothermal Reservoir Engineering, Proceedings, 10 p.

Hulen, J., Norton, D., Kaspereit, D., Murray, L., van de Putte, T., and Wright, M., 2003, Geology and a working conceptual model of the Obsidian Butte (Unit 6) sector of the Salton Sea geothermal field, California: Geothermal Resources Council, Transactions, v. 27, 13 p.

Kurilovich, L., Norman, D., Heizler, M., Moore, J., and McCulloch, J., 2003, 40Ar/39Ar thermal history of the Coso geothermal field: Stanford University, 28th Workshop on Geothermal Reservoir Engineering, Proceedings, 8 p.

Lutz, S.J., Schriener, A., Schochet, D., and Robertson-Tait, A., 2003, Geologic characterization of pre-Tertiary rocks at the Desert Peak East EGS project site, Churchill County, Nevada: Geothermal Resources Council, Transactions, v. 27, p. 865-870.

Moore, J.N., Christensen, B., Browne, P.R.L., and Lutz, S.J., 2003, the mineralogic consequences and behavior of descending acid-sulfate waters – An example from the Karaha-Telaga Bodas geothermal system, Indonesia: Canadian Mineralogist, in press.

Moore, J. Allis, R., and Norman, D., 2003, New insights into the time-temperature-composition history of the volcanic-hosted geothermal system at Karaha-Telaga Bodas, Indonesia: Geothermal Resources Council, Transactions, v. 27, 8 p.

Murphy, E.A., and Nash, G.D., 2003, Using thermal-infrared data to identify geothermal anomalies: Geothermal Resources Council, Transactions, v. 27, 8 p.

Nash, G.D., and Johnson, G.W., 2003, Conceptualization and implementation of a tectonic geomorphology study for geothermal exploration in the Great Basin, USA: Geothermal Resources Council, Transactions, v. 27, 8 p.

Nash, G.D., Moore, J.N., and Sperry, T., 2003, Vegetal-spectral anomaly detection at the Cove Fort-Sulfurdale thermal anomaly, Utah, USA – Implications for use in geothermal exploration: Geothermics, v. 32, p. 109-130.

Nemcok, M., Murray, B., Christensen, C., Allis, R., Moore, J., and Welker, B., Strength and stress constraints on the Karaha-Telaga Bodas geothermal reservoir: Geothermal Resources Council, Transactions, v. 27, 8 p.

Pal, D., and Nash, G.D., 2003, Mineralogic interpretation of Hymap hyperspectral data, Dixie Valley, Nevada: Geothermal Resources Council, Transactions, v. 27, 9 p.

Pickles, W.L., Nash, G.D., Calvin, W.M., Martini, B.A., Cocks, P.A., Kennedy-Bowdin, T., MacKnight, R.B., Silver, E.A., Potts, D.C., Foxall, W., Kasameyer, P., and Waibel, A., Geobotanical remote sensing applied to targeting new geothermal resource locations in the U.S. Basin and Range, with a focus on Dixie Meadows, Nevada: Geothermal Resources Council, Transactions, v. 27, 10 p.

Rose, P.E., Mella, M., and Kasteler, C., 2003, A new tracer for use in liquid-dominated, high-temperature geothermal reservoirs: Geothermal Resources Council, Transactions, v. 27, p. 403-406.

Wannamaker, P.E., and Sasaki, Y., 2003, Three-dimensional electromagnetic inversion combining a finite-difference forward solver with integral equations jacobians: Adelaide, Australia, Third Quadrennial Symposium 3DEM, Proceedings, 5 p.

Wannamaker, P.E., Stodt, J.A., Pellerin, L., Olsen, S.L., and Hall, D.B., 2003, Structure and thermal regime beneath South Pole region, East Antarctica, from magnetotelluric measurements: Geophysical Journal International, in press.

Presentations Made in FY 2003:

All Task leaders made oral and/or poster presentations corresponding to the above-listed papers at the Geothermal Resources Council Annual Meeting in Morelia, Mexico, and at the Stanford Geothermal Reservoir Engineering Workshop, at Stanford University, California.

Planned FY 2004 Milestones:

Task 1

Complete 3D conceptual models for SW Salton Sea and Dixie Valley	Aug 04
Prepare and submit papers on above to peer-reviewed journals	Sep 04

Task 2

Prepare paper summarizing results of investigations at Glass Mountain for Stanford	Sep 04
Prepare Karaha-Telaga Bodas summary paper for peer-reviewed journals	Sep 04

Task 3

Dixie Meadows soil-mineral anomaly mapping	Jul 04
Thermal (TIR) study for thermal-anomaly detection	Jul 04
Tectonic geomorphology study	Jul 04
Collect available data for Fish Lake Valley, Buffalo Valley, and Blue Mountain	Sep 04
Create web-based GIS database for data sharing	Sep 04
Begin regional study using Landsat ETM data	Sep 04

Task 4

Document and publish a priori approach to MT and joint MT/DC inversion	Sep 04
Develop 3D inversion algorithms (Coso, Karaha)	Sep 04
Invert MT profiling data from Nevada to test for enhanced upwelling and heat flow	Sep 04
Complete and field-test Utah/EGI magnetotelluric instrument	Sep 04
Establish software to use Parkfield, CA, observatory as ultra-distant reference	Sep 04

Note: Tasks 5 and 6 closed as of the end of FY 2003

Geophysical Methods for Resource Exploration and Monitoring

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC03-76SF00098

Performing Organization: Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA 94720

Principal Investigator: Ernest L. Majer
Phone: (510) 486-6709
E-Mail: elmajer@lbl.gov

Collaborating Researchers: Roland Gritto, rgritto@lbl.gov

DOE HQ Program Manager: Dr. Roy Mink
Phone: (202) 586-5463
E-mail: Roy.Mink@hq.doe.gov

DOE Funding Allocation: $175K

Cost Share Funding: $100K

Project Objective: The project objective includes the improved understanding of the subsurface structure, lithology, and fluid paths in geothermal reservoirs. The knowledge of these properties will increase the reliability and reduce the risk of in-fill drilling associated with production and re-injection of spent geothermal fluids. Overall, the enhancement of underground fractures and the knowledge about subsurface flow will help in the resource management by improving the accuracy of exploration targets, increasing the overall resource, and reducing the cost of geothermal production.

This objective is achieved by extending and adapting current seismic techniques to improve the capability for imaging surface features that control fluid flow in geothermal environments. The objective of the work previous to FY2003 was concerned with the detection and location of faults and fractures based on an existing 3D seismic data set collected at the Rye Patch geothermal reservoir. The current (FY2003) work is aimed at investigating how the presence of discrete models of fault and fracture zones can be detected and distinguished in seismic surface and borehole data.

Background/Approach: It is widely accepted that an increase in water circulation is needed to improve the efficiency of geothermal systems. Discrete faults with increased permeability present pathways for an increase in water flow. Similarly, zones of increased fracturing may constitute flow paths with even higher permeability depending on the fracture density. It is therefore desirable to detect and map faults and fracture zones and characterize their physical properties. Surface and borehole seismic imaging methods can generally be used to estimate these properties, but further development is needed for the application in geothermal areas.

Seismic wave propagation in a homogeneously layered velocity model can lead to complicated wave fields even in the absence of structural features like faults or fracture zones. If these features are present, however, the seismic wave field becomes much more complicated and the seismic "foot print" of the fault/fracture zones may be masked and difficult to observe. Therefore, it is important to study the characteristics of seismic wave interaction with faults and fracture zones to establish typical patterns that can be recognized in seismic field data. General questions to investigate include the depth extent of faults. Is the seismic signature of blind faults (i.e., the fault plane doesn't break the surface) different from faults extending all the way to the surface? How can faults be distinguished from zones of high fracturing? Other parameters include the strike and dip as well as width of the fault or fracture zone. The fracture stiffness may be estimated from seismic waves, which could yield such important parameters as contact area or degree of mineralization within a fault or fracture. Numerical modeling of seismic wave interaction with faults and fracture zones is an important tool to investigate the physics of the problem and to develop new imaging methods to be applicable to geothermal areas.

Finite-difference modeling was used to simulate seismic wave propagation in a geothermal area with a layered velocity structure in the presence of different types of faults. The velocity model, the source and receiver geometries, as well as the source parameters were taken from previous studies at the Rye Patch geothermal reservoir. The parameters of the fault were modeled based on equivalent medium theory, where the orientation of the fault relative to the finite-difference grid and the fault stiffness are translated into elastic constants. The various investigated fault and fracture models represented weak structures with low isotropic stiffness or high compliance relative to the surrounding background medium.

Status/Accomplishments: The projected was completed at the end of 2003. A suite of discrete fault and fracture models were investigated to study the foot-print of these features in seismic surface data. Faults with surface expression as well as blind faults were studied in addition to fracture zones. The results indicated that faults can be detected by single seismic lines, as long as the receivers are in the vicinity of the fault tip (within a distance of 2-3 wavelengths of the seismic waves). Faults terminating close to the surface leave a most pronounced seismic signature in the data by blocking the direct seismic (P) waves creating a seismic shadow along the receiver line behind the fault. At the same time wave conversion from P- to S-waves was observed. The apex of the converted waves in the seismograms indicated the location of the fault tip below the array. Blind faults have a diminished shadowing effect, because of wave front healing of the waves along their path from the fault tip to the receiver array. If the fault tip is to deep, the blocking effect may disappear. However, the conversion from P- to S-wave will still indicate the approximate location of the fault. Fracture zones are characterized by their guiding effect of seismic energy that can lead to advanced travel times relative to the propagating body waves that don't interact with the fracture zones. At the same time, converted S-waves can indicate the lateral extent of the fracture zone. Because of their characteristics, fracture zones can possibly be distinguished from faults in the subsurface. Furthermore, fault zone guided waves and multiple reflected waves within fracture zones that arrive at later times on seismograms are very distinct indicators for the presence of faults or fracture zones.

In summary, the project generated interesting results of seismic wave interaction with faults and fracture zones, which indicated that the foot-print of these features are clearly visible and often distinguishable in single seismic receiver lines. As a consequence, many previously collected 1-D and 2-D seismic data sets may still contain valuable information regarding the presence of blind faults. These data sets should be revisiteVd, supported by numerical modeling activities, to determine the presence and approximate location of suspected subsurface faults. Although 3D seismic surveys have to be conducted if the dip and the fault properties are required in greater detail, the old data sets can reveal enough information about fault and fracture geometries that the 3D surveys can be minimized, which can result in cost saving of more than 50%.

Reports & Articles Published in FY 2003:

Gritto, R.; Daley, T. M.; Majer, E. L., (2003): Estimating Subsurface Topography from Surface-to-Borehole Seismic Studies at the Rye Patch Geothermal Reservoir, Nevada, USA, Geothermics, Vol. 32, No.3, pp. 275-295.

Presentations Made in FY 2003:

Gritto, R.; Daley, T. M.; Majer, E. L. (2002): Integrated seismic studies at the Rye Patch geothermal reservoir, Geothermal Resources Council Transactions, Vol. 26, pp. 431-435.

Gritto, R.; Majer, E. L. (2003): Seismic methods for resource exploration in enhanced geothermal systems, Geothermal Resources Council Transactions, Vol. 27, pp. 223-226.
Gritto, R.; Majer, E.L. (2003): Numerical seismic studies of fault detection in geothermal reservoirs, EOS, Vol. 84, pp. 1138-1139.

Planned FY 2004 Milestones:

Because the projected was completed at the end of 2003, there are no milestones planned for 2004.

Remote Sensing for Hidden Geothermal Resources

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory
University of California
7000 East Ave. L-644
Livermore CA 94550

Principal Investigator: Dr. William L. Pickles
Phone: (925) 422-7812
E-Mail: pickles1@llnl.gov

Collaborating Researchers: Prof. Donald C. Potts, UC Santa Cruz, Biology potts@biology.ucsc.edu,
Prof. Eli A. Silver, UCSC, Earth Science, esilver@es.ucsc.edu,
Ty Kennedy-Bowdoin, UCSC, tbowdoin@emerald.ucsc.edu,
Dr. Brigette A. Martini, HyVista Corp., martini@hyvista.com

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@EE.DOE.GOV

DOE Funding Allocation: 300 $K

Cost Share Funding: 80 $K UC Santa Cruz, Professors and grad student salaries, in-kind

Project Objective: Our objective is to simplify, regionalize, and increase accuracy in targeting new geothermal resource development locations. We are moving hyperspectral remote sensing to the next level in usefulness for effective targeting of new geothermal resources and subsurface model development by increasing the accuracy and speed of targeting. We are increasing the size of the areas explored in one image acquisition mission. This will allow us to develop a better understanding of hidden geothermal resources on a regional scale. By combining our evolving remote sensing methods with other exploration techniques, we hope to increase accuracy and speed over large regions, which should lower the cost of exploration dramatically. The improved combined exploration methodologies resulting from this project will lead to more developable resources, sooner, and at lower cost, which will increase the supply of geothermal heat and power. It should also lower the cost of electricity produced by reducing exploration costs. Regional resource understanding may increase the number of states that produce geothermal electrical power and/or heat.

Background/Approach: The long-term goal of our remote sensing program is to increase the precision, accuracy, and speed of regional geothermal resource exploration. We want to use the remote sensing methods we have developed at Mammoth and Long Valley (see http://eed.llnl.gov/other/martini/ and http://emerald.ucsc.edu/~bmartini/defense2_files/frame.htm) in additional geothermal districts. We are integrating our remote sensing methods with other exploration methods such as aeromagnetics, 2D

seismic, and borehole data. Our large area imaging techniques allow exploration targeting and subsurface modeling to be regionalized. We use only one or a few image acquisition days for each site. Our remote sensing techniques provide a planning tool for deploying other, more costly conventional exploration methods that are more localized.
Status/Accomplishments: This year we have concentrated on analyzing the hyperspectral imagery of Dixie Meadows that was acquired in August 2002, and doing new hyperspectral image acquisitions at significant new sites in Nevada

The table below lists the image acquisitions and site field trips taken in FY 2003.

- Fish Lake Valley NV South imaged by NASA JPL AVIRIS (funded by NASA) March 2003
  - Field trip Pickles June 2003

- Fish Lake Valley NV North imaged by HyVista Corp. July 2003
  - Field trip Pickles June 2003

- Humboldt/Rye Patch district imaged by HyVista June 2003
  - Field trip Pickles and Al Waibel May 27 thru June 3 2003

- Eastern Range NV imaged by HyVista June 2003
- Blue Mountain NV imaged by HyVista June 2003
  - Field trip Pickles June 2003

- Brady Hot springs and Desert Peak imaged by HyVista June 2003
  - Field trip Calvin June 2003

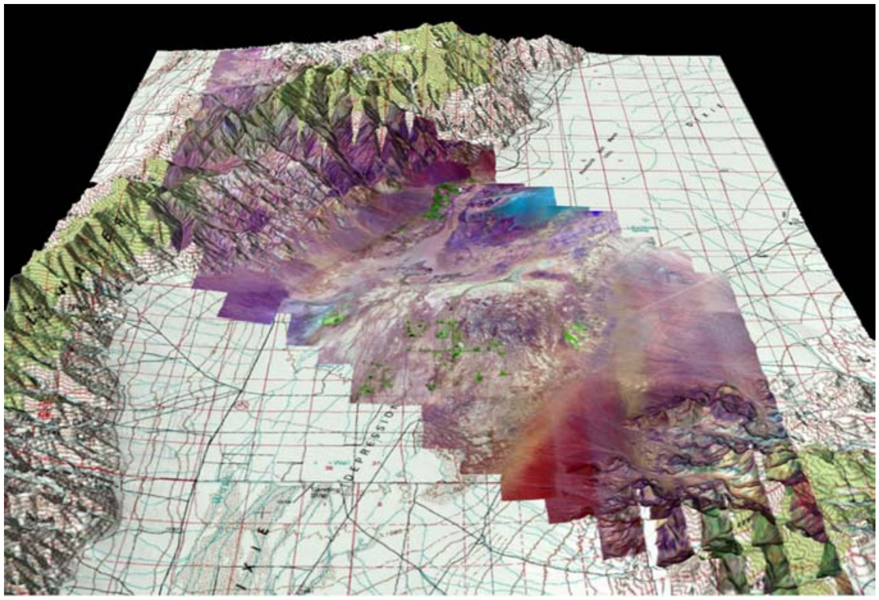
- Dixie Meadows NV- Stillwater to Clan Alpine imaged by HyVista August 2002
  - Extended field trips Kennedy-Bowdoin May, June, July 2003
  - Group field trip June 2003

All the imagery is being shared between LLNL, UCSC, UU, and UNR for analysis and is available to industry as well.

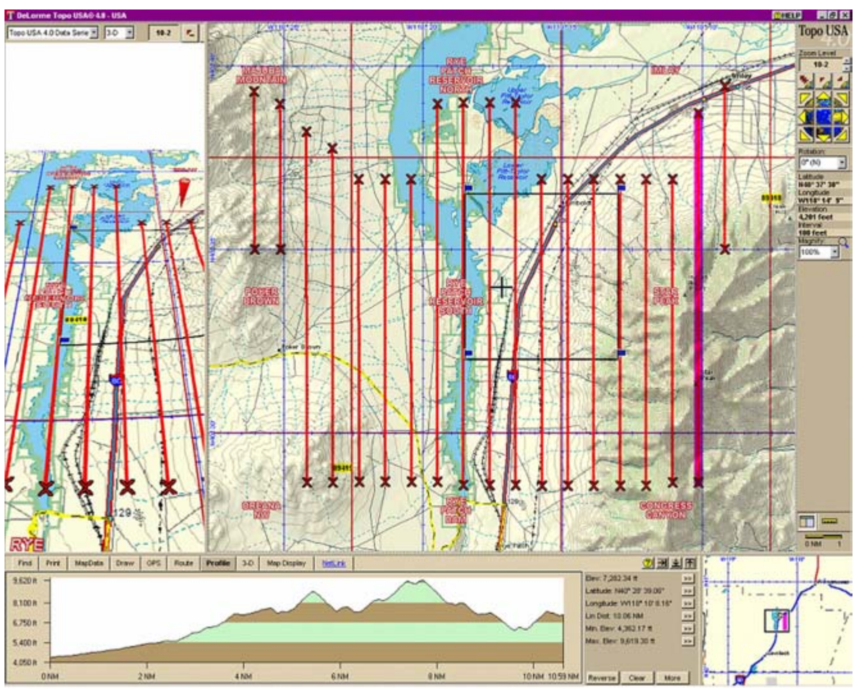
The Dixie Meadows hyperspectral imagery analysis has been done by Ty Kennedy-Bowdoin and Dr. Brigette Martini. Kennedy-Bowdoin's Dixie Meadows analysis is part of his Master Thesis at UC Santa Cruz. He has been able to do altered mineral mapping in the Stillwater Range, fault mapping in the Stillwater and west basin, and structure interpretation and targeting for potential drilling.

Dr. Brigette Martini, who is at HyVista Corp. in Sydney AU, has produced altered mineral mapping in Clan Alpine and fault mapping in Clan Alpine and has compared the hyperspectral image analysis to Smith's published magnetic surveys.

The following figure shows “RGB” images of all the Dixie Meadows flightlines mosaiced together.



The following figure shows a map of the Humboldt/Rye Patch flightlines that were acquired this year.



In FY04 we will be analyzing the Humboldt/Rye Patch and the Fish Lake Valley hyperspectral imagery.

Reports & Articles Published in FY 2003:

W. L. Pickles, G. D. Nash, W. M. Calvin, B. A. Martini, P. A. Cocks, T. Kennedy-Bowdoin, R. B. MacKnight IV, E. A. Silver, D. C. Potts, W. Foxall, P. Kasameyer, Geobotanical Remote Sensing Applied to Targeting New Geothermal Resource Locations in the US Basin and Range with a focus on

Dixie Meadows NV, Geothermal Resources Council Transactions, Vol. 27, p. 673-675. See also Livermore National Laboratory report UCRL-JC-153443.
B.A. Martini, E.A. Silver, W.L. Pickles, P.A. Cocks, Hyperspectral Mineral Mapping in Support of Geothermal Exploration: Examples from Long Valley Caldera, CA and Dixie Valley, NV, USA, Geothermal Resources Council Transactions, Vol. 27, p. 657-662.

B. A. Martini, New Insights into the Structural, Hydrothermal, and Biological Systems of Long Valley Caldera using Hyperspectral Imaging, Ph. D. dissertation, UC Santa Cruz, December 2002. http://eed.llnl.gov/other/martini/

B. A. Martini thesis chapter 3 and 4 are found at:

Hyperspectral Imaging in Long Valley Caldera: Volcano-associated biological communities
http://eed.llnl.gov/other/martini/chapter3.pdf
http://eed.llnl.gov/other/martini/Ch3_Figures.pdf

Hyperspectral Imaging in Long Valley Caldera: Tracking volcanogenic CO_2 and its lethal effects
http://eed.llnl.gov/other/martini/chapter4.pdf
http://eed.llnl.gov/other/martini/Ch4_Figures.pdf

Presentations Made in FY 2003:

W. L. Pickles, Geobotanical Remote Sensing Applied to Targeting New Geothermal Resource Locations in the US Basin and Range with a Focus on Dixie Meadows NV, Geothermal Resources Council 2003 Annual Meeting in Mexico.

B.A. Martini, E.A. Silver, W.L. Pickles, P.A. Cocks, Hyperspectral Mineral Mapping in Support of Geothermal Exploration: Examples from Long Valley Caldera, CA and Dixie Valley, NV, USA, Geothermal Resources Council 2003 Annual Meeting in Mexico.

Planned FY 2004 Milestones:

Complete verification field trips	Jun 04
Compare mapping with industry supplied field data	Jul 04
Report results	Aug 04

Localized Strain as a Discriminator of Hidden Geothermal Resources

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory
Earth Sciences Division
P.O. Box 808
Livermore, CA 94551-0808

Principal Investigator: William Foxall
Phone: (925) 424 3767
E-Mail: bfoxall@llnl.gov

Collaborating Researchers: Paul Kasameyer, LLNL; kasameyer1@llnl.gov
Donald Vasco, LBNL; dwvasco@lbl.gov

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $210K

Cost Share Funding: None

Project Objective: The objectives of our research are to investigate the role that strain concentrations along active faults play in localizing geothermal resources in the western Basin and Range, and to develop and test techniques to identify hidden potential geothermal resources by detection of strain anomalies on a regional basis. This research is designed to meet the objectives of the Geothermal Program by providing cost effective regional exploration for new resources, which will lead to an increase in the overall supply of geothermal power and heat.

Background/Approach: Most producing geothermal fields and known geothermal resources in the Basin and Range province appear to be associated with Quaternary active fault systems, within which hydrothermal fluids are presumed to circulate from depth to relatively shallow production depths through high permeability fractures. DOE-funded research at Dixie Valley (Barton et al., Proc. 22nd Stanford Workshop, 1997) indicates that hydraulically conductive fractures within the Stillwater fault zone are those that have orientations such that the fractures are critically stressed for normal shear failure under the regional stress field. Caskey and Wesnousky (Proc. 25th Stanford Workshop, 2000) presented evidence that the geothermal field occupies a 10 km-long gap between prehistoric Holocene ruptures of the fault segments on either side. Modeled Coulomb failure stress is high within the gap owing to the stress concentrations at the ends of the ruptures. These results suggest that a major contributing factor to the enhanced permeability at fault-hosted geothermal systems may be localized stress and strain concentrations within fault zone segments. This notion is generally consistent with the common occurrence of geothermal fields within fault offsets (pull aparts) along strike-slip fault systems, where the local strain field has a large extensional component (e.g., Salton Sea and Coso).

Geodetic measurements, seismicity, geology, and remote sensing can be used to investigate whether localized perturbations in the magnitude and orientation of the regional strain field are systematically associated with fault-hosted hydrothermal systems. The current focus of our research is to evaluate the utility of repeat-orbit synthetic aperture radar interferometry (InSAR) as a reconnaissance tool by testing its capability to detect localized strain anomalies directly. InSAR is a satellite-based geodetic technique that has the potential of measuring surface strains on the order of 10^{-6} to 10^{-7} on a regional scale with a spatial resolution of 25 meters. The basis for the technique is that the difference between the phases of the radar echos received from an imaging element (pixel) on the Earth's surface at nearby satellite positions during two different orbits is proportional (in part) to displacement of the pixel in the time interval between the two orbits. Mapping the phase changes produces an interferogram, which is processed to recover a map of surface deformation covering an area of approximately 100 x 100 km.

Our study is centered on the Central Nevada Seismic Zone and the Walker Lane belt, where both regional strain and much of the current geothermal production are concentrated. The broad geographical coverage afforded by InSAR allows us to also include adjacent areas of potential interest. Work during FY02 focused on analysis of localized, production-related ground subsidence imaged by InSAR over the relatively well-studied Dixie Valley geothermal field. The aim of these analyses was to investigate the structural and hydrological factors that contribute to localization of the resource along this segment of the Stillwater fault zone. These factors, and in particular their relation to the local strain field, can then be used to identify attributes that can be applied to the regional reconnaissance for hidden resources. Continuation of the Dixie Valley studies in FY03 included further analyses of the InSAR data and monitoring the aftershocks of an M4.2 earthquake that occurred directly under the Dixie Valley field. Following this, we shifted the focus of the research to assessing the capability of InSAR to detect and analyze localized strain perturbations on a regional basis.

Status/Accomplishments: We acquired and processed five European Space Agency Earth Resources Satellite (ERS) scenes centered on Dixie Valley to construct the interferograms summarized in Table 1.

Table 1. Orbit pairs for ERS-1/2 descending Track 213, Frame 2804

Orbit 1	Orbit 2	Time Interval	ΔT	B_{perp} (m)
2-10087	2-12091	3/35/97 - 8/12/97	4.8 mo	3
2-5077	2-10087	4/09/96 - 3/25/97	10.5 mo	5
2-5077	2-12091	4/09/96 - 8/12/97	1.3 yr	8
1-5869	1-24750	8/29/92 - 4/08/96	3.5 yr	11
1-5869	2-10087	8/29/92 - 3/25/97	4.5 yr	93
B_{perp} in the last column is the offset between the two satellite positions.				

Subsidence over the Dixie Valley field is imaged as an interference pattern that is clearly defined in the 4.8 month, 10.5 month and 1.3 year interferograms. Our initial inversion of the subsidence map derived from the 10.5 month interferogram used an horizontally-layered model. The best-fitting inverse solution obtained using this model suggested that the dominant source of the subsidence is reduction of the volume and pressure of hot water discharged from the Stillwater fault into the valley fill at depths less than 500m, caused by drawdown in the fault zone resulting from production (Foxall and Vasco, Proc 28th

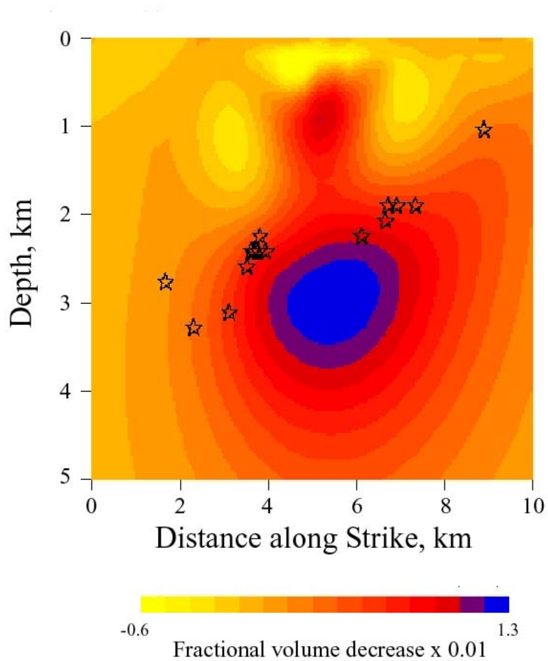


Figure 1: Fractional volume reduction within a 50° NE-dipping planar layer. Stars are intersection points of geothermal wells.

Stanford Workshop, 2003). This result is consistent with a model previously proposed based on well temperature data. We carried out further inversions in FY03 using an alternative model in which fluid volume changes are restricted to a narrow layer that dips 50° NE, representing the westernmost piedmont fault identified by Smith et al. (GRC Trans., 2001) basin-ward of the main range front fault in the vicinity of the Dixie Valley field. Blackwell et al. (GRC Trans., 1999) concluded that the Section 7 and 33 production zones at Dixie Valley are located on such a piedmont fault or faults, rather than on the main range-front fault. As shown in Figure 1, the predominant reduction in fluid volume in this model is centered at production depths (~3 km), but there are also significant volume changes both below the production zone and at depths less than 1 km. As in the flat-layered model, the shallow volume change is required to fit the predominantly short-wavelength character of the surface subsidence pattern. The inversion result provides a moderate fit to the overall trend of the data, indicating the viability of the dipping fault model, but the scatter is significantly greater than that obtained with the shallow flat-layered model. However, it is likely that the fit could be improved by more detailed refinement of the subsurface fault geometry, and perhaps by combining fluid changes within the fault zone with shallow outflow.

The occurrence of an M4.2 earthquake directly beneath the Dixie Valley field on January 23, 2003 provided a potential opportunity to investigate fault structure and strain conditions in the vicinity of the field. To take advantage of this “target of opportunity” we installed an eight-station microearthquake network surrounding the epicentral area on January 30 to record the aftershocks. We operated the network until early April. Preliminary examination of the data indicates that several events were recorded. High-resolution relative locations of these events should provide information about the geometry of the fault zone in the vicinity of the field, and focal mechanisms for the larger events will give an insight into the local strain field. We plan to complete these analyses during FY04.

We began the regional strain study by evaluating the interferometric data quality obtainable on a regional scale over increasing time periods, based on the interferograms listed in Table 1. In order to capture measurable cumulative ground surface displacements associated with the relatively low regional strain rates in the NW Basin and Range, interferograms need to span intervals of 7 to 10 years. However, the signal/noise ratio of interferograms in general degrades as the time interval spanned by the pair of satellite orbits increases. This is due to temporal phase decorrelation caused by sub-pixel displacements, resulting, for example, from plant growth, and changes in the reflective properties of the ground surface during the interval between the orbits. The quality of the interferograms in Table 1 over the valleys is generally excellent for the 4.8 month to 1.3 year time intervals, but coherence rapidly degrades over forested slopes in the intervening ranges. Local salt deposits also causes decorrelation over some areas within valleys. Temporal decorrelation significantly degrades the overall signal/noise ratio of the 3.5-year interferogram, and is becomes severe in the 4.5-year image. Large parts of the localized interference pattern at the Dixie Valley field remain clearly visible on the 3.5-year interferogram and can still be discerned on the 4.5-year interferogram, indicating that usable signal/noise ratios can be expected to be achieved locally for time intervals as long as 5 years or more. However, the overall data quality obtained over these longer intervals precludes discrimination of subtle strain signatures on single-pair interferograms. The solution we are adopting to solve this problem is to stack several single-pair interferograms of the same scene spanning different time intervals, which reinforces coherent, linearly increasing strain signals and minimizes the noise. An equally important function of stacking is to eliminate spurious signals on single-pair interferograms caused by tropospheric phase delays. The results of the data evaluation indicate that stacking should produce adequate signal/noise ratios for a significant proportion of the unforested areas over time intervals of up to 10 years.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003:

Foxall, B., and D. Vasco, Inversion of synthetic aperture radar interferograms for sources of production-related subsidence at the Dixie Valley geothermal field, Proc. 28th Workshop on Geothermal Reservoir Engineering, Stanford University, California, p. 181-187, Jan. 2003.

Planned FY 2004 Milestones:

Acquire multiple-pass SAR data sets (or let data processing subcontract)	Feb 04
Obtain preliminary stacking results	Aug 04
Report	Sep 04

Structural Controls, Alteration, Permeability and Thermal Regime of Dixie Valley from New-Generation MT/Galvanic Array Profiling

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant No.: FG07-02ID14416

Performing Organization: University of Utah
Energy & Geoscience Institute
423 Wakara Way, Ste 300
Salt Lake City, UT 84108

Principal Investigator: Philip E. Wannamaker
Phone: (801) 581-3547
E-Mail: pewanna@egi.utah.edu

Collaborating Researchers: N/A

DOE HQ Program Manager: Jay Nathwani
Phone: (303) 275-4756
E-mail: Jay.Nathwani@go.doe.gov

DOE Funding Allocation: $164K

Cost Share Funding: None formally, but contractor Quantec Geoscience discounted survey by 15%

Project Objective: A new-generation MT/DC array resistivity measurement system was applied at the Dixie Valley thermal area. Basic goals of the survey are 1), resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single range-front fault versus shallower, stepped pediment; 2), delineate fault zones which have experienced fluid flux as indicated by low resistivity; 3), image the disposition of resistive, possible reservoir formations in the subsurface; and 4), from a generic standpoint, investigate the capability of fully sampled electrical data for resolving subsurface structure. Broader project objectives include increasing the number of states with geothermal electric power facilities, reduced the levelized cost of generating power, and increase the power/heat energy supply for homes and businesses by improving exploration technology.

Background/Approach: Images of subsurface resistivity have suffered in resolution due to limited data type, inadequate data sampling, and non-optimal inversion approaches translating data to models. We have applied a new-generation array magnetotelluric/galvanic (MT/DC) system in a contiguous bipole deployment over three profiles at the Dixie Valley thermal area (Figure 1). As discussed by Madden (1971), MT is attuned to conductive structures primarily while the DC results improve resolution of resistive structures. This well-sampled data set is being analyzed using a new inversion algorithm for resistivity image construction based on stabilization using a-priori constraints. A specific goal of the survey is to resolve a fundamental structural ambiguity at the Dixie Valley thermal area (single range-front fault versus shallower, stepped pediment) (Blackwell et al., 1999, GRC Trans.; 2000, Proc. WGC) (Figure 2). Data were obtained in year 1, most analysis will take place in year 2.

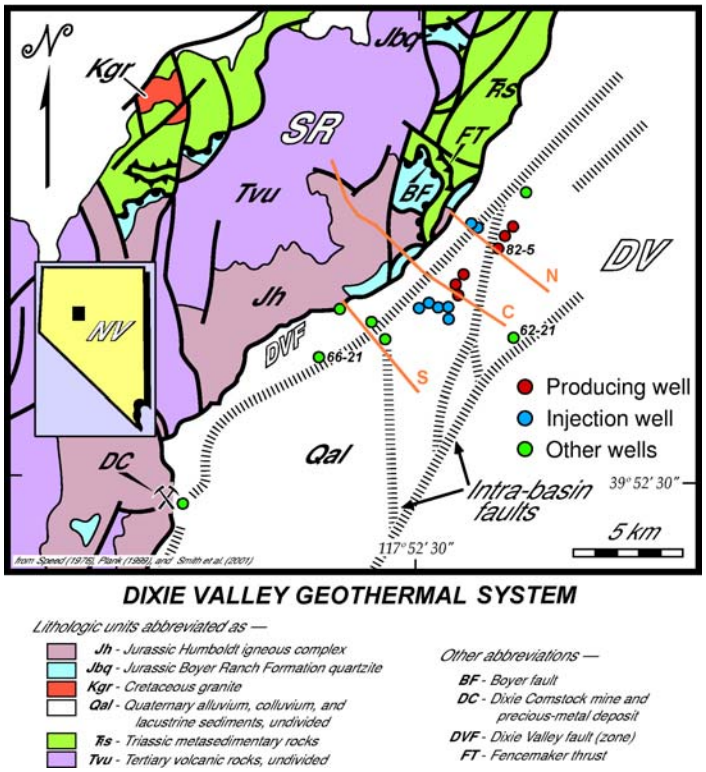


Figure 1. Simplified geological map of the Dixie Valley (DV)-Stillwater Range (SR) area surrounding the Dixie Valley thermal field. Orange lines show acquired contiguous MT/DC profiling through the system and adjacent fumarole fields. Lines are labeled N (north), C (central) and S (southern). Original figure courtesy Jeff Hulen.

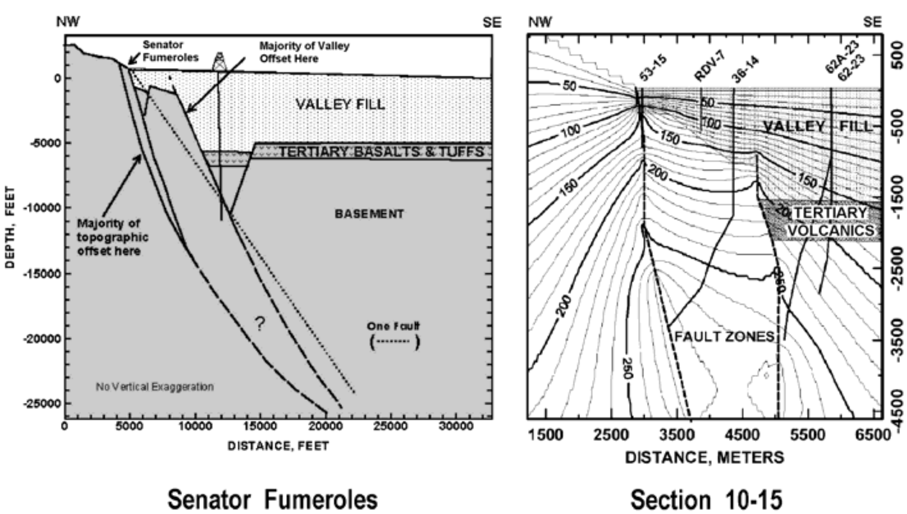


Figure 2. Left: fault splay model of the Dixie Valley/Stillwater Range bounding structure compared to the single fault model (Blackwell et al., 1999.). Right: cross section of Dixie Valley in the southern lease area based on the two fault interpretation (Blackwell et al., 2000). Graphics courtesy of Dave Blackwell.

Status/Accomplishments: MT/DC surveying was carried out on three, 4-6 mile long profiles totaling 14 line miles, each crossing the Stillwater fault zone approximately at right angles (Figure 1). The acquisition was by contract to Quantec Geoscience, Inc., who recently developed the system for exploration problems in the mining industry. The frequency range of the MT data is ~10 kHz to 0.03 Hz. These lines cross the Senator Fumaroles area, the Cottonwood Creek and main producing area, and the low-permeability region through the section 10-15 area. With array MT data, complete lateral sampling of the response is achieved through contiguous bipole deployment (Torres-Verdin and Bostick, 1992, Geophysics). In such a deployment, near-surface "static" distortions do not require qualitative correction but instead are included directly in the inversion process.

Our approach to the inversion of array MT data to yield resistivity cross sections is based on the a-priori, maximum likelihood estimates of Tarantola (1987, Elsevier) and utilizes the finite element platform of DeLugao and Wannamaker (1996, Geop. J. Int.). The approach applies just the smoothing implicit in the a-priori step estimate unlike the explicit smoothing of other EM inversion efforts. The a-priori damping factor is updated each iteration to achieve stabilization in terms of fundamental parameter correlations characteristic of the physics of diffusive EM (e.g., conductivity-dimension) rather than brute-force suppression of spatial derivatives. Also, the parameters defining the image grow both laterally and vertically with depth, thereby preserving the influence of individual parameters at the surface according to basic EM scaling, and thus stabilizing the parameter step and increasing depth of exploration. Inversion capability for joint MT/DC imaging including the induced polarization component has recently been completed under support of the Western U. S. Geothermal Systems contract (J. Hulen, P.I.).

To date, an inversion of the MT data for the northern Senator Fumaroles line has been produced (Figure 3). High resistivities (~1000 ohm-m) are seen under the Stillwater Range below 500 m depth and extending to the southeast under the pediment. Moderately high values (~100 ohm-m) persist at rather shallow depths (~400 m) from the topographic scarp where Senator fumaroles are located to a distance of about 1-1/2 km southeast just past well 38-32. Values of 100 ohm-m are more consistent with rock than alluvium (e.g., Ward et al., 1978, Geophysics), although alteration of the rock is a possibility. The alluvium of the main part of Dixie Valley is moderately conductive (10-25 ohm-m) in the upper 400 m, and quite conductive in the 500-1000 m depth range (< 3 ohm-m). A low resistivity limb dips upward from ~1 km depth to the near-surface under well 38-32 near the west flank of Dixie Valley. Senator fumaroles itself does not exhibit a strong resistivity expression.

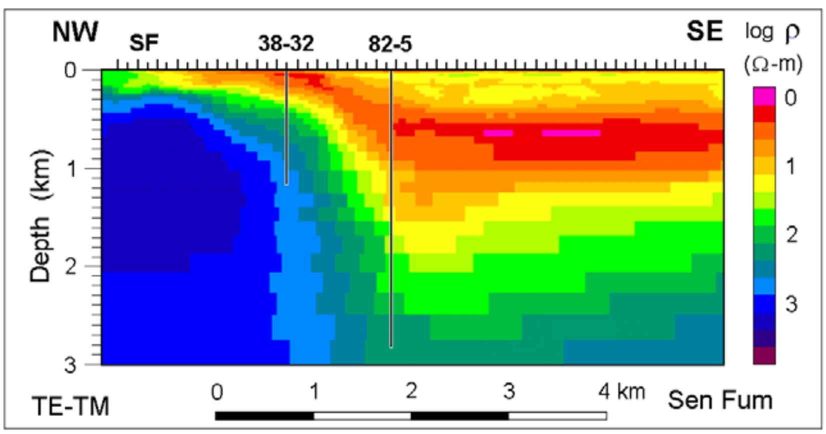


Figure 3. Electrical resistivity section for the northern (N) profile of Figure 1 derived from 60 array MT sites taken with contiguous, 100 m long electric field bipoles. Tick marks are located at bipole centers. Bedrock-alluvium interface is interpreted to lie near the 70-100 ohm-m "contour". Senator fumaroles are denoted SF, and wells 38-32 and 82-5 are projected onto section.

The inversion to this point suggests that shallow basement rocks extend for a considerable distance to the southeast before plunging steeply down the main range-front fault. It thus is more supportive of the multi-fault basement model than that of the single main fault (Blackwell et al., 1999, 2000). However, the structural interpretation remains somewhat non-unique: although Stillwater Range lithologies were intersected at a depth of ~400 m in well 38-32, near where the step in resistivity to values of 100 ohm-m or more occurs, an unknown amount of slide block material may exist over the main Dixie Valley range-front fault here to complicate the structural framework (Johnson and Hulen, 2002, GRC Trans.). A particularly low resistivity zone flanks the interpreted main offsetting fault and may be due to alteration from geothermal fluid outflow and upflow. There also is a near-surface concentration of such intersected by well 38-32.

Lateral sampling uncertainties in data acquisition are removed by the contiguous bipole deployment, which helps to maximize the resolution of resistivity structure. Remote referencing and robust processing have generally yielded high quality data even in a field where power production has already been established. Incorporation of EM and galvanic data sets in principle should improve resolution of resistivity structure beyond that possible from either data set alone. Determining the structural framework at the Dixie Valley thermal area should improve thermal and reservoir models of the system. The project brings to geothermal exploration new technology developed recently within the mining industry, where the problem scales are similar. Quantec Geoscience is testing the joint inversion capability developed by the P.I. and has ported the MT component to a Beowulf cluster. We are very grateful to Caithness Energy Co. for access to the property and encouragement in the surveying.

Reports & Articles Published in FY 2003:

Wannamaker, P. E., 2003, Initial results of magnetotelluric array surveying at the Dixie Valley geothermal area, with implications for structural controls and hydrothermal alteration, Geothermal Resources Council Transactions, 37-40.

Presentations Made in FY 2003:

Annual GRC meeting, Morelia, Mexico, October 12-15, 2003.

Planned FY 2004 Milestones:

Complete MT inversions for other profiles.	Mar 04
Incorporate galvanic (DC) data into inversion models.	May 04
Complete and submit paper on survey results.	Aug 04

3D Magnetotelluric Modeling and Inversion

Reporting Period: FY 2003 (October 1, 2003 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-0750

Principal Investigator: Chet Weiss and Gregory Newman
Phone: (505) 284-6347
E-Mail: cjweiss@sandia.gov

Collaborating Researchers: Mike Hoversten (LBNL), Randall Mackie(GSY-USA) and William Cumming (Cumming Geoscience)

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $107K

Cost Share Funding: $100K GSY-USA, Cumming Geoscience, LBNL, EMI, UC, USGS

Project Objective: The objective of the project is to enable increased use of magnetotellurics (MT) in geothermal exploration and development using detailed, realistic synthetic and field data sets, for modeling and inversion of magnetotelluric data. The project is directly related to the goals of the Geoscience R&D portion of the overall program, which are to address characterization and management of the geothermal resource via increased understanding and enhancement of underground fractures, improved understanding of underground flows, and resource management through re-injection of spent geothermal fluid. Subsurface imaging using magnetotelluric data has the potential to help define fluid pathways and barriers, such as faults and fractures. Better subsurface characterization will help reduce the cost for generating geothermal power, and will also provide the means to help identify new locations with geothermal resources, thereby addressing the goal to increase the number of states with geothermal power facilities.

Background/Approach: Electrical and electromagnetic (EM) methods are currently used in geothermal exploration to detect subsurface resistivity patterns that indicate geothermal resources. Of the EM methods, the magnetotelluric (MT) method has been a commonly used tool in geothermal exploration and development, but has been limited because of our inability to model and analyze MT data arising from complex 3D geothermal systems. Recent advances in 3D MT data inversion, an emerging technology, have the potential for characterizing complex geothermal systems, but critical data is still lacking to demonstrate the advantages that can be gained by acquiring and analyzing MT data in three dimensions. This project will address this issue, by applying 3D MT modeling inversion to realistic MT synthetic and field data sets. The project will therefore provide the ability, for the first time, to image large geothermal reservoirs in a single self-consistent model. We believe the use of 3D imaging/inversion, rather than two-dimensional imaging, can remove the artifacts inherent in two-dimensional inversion of three-dimensional data. Demonstrating this in the geothermal context will push geophysical characterization of geothermal systems beyond the current state and provide a quantitative tool for geothermal well location. Sandia has already developed the massively parallel 3D EM finite difference modeling and inversion codes that will be applied in the project for large-scale 3D MT modeling and inversion, and has access to the required high-end computational resources needed to complete the data simulation phase of the project (Newman and Alumbaugh, 2000; Newman et al., 2002a and 2002b). The simulation comprises two field investigations, where 3D MT data sets are now being acquired. In the first field study, we are collaborating with Phil Wannamaker of UURI to characterize the geothermal resource at Coso California. Coso represents a highly complex 3D geothermal system, where data acquisition is now underway over rugged topographic conditions. Realistic interpretation of Coso field data will require 3D MT modeling and inversion capability. We will begin working with Wannamaker on the data interpretation this fall. In the second field investigation, we are using MT data to image in 3D the volcanic East Rift Zone and deeper magma chambers on the Kilauea volcano in Hawaii. In collaboration with other institutions (Lawrence Berkeley (LBNL), University of California (UC), United States Geological Survey (USGS), and Electromagnetic Instruments Inc.(EMI)) a state-of-the-art 3D MT survey was carried out over the Kilauea volcano in 2002 and 2003 (Hoversten et al., 2003). Sandia has participated in the field survey and will provide virtually unlimited time on SNL massively parallel computer systems for 3D data interpretation and modeling in close collaboration with LBNL. The successful 3D interpretation of the Kilauea data set will push the envelope of large-scale 3D magnetotelluric forward, especially in the area of inverse modeling in the presence of rugged topography and coastal effects.

Status/Accomplishments: In FY03 data acquisition at Coso was still ongoing, and we have yet to receive field data to analyze. Modeling and analysis of the Coso data is set for FY04. However, data acquisition over Kilauea has progressed nicely, and we completed the 3D MT survey late last year. On the basis of this data, we have carried out 3D MT modeling to better access the effects of the land-ocean contact on the MT Kilauea data set. The 3D model used for assessing the topography and coastal effects of Hawaii (Figure 1) was modified to add the 3D magmatic structure presented by Ryan (1988). This model (Figure 1) was an approximate representation of the Ryan model, in that we could only accurately digitize the contours of the structure at a depth of 1 Km below surface. The structure at 1 km was continued vertically to a depth of 10 km. Below 10 km we constructed a magma conduit to a depth of 40 Km that dipped slightly to the south, based on figures presented in Ryan (1988). This magmatic structure was given a resistivity of 1 Ω-m within a 100 Ω-m host. The model had 107 x 103 x 123 cells in the x, y, and z directions respectively. Cells in the area of the survey (southeast quadrant of the island) were 1000 x 1000 x 200 m in x, y and z directions respectively; with cell dimensions grading to larger sizes toward the boundaries of the model. By including the magma chamber in the island model, we find the spatial variation in the orientation of the polar diagrams agree well between the field (Figure 2) and model data. There is some difference however, which may indicate that the modeled magmatic structure is either not large enough or does not have low enough resistivity, but for the most part the simulated data are consistent with the field data. This comparison lends confidence to both the data sensitivity to magmatic structure and the ability to model and in invert in 3D this coming year. Work for improving the efficiencies of the 3D MT modeling and Inversion-codes has progressed. We are currently experimenting with an algebraic multigrid (amg) scheme to accelerate the solution of 3D MT modeling problems at low frequencies. Preliminary results show a significant reduction in simulation time (factor of ten), but more work remains in testing the robustness of the amg scheme.

Besides this work, we have completed an initial suite of 3D volcanic models reflecting the resistivity geometry typical of a distributed permeability, 230-330°C geothermal reservoir beneath an andesitic-silicic volcanic massif, like Medicine Lake, California. We are currently waiting for additional input from our industrial sponsors for new Basin and Range 3D geothermal reservoir models to simulate this coming year.

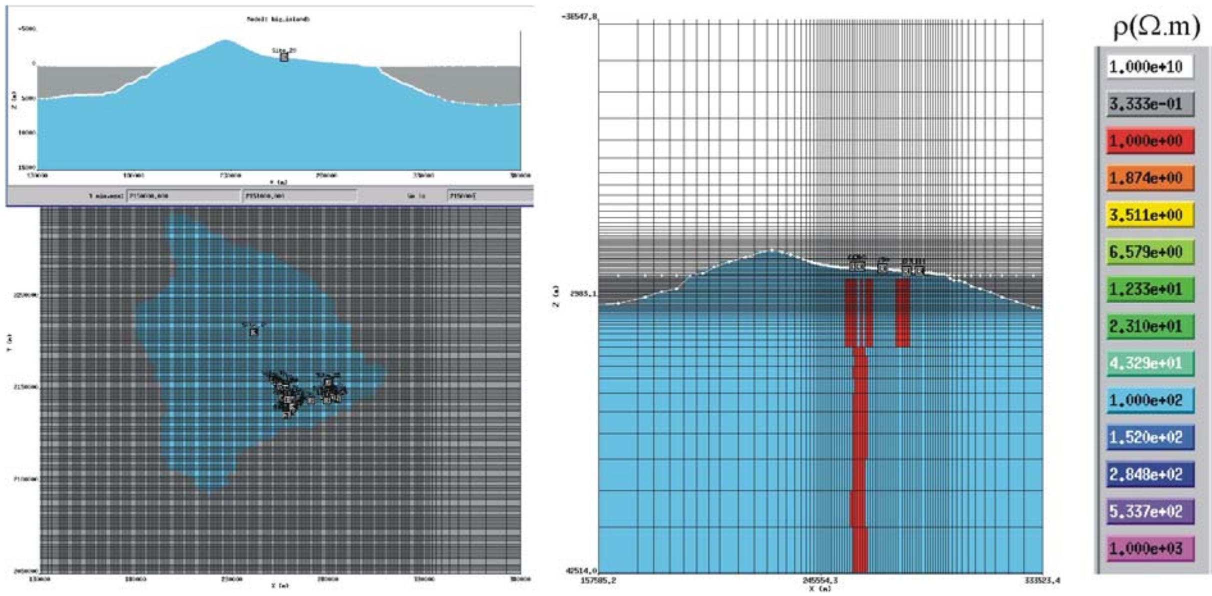


Figure 1. Full scale 3D numerical model of the entire island of Hawaii and surrounding sea floor. The model comprises over 14 million cells and includes the 3D Magmatic structure of Ryan (1988). Results show that the 3D topography and coastal effects depart from 2D below 100 seconds This model was simulated using 512 processors on Sandia National Laboratories Ascii-Red and brings a level of numerical complexity to geothermal system models that have not previously been possible. Color bar scale is in unit of resistivity ρ(Ω.m).

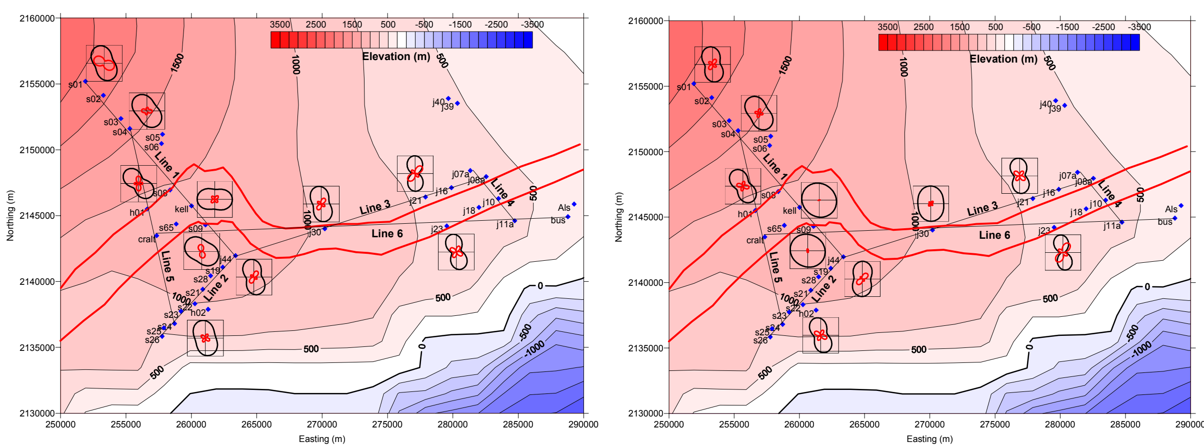


Figure 2. August 2002 MT site map and impedance polar diagrams for field data at 0.01 Hz are plotted at selected sites to illustrate the spatial variation in MT impedance (left). To the right is the simulated impedance polar diagrams based on the 3D numerical model of the entire island of Hawaii, including the 3D magmatic structure of Ryan (1988), and surrounding sea floor. Overall correspondence between the predicted and observed data is quite, good, but with some discrepancy directly over the east rift zone.

Project Impact: The impact of this project on geothermal resource evaluation and delineation will be significant. Magnetotellurics has a long history in geothermal exploration. This project at completion will demonstrate the full potential of MT for characterizing geothermal systems in three-dimensions in two critical ways. First, generation of synthetic MT data sets over realistic geothermal systems will allow for testing standard MT imaging methodologies, such as 2D MT inversion, to determine their optimality and robustness. Second, 3D MT inversion is now an emerging technology. Its potential for characterizing complex geothermal systems appears to hold great promise, but critical data is still lacking demonstrating the advantages that can be gained by acquiring and analyzing MT data in three dimensions. This project will address this issue, by applying 3D MT modeling inversion to realistic MT synthetic and field data sets. The project will therefore provide the ability, for the first time, to image large geothermal reservoirs in a single self-consistent model. We believe the use of 3D imaging/inversion, rather than two-dimensional imaging, can remove the artifacts inherent in two-dimensional inversion of three-dimensional data. Demonstrating this in the geothermal context will push geophysical characterization of geothermal systems beyond the current state to provide a quantitative tool for geothermal well location.

Reports & Articles Published in FY2003:

Presentations Made in FY 2003:

Newman, G., Hu J. and Tuminaro, R, 2003, An algebraic multigrid method for Maxwell's equations on the frequency domain: In proceedings of the 2003 Progress in Electromagnetic Research Symposium (PIERS), Hawaii, Oct. 13-16.

Planned FY 2004 Milestones:

Finish efficiency improvements in 3D MT modeling and Inversion codes	Jan 04
Complete experiment design for augmented 3D MT data acquisition at Coso	Mar 04
Complete realistic simulation of fault-type and Basin and Range geothermal systems	Apr 04
Submit technical papers describing work	Sep 04

References:

Hoversten, G. M., Gasperikova, E., Newman, G. and Kauahikaua, J., 2004, Magnetotelluric Investigations of the Kilauea Volcano, Hawaii: submitted J. Geophys. Res.

Newman, G. A., and Alumbaugh, D., L., 2000, Three-dimensional magnetotelluric inversion using non-linear conjugate gradients: Geophys. J. Int., 140, 410-424.

Newman, G. A., Hoversten G. M., and Alumbaugh D. L., 2002a, 3D magnetotelluric modeling and inversion: applications to sub-salt imaging: In M. S. Zhdanov and P. E. Wannamaker (Eds.): Three-Dimensional Electromagnetics, Proceedings of the Second International Symposium, Chapter 8, 127-152, Elsevier, Amsterdam.

Newman, G. A., Recher, S, Tezkan, B, and Neubauer F., 2003, Three dimensional inversion of a scalar radio magnetotelluric field data set: Geophysics, 68, 791-802.

Ryan, M.P., 1988, The mechanics and three-dimensional internal structure of active magmatic systems: Kilauea volcano, Hawaii. *J. Geophys. Res*. 93, No. B5, 4,213-4.

Innovative Geothermal Exploration Techniques

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC03-76SF00098

Performing Organization: Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA 94720

Principal Investigator: B. Mack Kennedy
Phone: (510) 486-6451
E-Mail: bmkennedy@lbl.gov

Collaborating Researchers: Matthijs van Soest, Curt Oldenburg, G. Mike Hoversten

DOE HQ Program Manager: Roy Mink
Phone: (202) 586-5463
E-mail: Roy.Mink@hq.doe.gov

DOE Funding Allocation: $243K

Cost Share Funding: $200K

Project Objective: To develop new techniques for assessing existing and finding new hidden geothermal systems. Specific objectives include: (1) develop geochemical and isotopic techniques to identify "hidden" hydrothermal systems. (2) Enhance existing numerical simulators to couple subsurface and subaerial CO_2 gas emissions for design of exploration survey strategies. (3) And evaluate three-dimensional magnetotelluric data acquisitions systems and imaging algorithms for geothermal resource exploration and delineation.

Background/Approach: Project 1: Noble gas isotope geochemistry and hidden geothermal systems. Noble gas isotope and abundance systematics in geothermal fluids are indicative of fluid and heat source and provide information regarding fluid evolution, mixing, and flow path. Therefore, noble gases are potentially very useful geothermal exploration tools, which (a) provide a definitive distinction between crustal and magmatic heat sources and (b) in the case of crustal heat sources, provide an evaluation of the presence, size, and involvement of a deep-crustal (mantle) derived component.

Project 2: Simulation of coupled subsurface and subaerial CO2 gas emissions. Detecting and locating anomalous gas emissions from areas with known geothermal resource potential may be a way of locating hidden geothermal systems. In order to assess the potential feasibility of this approach, it is necessary to understand what levels of gas concentrations are likely under expected conditions of wind speed, atmospheric stability, and gas seepage flux. Funding for this project is leveraged by non-geothermal studies related to CO2 sequestration.

Project 3: Evaluation of 3D magnetotelluric data acquisition systems and imaging algorithms. A critical aspect of resource identification and delineation is the ability to remotely and inexpensively image subsurface fluids and fluid reservoirs. In collaboration with the scientists from the USGS and UC Berkeley, this project evaluates the feasibility of magnetotelluric (MT) data to image sub-surface aquifers and structures.

Status/Accomplishments: Project 1: Noble gas isotope geochemistry and hidden geothermal systems. Noble gases have been underutilized in studies of the geothermal potential of the Basin and Range and surrounding areas. Therefore, data from specific case studies, like that at Dixie Valley, cannot be put into the greater context of the Basin and Range geotectonic province and its importance with respect to locating other geothermal systems. For instance, it is not known if the definitive occurrence of excess ^{3}He in Dixie Valley geothermal fluids is an anomaly or is a general phenomenon related to the extensional tectonic regime defining the Basin and Range. To place Dixie Valley, as well as other Basin and Range geothermal systems, into an appropriate isotopic context, we initiated a sampling campaign to map the helium isotopic composition of fluids throughout the Basin and Range in Nevada, Utah, California, and Idaho, and neighboring systems, such as the Cascade volcanic suite. More than 60 samples have been analyzed with another 30 in the process of being analyzed. The acquired data will complement concurrent geochemical and isotopic studies conducted by researchers at the University of Nevada, Reno (UNR) and the USGS and will provide an extensive database for identifying regional trends and anomalies, for comparison with regional and local heat flow data and gas and water geothermometry.

Project 2: Simulation of coupled subsurface and subaerial CO2 gas emissions. We have developed a coupled modeling framework for modeling CO2 transport in the subsurface and dispersion in the atmospheric surface layer. This framework can be used to predict expected down-wind concentrations in order to specify locations of maximum gas concentration where gas detection instrumentation should be located.

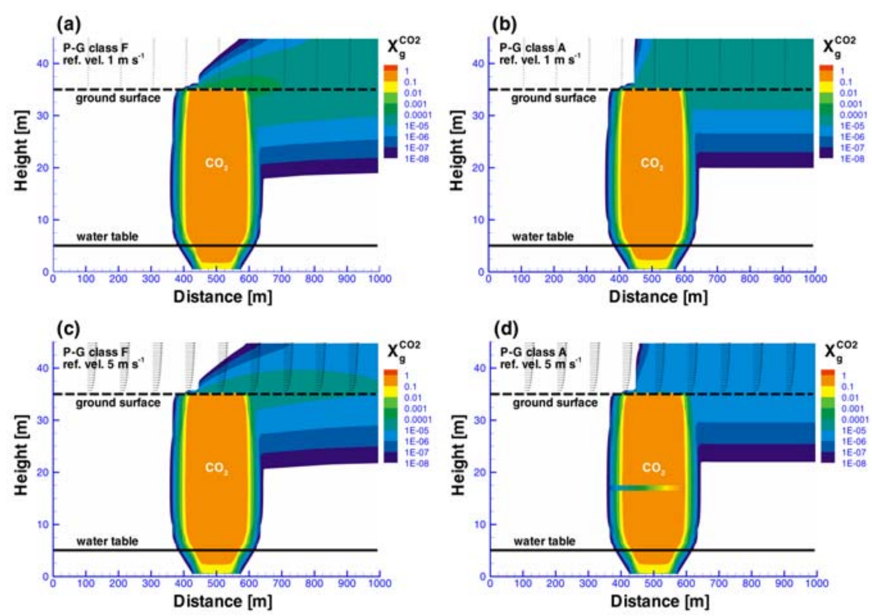


Figure 1. Gas phase mass fraction of CO_2 and gas velocity vectors in the coupled subsurface–surface layer model domain six months after CO_2 seepage begins.

The simulation capability is called T2CA (TOUGH2 for CO_2 and Air) and is an extension of the TOUGH2 reservoir simulator. T2CA includes both subsurface and atmospheric surface layer regions. The approach for the subsurface follows the standard multi-component and multiphase methods in TOUGH2, while for the surface layer we have added standard modeling methods from the field of atmospheric transport modeling. We present in Figure 1 preliminary results for various combinations of wind speed and atmospheric stability. As shown in Figure 1, CO_2 concentrations in the subsurface can be very high, while mixing in the surface layer is very effective at reducing CO_2 concentrations to levels that will be difficult to distinguish from natural background variation. These preliminary results suggest that detection by soil-gas sampling and surface flux measurement are more promising approaches for common gas components such as CO_2 unless instruments are very close to the source

Project 3: Evaluation of 3D magnetotelluric data acquisition systems and imaging algorithms. The Kilauea Volcano, Hawaii was selected as field site for evaluation of 3D magnetotelluric data as a potential geothermal exploration and reservoir delineation tool. The site was chosen to leverage previous work and funding provided by the USGS for an MT survey of the volcano, along with an extensive non-electrical geophysical data base. Kilauea also provides a site with extreme and difficult topography, high electrical contrast and an active geothermal environment with extreme variations in temperature, water salinity, fracture density and rock type. The experiment combined a total of 33 stations divided among six linear arrays arranged on the volcano in summit caldera-crossing, rift zone crossing, and rift zone-parallel transects, encompassing both the southwest and the east rift zones. The data acquisition phase was completed in September 2003, providing a complete 3D data set which has been used to (1) demonstrate that high quality MT data could be acquired in a multi-station mode in the harshest geothermal environments. (2) Demonstrate that remote magnetic field measurements could be used with local electric field measurements to produce accurate local impedance measurements, thus doubling the number of high-cost helicopter sites that could be acquired within budget. (3) Generate an inverse conductivity structure of the field site that ties in well with previous seismic and potential field survey results. (4) Demonstrate that the interpretations of the combined MT and existing seismic data sets are able to distinguish partial melt zones and magma conduits from fracture zones containing fresh or brackish water. And (5) construct a three-dimensional model of the entire island-ocean complex that accurately predicts the observed MT data at low frequencies where the island-ocean interactive effects are dominant.

Reports & Articles Published in FY 2003:

Evans, W.C., Van Soest, M.C., Mariner, R.H., Hurwitz, S., Ingebritsen, S. E., Wicks Jr., C. W., & Schmidt, M.E. Magmatic intrusion west of Three Sisters, central Oregon, USA: The perspective from spring geochemistry. Geology, 2004, v.32, no. 1, p. 69-72.

Van Soest, M.C. & Kennedy, B.M., Helium isotopes in hot springs and (hot) wells of the Basin and Range; a progress report. Submitted, 2004 Stanford Geothermal Workshop.

Van Soest, M.C., Evans, W.C., Mariner, R.H., & Schmidt, M.E., Chloride in hot springs of the Cascade volcanic are the source puzzle. Submitted, Water-Rock Interaction, 2004.

Hoversten, G.M., Gritto, R., Washbourne J., and Daley, T.M., Pressure and fluid saturation prediction in a multicompnent reservoir, using combined seismic and electromagnetic imaging. In press, Geophysics, 2003.

Hoversten, G., M., Milligan, P., Byun, J., Washbourne, J., Knauer, L., C., Harness P., Crosswell electromagnetic and seismic imaging: An examination of coincident surveys at a steam flood project. In press, Geophysics, 2003.

Gasperikova, E., Hoversten, G., M., Ryan, M., P., Kauahikaua, J., Newman, G., A., Cuevas, N., Magnetotelluric Investigations of Kilauea Volcano, Hawaii. Part I: Experiment Design and Data Processing. J. Geophys. Res. (Submitted July 2003).

Hoversten, G. M., Gasperikova, E., Newman, G., A., Kauahikaua, J., Ryan, M., P., Cuevas, N., Magnetotelluric Investigations of Kilauea volcano, Hawaii. Part II: Numerical Modeling and Data Interpretation. J. Geophys. Res. (Submitted July 2003).

Oldenburg, C.M., and A.J.A. Unger, On leakage and seepage from geologic carbon sequestration sites: unsaturated zone attenuation, Vadose Zone Journal, 2, 287–296, 2003.

Oldenburg, C.M., J.L. Lewicki, and R.P. Hepple, Near-surface monitoring strategies of geologic carbon dioxide storage verification, Lawrence Berkeley National Laboratory Report LBNL-54089, October 2003.

Oldenburg, C.M., and A.J.A. Unger, Coupled subsurface-surface layer gas transport and dispersion for geologic carbon sequestration seepage simulation, Vadose Zone Journal, submitted, 2003.

Presentations Made in FY 2003:

Oldenburg, C.M., and A.J.A. Unger, Transport and dispersion processes for CO2 in the unsaturated zone and surface layer, Second Annual Conference on Carbon Sequestration NETL, Alexandria, VA, May 5–8, 2003.

Van Soest, M.C (Invited lecture) Magmatic Helium in the Three Sisters Area, Central Oregon Cascades. subtitle: Where does it come from, how does it get there, and what does it mean? USGS, Menlo Park, CA., April 2003.

Van Soest, M.C., Evans, W.C., Mariner, R.H., & Schmidt, M.E. Helium and carbon isotope systematics of springs in the Separation Creek drainage system, Three Sisters area, Central Oregon Cascades. AGU 2002 Fall meeting, San Francisco CA, Dec. 6-10 2002.

Van Soest, M.C., Evans, W.C., Mariner, R.H., Kennedy, B.M., & Schmidt, M.E. The Geochemistry of the Geothermal and Hydrologic System of the Separation Creek Drainage, Three Sisters area, Central Oregon Cascades. GSA 2003 annual meeting, Seattle WA, Nov. 2-5 2003.

Planned FY 2004 Milestones:

Project 1:

Complete analyses of existing samples	Jan 04
Present preliminary results at Stanford Workshop	Jan 04
Continue to build on the helium isotope data base	Sep 04

Project 2:

Continue to apply coupled model for a range of case scenarios	Sep 04
Compile data for near-surface CO2 concentrations for statistical analysis of anomalies	Sep 04
Evaluate existing CO2 soil gas detection methods based on case scenario results	Sep 04
Submit manuscript detailing results and recommendations	Sep 04

Project 3:

MT data acquisition at one of two potential additional Basin and Range geothermal sites	Sep 04
Initiate data processing, modeling and imaging	Jul 04
Initiate integration of seismic data interpretation	Jul 04
Submit publication in peer reviewed journal	Sep 04

Origins of Geothermal Fluids Based on Low Abundance Isotopes

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory

Principal Investigator: Gregory Nimz
Phone: (925) 423-2766
E-Mail: nimz1@llnl.gov

Collaborating Researchers: Fraser Goff, Los Alamos National Laboratory
Cathy Janik, U.S. Geological Survey

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@ee.doe.gov

DOE Funding Allocation: $40K

Cost Share Funding: None

Project Objective: Finalize data bases for the chemical and isotopic hydrologic study performed at the Dixie Valley Geothermal Field during previous years, and write a peer-review publication for this study.

Background/Approach: A regional hydrochemical and isotopic study was performed at the Dixie Valley Geothermal Field from FY96 to FY01. The project generated a very large data set which require compilation, quality assurance checking, and integration. The results were very high quality and suitable for publication in one of several peer-review scientific publications. Because of the complexity of the data sets, integrative interpretation required substantial chemical/isotopic modeling and calculation.

Status/Accomplishments: A finalized and standardized data base has been created. A manuscript for peer-review publication has been written (approximately 11,500 characters, 4 tables, 12 figures). The paper is at present being reviewed and revised to a more publication-acceptable length by the collaborating researchers/co-authors.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003: None.

Planned FY 2004 Milestones:

Characterization of 3D Fracture Patterns at the Geysers and Coso Geothermal Reservoirs by Shear-Wave Splitting

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG07-00ID13956

Performing Organization: University of North Carolina at Chapel Hill
Dept of Geological Sciences CB#3315, Mitchell Hall
Chapel Hill, NC 27599

Principal Investigator: J. A. Rial
Phone: (919) 966-4553
E-Mail: jar@email.unc.edu

Collaborating Researchers: G. Vlahovic, M. Elkibbi, M. Yang, A. Gero (UNC-CH),
V. Pereyra, L. Carcione (Weidlinger Associates)

DOE HQ Program Manager: J. Renner, INEEL technical monitor
Phone: (208) 526-9824
E-mail: rennerjl@inel.gov

DOE Funding Allocation: $467K (three years)

Cost Share Funding: N/A

Project Objective: We apply our results from the processing of shear-wave splitting data to thoroughly describe subsurface fracture networks at The Geysers and Coso geothermal reservoirs. The project is aimed at developing a computer-based methodology to produce 3D maps of crack geometry, crack distribution, and crack density in fractured reservoirs. The latter crack parameters are crucial in determining directions of underground fluid flow as well as areas of increased permeability, essential in locating production targets. Due to the records time-span, we are also capable of tracking temporal changes in the general behavior of crack systems.

The raw data for the project consisted of seismographic recordings of microearthquakes (MEQ) detected over many years by arrays of sensors at both The Geysers and Coso. With the experience acquired in the processing and interpretation of these data in past years, we developed a novel computer-based technology for the exploration of fractured reservoirs, which consists of the following software packages (three modules written in Matlab-compatible language):

(1) Module one: Data processing package.
(2) Module two: Forward modeling package.
(3) Module three: Inverse modeling package.

Background/Approach: A shear-wave propagating through rocks with crack-induced anisotropy splits into two waves, a fast one polarized parallel to the predominant crack orientation, and a slow one polarized perpendicular to it. For waves traveling within the shear-wave window of a given seismic station, the measured polarization direction ϕ of the fast shear wave typically parallels the strike of the predominant subsurface crack system regardless of its initial polarization at the source. Exceptions, however, have been discerned and carefully studied in the case of dipping cracks or when more than one crack system is involved. The delay time δt between the arrival of the fast and the slow S-waves is proportional to the crack density, or number of cracks per unit volume.

The analysis of split shear waves is thus a valuable technique to detect and map the main orientation and fracturing intensity in the subsurface. When fully developed as a computer application, this approach has the potential of becoming a highly desirable technical and industrial resource to advance the exploration of fracture-controlled geothermal, hydrocarbon, and water reservoirs. For the last few years we have studied and processed shear-wave splitting data in two seismically active, fracture-controlled environments, The Geysers (NW and SE Geysers) and Coso geothermal fields, California, using 16- and 14-station seismic arrays of 3-component, mostly down-hole instruments running at frequencies ranging from 400 to 480 samples/sec. From the analysis and processing of over 60,000 local micro-earthquakes, we have to date collected what is arguably the world's most complete set of high resolution, high quality shear-wave splitting observations.

Status/Accomplishments: Based on shear-wave splitting analysis results, we have successfully tested the possibility of using a large dataset of observed polarizations of the fast wave (ϕ) and delay times between the fast and slow waves (δt) to invert for subsurface fracture geometry and density in The Geysers geothermal reservoir. Essentially, our inversion efforts have identified regions of different crack densities in The Geysers field and imaged in 3D the fracture geometry in the subsurface. We have also explored in detail, through inversion experiments, problems related to ray azimuthal coverage, non-uniqueness of crack-induced anisotropy models, and complementarity between polarization and delay time data.

Additionally, we have developed an automatic interactive inversion scheme, which inverts simultaneously for crack strike, dip, and density (Figure 1a-b,Yang, 2003). Multiple, intersecting crack systems can also be modeled (e.g., Elkibbi et al., 2003).

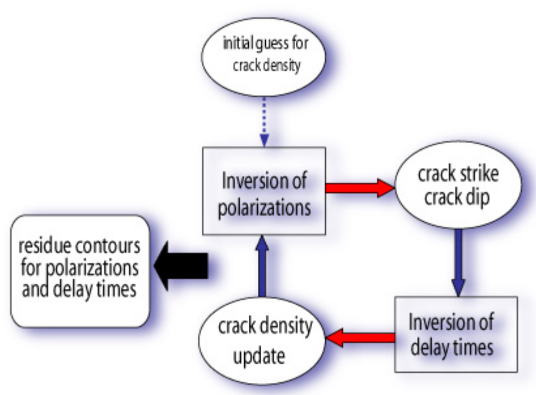


Figure 1a. Flow chart of the interactive inversion scheme to obtain crack geometry and crack density in the subsurface. The residue contour functions depict the absolute minima in polarization and delay time residue in the space of models described by strike and dip (see Fig.1b).

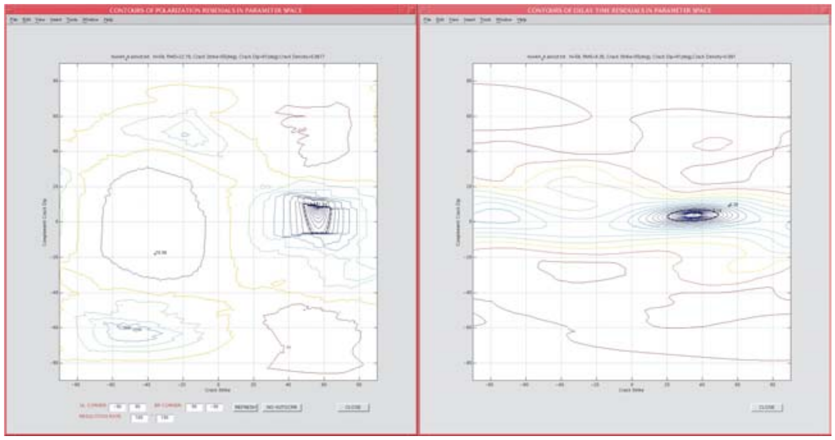


Figure 1b. Result of inversion for seismic station S4 in NW Geysers. The polarization (left) and the delay time (right) residual functions (RMS of observed-calculated) are plotted as contour maps on the model space of crack strike and dip. In this example absolute minima closely correspond to the same model. The horizontal axis is strike and the vertical the dip complement in both plots. The dashed contours around the minima mark the 95% confidence level in each case. Interactive search for the best solution is performed for each station. These residue maps are examples of those indicated to the left of the flow chart in Fig.1a (from Yang, 2003).

Based on seismic ray coverage and depending on the spatial patterns and azimuthal distributions of observed polarizations and delay times in equal-area projection plots, we modeled crack-induced anisotropy by a) a single system of vertical cracks, b) a single system of non-vertically dipping cracks, or c) two intersecting sets of vertically and/or non-vertically dipping cracks.

In The Geysers, inversion results indicate that the majority of observed ϕ and δt parameters agree with models of transverse isotropy that represent vertical to steeply dipping fractures striking generally parallel to the NNE direction of maximum compressive stress in the region. The recording of two main polarization directions by the same station is an example of deviation from horizontal transverse isotropy conditions (i.e., parallel vertical fracture systems). Inversion of ϕ and δt parameters indicate that, depending on their azimuthal distribution, these observations can be modeled by a single system of non-vertically dipping fractures (e.g., station S6 in SE Geysers) or by biplanar intersecting fracture systems (e.g., station S2 in NW Geysers). Figure 2 summarizes all station-by-station inversion results for subsurface crack geometry and crack density in NW and SE Geysers. The percentages of shear-wave velocity anisotropy (SWA), modeled for all stations in NW and SE Geysers, average about 3.8% and are consistent with values of SWA in the Earth's crust ranging typically between 1% and 5%. Shear-wave velocity anisotropy is defined as:

$$SWA = \{\frac{\max(V_{sf}) - \min(V_{ss})}{\max(V_{sf})}\} \times 100 \;\; ;$$

where V_{sf} and V_{ss} are respectively the fast and the slow split shear-wave velocities (Crampin 1989; Crampin 1994). Higher values of SWA percentages occur in The Geysers and should be expected in this area of rather high heat flow (Walters 1996; Crampin & Zatsepin 1995). Based on modeling results from station S2 in NW Geysers, which show a significantly larger than average SWA=6.8%, we were able to delineate a volume of increased crack density and rock permeability in the immediate vicinity of a fault zone, which may be of interest to geothermal production.

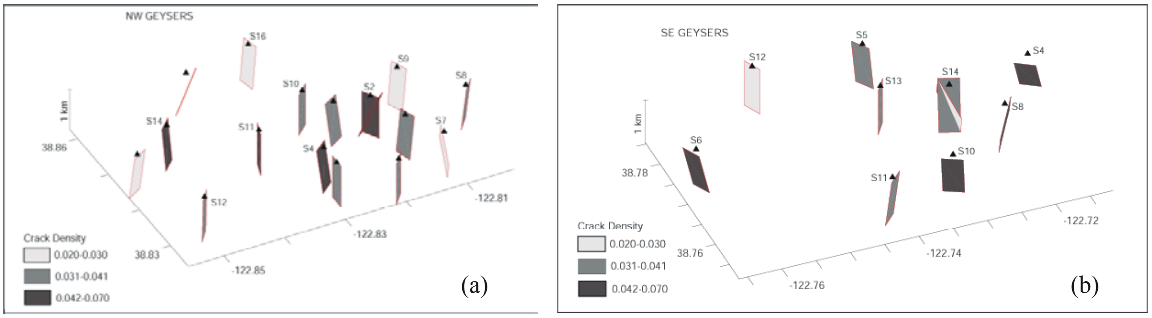


Figure 2. Summary of shear-wave splitting inversion results: 3D representation of subsurface crack geometry and crack density in (a) NW Geysers and (b) SE Geysers, for stations with a minimum of 20 events recorded. Crack models are represented by oriented rectangles showing the strike and dip of crack and microcrack systems in the neighborhood of each seismic station down to a depth of 1000-1250m. Different crack shades denote different crack densities. Black triangles are seismic stations (from ElKibbi et al., 2003).

Reports & Articles Published in FY 2003:

ElKibbi, M. and Rial, J. A. (2004). The Geysers geothermal field I: Results from shear-wave splitting analysis in a fractured reservoir. Geophysical Journal International, (in review).

ElKibbi, M., Yang, M., and Rial, J.A. (2004). The Geysers geothermal field II: modeling crack-induced anisotropy in the subsurface. Geophysical Journal International, (in review).

ElKibbi, M., and Rial, J.A. (2003). Shear-wave Splitting: an Efficient Tool to Detect and Simulate 3D Fracture Patterns at The Geysers, California. Proceedings, 28th Stanford Workshop on Geothermal Reservoir Engineering 2003, p.143-149, Stanford University, Stanford, CA. (27-29 January 2003).

Yang, M., ElKibbi, M., and Rial, J.A. (2003). Modeling of 3D Crack Attributes and Crack Densities in Geothermal Reservoirs. Proceedings 28th Stanford Workshop on Geothermal Reservoir Engineering 2003, p. 321-327, Stanford University, Stanford, CA. (27-329 January 2003).

Presentations Made in FY 2003:

"Modeling of 3D Crack Attributes and Crack Densities in Geothermal Reservoirs". Twenty-eighth Stanford Workshop on Geothermal Reservoir Engineering, January 2003, Stanford, CA.

"Shear-wave Splitting: an Efficient Tool to Detect and Simulate 3D Fracture Patterns at The Geysers, California". 28th Stanford Workshop on Geothermal Reservoir Engineering, January 2003, Stanford, CA.

"Characterization of Fracture Patterns in The Geysers Geothermal Reservoir by Shear-wave Splitting". U.S. Department of Energy (DOE) Peer Reviewed Presentation, July 2003, Golden, Colorado.

Planned FY 2004 Milestones:

Submission of DOE Proposal for the development of a real-time methodology to detect subsurface fractures in Engineered Geothermal Systems.

The main objective of this project can be summarized as the development of a methodology to detect, in real-time, the geometry, intensity, size and time evolution of pre-existing and stimulated subsurface fractures in engineered geothermal systems (EGS). To test and validate the methods the project will make extensive use of available data from natural and injection-induced microearthquake activity. We shall use a full inversion of shear-wave splitting data just developed by our group with DOE funding to detect the 3D geometry and density of cracks and develop new and effective methods of analyzing and extracting relevant information from seismograms. Specifically, efforts will be directed towards the interpretation of frequency-dependent shear-wave splitting (FDS), dispersive properties of the split waves and the analyses of multiple splitting, caused by more than one crack systems along the ray between source and receiver. In addition, P and S wave attenuation will be used to identify areas of anomalous temperatures. The database includes several years of continuously recorded seismicity from The Geysers and Coso augmented with data obtained from newly deployed dense seismic arrays in The Geysers, that includes data recorded at 500sps, ideal for the study of SWS and FDS. It is also expected that the proposed research will use data from a massive hydrofracturing experiment to be conducted in the eastern flank of the Coso reservoir during the project's lifetime.

References:

Crampin, S., 1989. Suggestions for a consistent terminology for seismic anisotropy, Geophys. Prosp., 37, 753.

Crampin, S., 1994. The fracture criticality of crustal rocks, Geophys. J. Int., 118, 428-438.

Crampin, S. & Zatsepin, S.V., 1995. A new understanding of shear-wave splitting, in EAGE 57th Conference and Technical Exhibition abstract, Glasgow, Scotland, 29 May-2 June.

ElKibbi, M., Yang, M., and Rial, J.A. (2003). The Geysers geothermal field II: modeling crack-induced anisotropy in the subsurface. Geophysical Journal International, (in review).

Walters, M.A., 1996. Field data and references for a northeast-trending extensional zone, The Geysers-Clear Lake region, California. Unpublished report submitted to Lockheed Idaho Technologies Company, pp. 12.

Yang, M., 2003. Inversion of shear-wave splitting data in geothermal reservoirs, Masters thesis, University of North Carolina, Chapel Hill, NC.

III. DRILLING RESEARCH

High-Temperature Electronics

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:	DE-AC04-94AL85000
Performing Organization:	Sandia National Laboratories Geothermal Research Department MS 1033, P.O. Box 5800 Albuquerque, NM 87185-1033
Principal Investigator:	Randy Normann
Phone:	(505) 845-9675
E-Mail:	ranorma@sandia.gov
Collaborating Researchers:	Joe Henfling & David Chavira - SNL
DOE HQ Program Manager:	Raymond LaSala
Phone:	(202) 586-4198
E-mail:	Raymond.LaSala@ee.doe.gov

DOE Funding Allocation:	$770K
Cost Share Funding:	$200K

Project Objective: Develop and evaluate new HT components such as microprocessors, passive devices, and batteries, and assist the industry in the development of a new PTS tools, a gamma tool, and a flow tool for geothermal well logging.

Background/Approach: The high-temperature electronics project is totally dependent on research funded by other government organizations for new high-temperature components and materials. We farm the NASA, NETL, DARPA and DOD programs offering researchers the opportunity to demonstrate new component developments within the geothermal environment. There were two fundamental tasks in 2003.

Task 1. Component Development and Evaluation

Sandia worked with a large number of companies to evaluate components needed to produce geothermal logging and drilling tools. Most of the companies used their own funding to work with Sandia. For high-temperature batteries we worked with Eagle Picher Technologies, for capacitors we worked with Johanson Dielectrics, Anderson Inc. for hydrogen getters, Solid State Devices for power electronics and Photosonic for a new PTS tool. Sandia shares its information with the service industry to help jump start the industry to building tools needed by a growing geothermal industry.

Task 2. High-Temperature Standards and Key Component Development

A standard is needed to better organize high-temperature research across the various industries. By taking the lead in creating a high-temperature electronics standard, Sandia is insuring that geothermal issues are given representation.

Status/Accomplishments: Delivered HT83SNL00 demonstrators to service companies: Sandia delivered two more HT83SNL00 high-temperature chip set demonstrators to Well Technologies (Smart well instrumentation) and Rockwell International Control Systems (225°C motor control). The HT83SNL00 chip set can operate up to 300°C. This is a 150% improvement over existing technology.

Conducted a successful joint demonstration test with Photosonic new PTS tool: Photosonic has built a 250°C PTS tool based on the Sandia HT83SNL00 chip set.

Field test thermal batteries: A great deal of effort was placed on creating a thermal battery in 2003. Two chemistries were laboratory tested and field tested with Sandia's SOI (Silicon-on-Insulator) however, one chemistry failed to operate when assembled into the tool and the second chemistries operated for a several hours before shorting out. The good news is that battery development is being moved from Sandia to private industry. Eagle-Picher Technologies has proposed to fund an internal development program with aid from Sandia.

Completed a high-temperature electronics standard called HT2L (High-Temperature Long-Life Standard): Sandia conducted two industry reviews of the high-temperature component standard. The first meeting was with future customers such as Welaco (geothermal service company), Boeing (aerospace), Baker Hughes (oil patch service company), USGS, E-Spectrum (small tool developer) and others. The second was an international review conducted at the European high-temperature electronics conference. Finally, the HT2L standard was been given to a number of major component manufacturers such as Motorola, International Rectifier, Kemet, Honeywell and other smaller companies. This is a voluntary standard asking component manufacturers to meet a standardized method to document their components operating life at a specific set of elevated temperatures.

Evaluated Entran's 300°C pressure sensor: Sandia has found the drift rate to be too high for most geothermal application. Kulyte is designing a solid-state 300°C pressure sensor for 2004.

Evaluated Saint-Gobain gamma detectors: Sandia unfortunately uncovered that the advertised 250°C gamma detectors didn't exist. Saint-Gobain has reduced their specification to 200°C.

Assisted the National Energy Technology Laboratory (NETL) deep trek program: Sandia aided NETL's Deep Trek project in starting an industry joint partnership for the creation of high-temperature SOI electronics.

Reports & Articles Published in FY 2003:

R. A. Normann, "Proposed High Temperature, Long-Life (HT2L) Industry Specification", July 2003 High-Temperature European Network Conference, publication out to press.

R. A. Guidotti, R. A. Normann, F. W. Reinhardt and J. Odinek; "Development of High-Temperature Batteries for Use in Geothermal and Oil/Gas Boreholes", GRC, Oct 12-15, 2003, vol. 27, pg 173-176,

Presentations Made in FY 2003:

"Sandia High-Temperature Electronics Efforts in Support of the Geothermal Industry", R. A. Normann; NASA/JPL 2003 workshop on Electronics for Extreme Environments.

"Proposed High Temperature, Long-Life (HT2L) Industry Specification", R. A. Normann; presented at the July 2003 High-Temperature European Network Conference.

"Development of High-Temperature Batteries for Use in Geothermal and Oil/Gas Boreholes", R. A. Normann presented at the Oct 2003 GRC

Planned FY 2004 Milestones:

Kulyte 300°C pressure sensor testing	Dec 03
Define the EPI program to support Sandia's tool development	Dec 03
Test Actel's Rad-Hard FPGA	Jan 04
Build HT tools with wired tubing for continuous monitoring	Apr 04
Cissiod SOI voltage reference	May 04
Conduct geothermal/aerospace industry workshop at HiTEC	May 04
Report on capacitor and SiC PC board testing	May 04
Deploy long term demonstration tool with fiber optic sensors	Jun 04
Write a commercial plan for ROM programming with E-Spectrum	Jun 04
Conduct 300°C tool test with Welaco and Baker Hughes	Jul 04
Test EPI prototypes	Aug 04

Wellbore Integrity and Lost Circulation

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: S. J. Bauer
Phone: (505) 844-9116
E-Mail: sjbauer@sandia.gov

Collaborating Researchers: None

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $728K

Cost Share Funding: $200K including both "in-kind" or direct funding.

Project Objective: This status sheet combines Advanced Wellbore Integrity Technologies and Polyurethane Grouting.

Reduce lost circulation costs by 30% and the cost of drilling a typical geothermal well by 5% by promoting best-available wellbore integrity systems that integrate lost circulation mitigation, drilling on to the next casing point, and cementing in the next casing. To meet Geothermal Program Goals of increasing the states producing electric power from geothermal energy, reducing the cost of generating geothermal power, and increasing the use of geothermal energy, it will be necessary to reduce geothermal drilling costs. Because drilling costs occur early in the life cycle of a geothermal project, high drilling costs are a significant barrier to geothermal development. Reduction of trouble cost is the most effective way to reduce geothermal drilling costs. The Advanced Wellbore Integrity Technologies task focuses on avoiding/mitigating wellbore integrity problems.

The task focuses on, given that severe lost circulation/cross flow is expected or encountered, what should be done to get the next casing string properly cemented in place at the least cost. While a technology specifically for lost-circulation control, e.g. polyurethane grouting, may be the only sure way of stopping severe cross flows, to minimize overall drilling costs, there is a need to take a broad system perspective considering how lost circulation impacts cementing, casing, well design, etc. The ultimate goal isn't lost-circulation control; it is maintaining wellbore integrity. That is, preparing the wellbore so that the next casing string can be cemented in properly. To reach this goal one should both use the best currently available technology and seek new revolutionary technologies. The tasks have been chosen to provide the driller with a "complete" and adequate set of technologies with multiple options to mitigate lost-circulation and cross-flow problems. One of the focused efforts in this task this year was improving polyurethane grout formulations. These studies initially focused upon evaluating the mechanical and chemical integrity of "off the shelf " polyurethane grouts when subjected to elevated temperatures in the presence of water. While cement grouting of casings will continue to be a requirement, cement plugs have proven inadequate to stop lost circulation and cross flows. New reactive plug technologies are needed. Rigid polyurethane was chosen for development as the first reactive plug because of favorable properties including it is relatively immiscible in water, it has a fast cure time, it is viscous, its density is close to that of water, etc. These properties have made rigid polyurethane the material of choice in civil engineering for sealing boreholes and dams with large voids and high inflows, conditions associated with the worst lost circulation problems.

Background/Approach: New wellbore integrity technologies are needed to facilitate change in the ineffective standard practice of fixing each lost-circulation zone as it is encountered. Drilling should be focused, not on lost-circulation control, but on the bigger question, "How do we get the next casing string cemented in with minimal lost time and low additional cost?" To facilitate growth of this new paradigm, the task is focused on the following technologies:

- Advanced methods for plugging lost circulation/cross-flow zones (e.g. polyurethane grout, twin-streaming sodium silicate and cement, and InstanSeal™)
- Adequate options for drilling ahead to the next casing point (dual-tube reverse-circulation drilling)
- Methods for reestablishing wellbore integrity after drilling ahead (e.g. fill and re-drill, wellbore lining, etc.)
- Alternative methods for primary cement placement (reverse-circulation and tremmie pipe cementing).

The first of these technologies was addressed by research which included developing emplacement systems for and determining the temperature limits of reactive plugs for cross flow. As background, lost circulation occurs when formation-fluid pressure is less than the fluid column pressure in the wellbore, so that some or all of the drilling fluid escapes into the formation instead of recirculating back up the well annulus. Lost circulation is particularly difficult to plug when it includes cross flow. Cross flow occurs when the wellbore encounters permeable zones whose pore pressures are not hydrostatically balanced. Lost circulation is often accompanied by further loss of wellbore integrity including sloughing, caving, washing out, or bridging. These phenomena are persistent in geothermal drilling, are very expensive – often accounting for 10-20% of the total cost for drilling a typical geothermal well – and cause many additional drilling problems such as stuck drill pipe, damaged bits, slow drilling rates, and collapsed boreholes. Most of the work to date has focused on polyurethane grout, a preferred reactive plug, based on its material properties and successful deployment at Rye Patch. The primary focus has been establishing the temperature limits of polyurethane grout to determine its suitability for setting a plug in a depleted reservoir. Once emplaced, the grout must be able to survive for up to 60 days (time to drill ahead and cement the next casing). Thermally driven hydrolysis of polyurethane grouts was discovered and investigated to determine potential degradation of index material properties as a function of time and temperature.

Work on the second, drill ahead, and third technology, reestablishing wellbore integrity, is currently limited to problem definition and scoping of future work. All four tasks are listed here to emphasize that the wellbore integrity approach was established by a systematic study of what is needed to provide the driller with a comprehensive set of wellbore integrity tools. Of course, this approach is predicated upon using standard drilling and cementing procedures properly (mud program, lost-circulation materials, bridging agents, cement plugs, etc.).

Making appropriate and timely decisions is key to drilling, i.e. when to fish and when to kick off. Decisions are based on experience, expected economic outcomes, and risk management. New technologies will have no impact until they can be incorporated into the decision making process. While this cannot be done until they have been tried and proven in the field, it is useful to examine how the new technologies discussed above may be applied.

Suppose proper use of standard drilling, mud program, and lost-circulation materials or bridging agents procedures have been applied and yet there is total loss of returns. Then a cautious use of the new technologies described above can be depicted. If there is cross flow and it is not plugged off, then subsequently applied cement will be washed away. Thus, the conservative action is to stop and plug the cross flow. If there is no cross flow, there are options for drilling ahead. If one drills ahead and problems only get worse to the point where it is unlikely the primary cement job will be successful - cross flow back up hole is detected at a later time - then restoring wellbore integrity is required (fill and re-drill). If one drills ahead and restoring wellbore integrity is not required, there are three primary cement job options: 1) conventional cementing (unlikely to work based on past experience that has driven the industry to plug each zone as it is encountered), 2) tremmie pipe (if there is adequate space in the annulus), and 3) reverse circulation.

Status/Accomplishments: Prior to embarking on developing polyurethane grouting for lost-circulation control, Sandia conducted a study and found no alternative materials with the advantages of polyurethane. As part of developing a comprehensive wellbore integrity program, another review of best-available lost-circulation control technologies was done. This review identified a new class of lost-circulation control materials: reactive pills. A Schlumberger product, InstanSEAL™ may provide many of the features desired in a advanced material for plugging cross flow (i.e. it may be an alternative to polyurethane grout that is already commercialized).

After the successful plugging of the cross-flow zone at Rye Patch, system studies were performed which led to the expansion of the project from plugging lost-circulation zones to Wellbore Integrity. One of the questions raised was “Why can’t the principles applied in the polyurethane grouting, in particular, fast setting before cross flow washes away the material, be applied to cement grouting.”

This question was discussed with industry experts including Halliburton, BJ Services, Dowell, Cementing Solutions, and Carter Technologies. The consensus was it might be possible using cement and sodium silicate. The reputation of sodium silicate in geothermal drilling is “tried it, doesn’t work.” That, however, is for batch jobs – pumping sodium silicate first then chasing it with cement. Laboratory tests were performed that demonstrate that for geothermal rocks the openings are too large for sodium silicate clinging to the walls to gel the subsequent cement. Thus, twin streaming will be needed in geothermal applications. In twin streaming, cement and sodium silicate are pumped at the same time through separate channels and then mixed downhole. The mixture can be designed to gel in seconds to minutes minimizing its potential to be washed away. Over time, sodium silicate and cement set up like normal cement.

Tremmie pipes (an alternate primary cement placement technique) allow cement to be placed into a formation that will not support the pressures encountered during a standard primary cement job. This method is more effective than a top-job performed by pouring cement down the annulus. Tremmie cementing is not new to geothermal drilling as a remedial process, but it has not been "the plan" using procedures perfected in minerals drilling. The concept of using a mobile minerals rig designed to handle large diameter pipe to set the surface casing followed by a smaller pipe-diameter deep rig was demonstrated cost effective at Soda Lake. This demonstration included both dual-tube reverse-circulation drilling and tremmie pipe cementing. Drilling the surface casing hole at Soda Lake was trouble free, but had severe lost circulation been encountered, the use of the dual-tube flooded reverse-circulation rig would have allowed drilling to continue without the usual cost increases of severe lost circulation.

During the system studies conducted in follow-up to plugging the cross-flow zone at Rye Patch, Halliburton recommended reverse-circulation cementing as an alternative primary cement placement technology. The concept of reverse-circulation cementing is not new; however, in the last few years new supporting technologies, such as downhole monitoring of the cement progress, has made the control of this process reliable. Halliburton has completed over twenty of these jobs in the last few years in wells that have defied other approaches to cementing. However, they have not been well publicized and thus have not been considered in geothermal cementing. This technology nicely complements Sandia's recommendation, because at the time the decision is made to drill ahead, it gives the drilling engineer another option. The success of the field program highlights this research in that a successful deployment of polyurethane grout demonstrated the in situ valid application of an advanced reactive plug as a grout material in geothermal environment.

The development of high temperature polyurethane formulations has not progressed as rapidly as hoped. Prior to Rye Patch, laboratory testing was done by baking samples in an oven, measuring compressive strength at ambient and elevated temperature, and measuring permeability at ambient temperature. A plug test was performed at 200°F and 500 psi differential pressure – comparable to in situ conditions at Rye Patch. After a week, during which leakage through the polyurethane plug was negligible, the temperature was increased to 300°F and the plug leaked excessively. Based on the results obtained in oven tests, it was assumed that changing to higher temperature polyurethane formulations would allow application temperatures in excess of 300°F. Subsequent testing demonstrated that combining temperature, pressure, and water introduces a new failure mechanism: hydrolysis, or reversing of the polymerization reaction. So far, results of subsequent testing have not been intuitive. The one-part formulation has the best stability and appears usable up to about 200°F to 250°F. The exact temperature depends upon how long the plug needs to last.

During the course of the laboratory program, the hydrolysis behavior of approximately 75 polyurethane grout samples up to 350°F was evaluated. Testing was completed at Sandia National Laboratories (SNL) and Adherent Technologies, Inc. (ATI) and polyurethane samples were subjected to hydrolysis under elevated temperature and pressure conditions as described below. Samples were then analyzed to investigate their retention of properties at the hydrolysis temperature over a period of several days. Thermo-mechanical analyses (TMA) were primarily employed; these experiments yielded softening temperatures for the materials. Gas chromatography/mass spectrometry (GCMS) was also conducted on the residual water in the sample tubes to identify hydrolysis products that might possibly be of environmental concern.

Reports & Articles Published in FY 2003:

Polyurethane Grout Hydrolysis Summary of 275°F Experiments, A. F. Hoyt, Adherent Technologies, Inc., August 2003.

Improving Lightweight Cement Evaluation in the Geothermal Environment; G. Batchellor, GWB Consultants, September 2003.

Methods of Cementing Lost Circulation Zones In Geothermal Wells, Carter, E. Carter Technologies Co., September 2003.

Improved Grout Systems for Geothermal Well Applications, D. Galbreath, Green Mountain International, Inc., September 2003.

Presentations Made in FY 2003:

From Plugging Lost-Circulation Cross-Flow Zones to Wellbore Integrity, A. Mansure and J. Westmoreland, Geothermal Resource Council, Morelia, Mexico, October 12-15

Planned FY 2004 Milestones:

Final Report on polyurethane as a cross flow plug material	Feb 04
Report on Sodium Silicate grout potential in geothermal environment	Aug 04

Hard-Rock Drill Bit Technology

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigators: Jack L. Wise and David W. Raymond
Phone: (505) 844-6359/(505) 844-8026
E-Mail: jlwise@sandia.gov; dwraymo@sandia.gov

Collaborating Researchers: Pat Gronewald & Jim Grossman – SNL

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $1,638K

Cost Share Funding: Task 1 – $92K; Task 3 – $310K; Task 4 – $9K

Project Objective: This multi-year project aims to significantly expand the range of applications for drag bits to include the hard, hot, abrasive, and fractured rock formations that are predominant at geothermal energy production sites. Specifically, an estimated reduction of 15% in overall geothermal well costs is being sought via a doubling of both bit life and penetration rate relative to conventional capabilities. Such an improvement in economy promises a substantial increase in viably exploitable geothermal resources. The combined benefits of the anticipated decrease in drilling cost and increase in resource availability are fully consistent with the goals of the DOE Geothermal Energy Program, namely: (1) supplying electrical power and/or heat to more U. S. homes and businesses, (2) reducing the generation cost of geothermal power, and (3) increasing the number of States with geothermal electric power facilities. The FY03 effort built upon prior-year work by means of continuing technical activities to accomplish the specific objectives noted below for four distinct, but interrelated, tasks:

Task 1. PDC (Polycrystalline Diamond Compact) Cutter Development and Testing: Create a database that identifies optimal cutter configurations for hard rock by showing the influence of design parameters on wear and durability. Generate and validate new cutter materials and designs for geothermal drilling.

Task 2. Self-Induced Bit Vibrations: Develop and demonstrate a prototype in-the-hole controllable damper for enforcing drill string stability in Sandia's Hard-Rock Drilling Facility (HRDF) and continue to refine the understanding of factors contributing to chatter in PDC bits.

Task 3. PDC Bit Development and Testing: Demonstrate the hard-rock drilling capabilities of state-of-the-art drag bits developed under the Sandia/industry CRADA established in FY02 to promote drag-bit use by the geothermal drilling community.

Task 4. Mudjet-Augmented PDC Bit: Conduct tests to characterize the nozzle/cutter/rock interaction process and guide the design of a second-generation mudjet-augmented PDC bit. Develop and validate alternate processes to fabricate diamond-coated orifices for passively pulsating/cavitating nozzles.

Background/Approach: Since the introduction of PDC cutters and bits in the 1970s, Sandia has worked with industry to extend this technology to drilling in harder (e.g., geothermal) formations by (i) identifying and correcting design and operational problems, and (ii) conducting field validation studies. Sandia's in-house test venues include the HRDF and the Linear Cutter Test Facility (LCTF). These resources are supplemented, as needed, by outside laboratory and field-test facilities. The Sandia-developed PDCWEAR code computationally simulates bit performance and wear, supporting the generation of new bit designs. Active industry and/or university participation in each task contributes additional expertise and capabilities while maintaining program focus on commercial needs and interests. Additional background and the approach for tasks within this technology area are described below:

Task 1. Geometry, material composition, and processing conditions jointly dictate the performance of PDC and TSP (Thermally Stable Polycrystalline diamond) cutters. On a cost-sharing basis, Sandia is individually partnering with U S Synthetic Corporation (USS), Dennis Tool Company (DTC), and Technology International, Inc. (TII) to evaluate the hard-rock performance of numerous cutter designs.

Sandia and USS are conducting fundamental parameter studies that involve the joint specification, production, and testing of nonstandard, nonproprietary cutter lots prepared with a wide range of features and pressing loads. Cutters are manufactured by USS, and then tested by both Sandia and USS using their complementary laboratory facilities to measure drop-impact damage and granite-log abrasion resistance at USS, and linear cutting forces and rotary drilling performance in Sierra White Granite at Sandia. Data acquired from the prescribed test protocols are being analyzed and publicly documented to identify design features contributing to improved cutter performance in hard rock.

Many commercial bits use PDC cutters with grooved, nonplanar interfaces between the diamond table and supporting tungsten-carbide substrate. The resultant "claws" of thicker diamond facilitate conduction of heat away from the cutting edge, reducing thermally accelerated wear. To identify optimal configurations, Sandia is conducting HRDF tests on cutters supplied by DTC with different claw interfaces.

The fracture toughness of TSP cutters is typically diminished relative to standard PDC products by the removal of cobalt binder to improve thermal stability. Testing on Sandia's HRDF is being done to validate the mechanical competence of TSP cutters that have been processed with new proprietary toughness-enhancing treatments under development by TII.

Task 2. PDC bits perform well in the laboratory in hard rock and have abrasion resistance that is competitive with rollercone bits traditionally used for geothermal drilling. Field experience, however, indicates that impact damage is the primary failure mode when PDC bits are used in hard rock. Some drill string dynamic dysfunctions (e.g., bit bounce and torsional vibrations) are thought to be the primary mechanisms contributing to impact-type failures. Many of these vibrations are self-induced. This type of vibration, or "chatter," occurs in drill strings equipped with PDC bits due to the interaction between the forces on the bit at the cutter/rock interface and the dynamic response of the drill string.

Our approach to characterize the parameters contributing to instability consists of a combination of testing and computational modeling. Testing consists of HRDF drilling experiments using instrumented fixtures that allow chatter to occur in the laboratory where it can be studied and characterized in a well-understood and controlled environment. Models that include the rock/bit interaction, bit/drill string design, and rock properties can then be developed and applied to field drilling configurations. This combination of testing and model development allows theories to be validated and refined. It also provides guidance for the development and subsequent evaluation of external controls to eliminate chatter.

One concept for enforcing drill string stability is a controllable damper that can be installed just above the bit in the bottomhole assembly (BHA). FY03 work focused on developing a prototype device with a magneto-rheological fluid that can be autonomously controlled during HRDF evaluation tests.

Task 3. Sandia and four bit manufacturers (ReedHycalog/Grant Prideco, Security DBS/Halliburton, Smith Bits – GeoDiamond, and Technology International, Inc.) are collaborating under a single-laboratory/multi-partner Cooperative Research and Development Agreement (CRADA) to produce and demonstrate drag bits for hard-rock applications. The highly instrumented drilling conducted under this task simultaneously accomplishes (1) a demonstration of baseline and state-of-the-art drag bits, and (2) a proof-of-concept test for Sandia's Diagnostics-While-Drilling (DWD) system.

Drilling for the CRADA is being carried out in three successive phases at the GTI Catoosa Test Facility, which features a well-characterized lithology with significant hard-rock intervals. Phases 1 and 2 involve the generation of baseline hard-rock drilling data for a conventional, widely known drag-bit design that is run, respectively, without (Phase 1) and with (Phase 2) surface and downhole data feedback to the driller from the DWD system. For Phase 3, each industry partner fabricates its own proprietary "best effort" bit, and then sends that bit along with an engineering team to Catoosa for a field demonstration in conjunction with Sandia. Each industry team monitors and applies real-time DWD data to control the operation of its bit. Each Phase 3 bit demonstration is performed using the same lithologic interval and BHA as the drilling done in Phases 1 and 2. Upon completion of its demonstration, each CRADA partner receives complete test documentation for its respective bit, including ROP (Rate of Penetration) and damage assessments as well as proprietary dynamic surface and downhole data.

Task 4. The hydraulic horsepower on a conventional drill rig is significantly greater than that delivered to the rock through bit rotation. This power can be effectively applied by using hydraulic designs that induce cavitation at the rock surface. Cavitation leads to better bit performance by improving hole cleaning at the bit/rock interface, by weakening or direct erosion of the rock, or by a combination of these effects. A nozzle that produces flow disruptions can generate cavitation. In this project, pulsations are produced by acoustic reflections at the entrance to an "organ pipe" internal to the nozzle waterway. The pulsations produce a structured cavitating flow regime at the nozzle exit that collapses against the rock, spawning high-velocity microjets. Very high impact pressures result from jet impingement against the rock surface.

Using cavitating jets with PDC bits can reduce cutting forces on drag cutters in hard rock to allow PDC bit use in formations characteristic of geothermal reservoirs. A bit that combines cavitating jets and PDC cutters yield performance improvements by two synergistic mechanisms wherein (i) high-pressure drilling fluid enters rock fractures and hydraulically pre-weakens the formation, and (ii) the high velocity jets blast away fine rock flour to increase the penetrating stress between the PDC cutters and the rock.

To exploit advantages offered by the incorporation of cavitating jets in fixed cutter bits, work in FY03 focused upon development of alternative processes to produce the cavitation-resistant orifices and characterization of the force reductions afforded by various nozzle/cutter configurations.

Status/Accomplishments: A summary of the accomplishments for each task appears below:

Task 1. During FY03, six additional lots of PDC cutters were designed and manufactured for the next round of the fundamental parameter study with USS.

For the claw-cutter studies, HRDF testing was completed on eight different claw-cutter designs that spanned the expected ranges of practical diamond-table thickness, claw thickness and width, and intervening substrate groove width. HRDF tests were also completed for (i) a ninth claw configuration with nominal, mid-range values for the noted parameters, and (ii) two baseline cutter sets that had planar interfaces and, respectively, thick and thin diamond tables. Testing showed that designs with a wide, deep claw element centered on the cutting edge perform best since an effectively thicker diamond table contacts the rock. HRDF testing was completed on several TSP cutters that were prepared using proprietary TII treatments to increase fracture toughness. Although the treated TSP samples developed cracks during drilling, the HRDF tests showed that fracture propagation was limited to shallow depths.

Also in FY03, an investigation started several years ago with partial funding support from DOE/Sandia was completed at New Mexico Institute of Mining and Technology. This work examined an alternate ultra hard cutter material, namely boron suboxide, which would offer nearly comparable hardness and improved temperature stability relative to PDC cutters. Problems, and possible solutions, were identified for increasing the fracture toughness of porous boron suboxide via metal infiltration.

Task 2. Our drilling tests in the Hard-Rock Drilling Facility have demonstrated that impact damage due to chatter is clearly one of the primary reasons why PDC cutters fail in hard rock. With these tests, we have shown that the severity of chatter can be reduced in a given rock/bit/drill string configuration with appropriate controls. Using computational modeling, we have predicted the requirements for an in-line damper based upon the dynamic properties of the drill string. We have developed a prototype controllable damper using magneto-rheological fluid technology. Laboratory investigations using this device will continue in the Hard-Rock Drilling Facility into FY04. We are currently developing concepts for advanced simulation facilities to prove these technology developments for eventual field-testing. We have developed an improved cutter force prediction model that can be used to predict the limits of stability for arbitrary bit cutting structures used in the field. This improved model will be used to determine the external controls necessary to enforce stability.

Task 3. Drilling tests were completed for all three phases of the drag-bit CRADA. Phase 1 and 2 results for the baseline drag bit showed a strong inverse correlation between rock strength and ROP, underscoring the need for improved bit designs and materials for hard-rock applications. The DWD-based control during Phase 2 yielded a bit run of 525 ft, which was 36% greater than Phase 1. Three of the four "best effort" drag bits demonstrated in Phase 3 significantly exceeded the baseline results for ROP and bit life.

Task 4. Cavitation-resistant orifices developed in an earlier stage of this project use tungsten-carbide supported polycrystalline diamond. The only disadvantage of this approach is the high cost of machining the orifice throat in the polycrystalline diamond. As a cost-reduction measure, Sandia and US Synthetic conducted research to produce near net-shape polycrystalline diamond orifices using a direct sintering. US Synthetic has successfully produced prototype orifices using this approach; minor tooling adjustments are currently being made to produce finished product for delivery to Sandia in early FY04.

Work commenced on characterization of nozzle/cutter interactions for low (2000-3000 psi) nozzle pressures. Fixturing allowed adjustment of the nozzle's formation standoff, cutter lead, and inclination angle, in addition to pressure/flow conditions, for characterizing the influence of these parameters on the cutting force. This testing and a final report will be completed early in FY04 for the entire project.

Reports & Articles Published in FY 2003:

- Wise, J. L., "Hard-Rock Drilling Demonstration of PDC Bits and DWD," in the DOE Geothermal Technologies newsletter insert (Vol. 8, Issue 1, June 2003, pp. 4 – 6) for the Geothermal Resources Council (GRC) Bulletin, Vol. 32, No. 3, May – June 2003.
- Hardy, J. A., "Processing and Characterization of Aluminum Infiltrated B6O/B4C Composites," MS Thesis – Materials Engineering, New Mexico Institute of Mining and Technology, May 2003.
- Finger, J. T., A. J. Mansure, J. L. Wise, S. D. Knudsen, and R. D. Jacobson, "Development of a System to Provide Diagnostics-While-Drilling," Sandia Report No. SAND2003-2069, June 2003.
- DOE Geothermal Technologies Program Peer Review, July 29 – August 1, 2003: (1) J. L. Wise, "PDC Cutter Development & Testing;" (2) D.W. Raymond, "Self-Induced Bit Vibrations;" (3) J. L. Wise, "PDC Bit Development & Testing;" and (4) D.W. Raymond, "Mudjet-Augmented PDC Bit."

Presentations Made in FY 2003:

- Wise, J. L., "Drag-Bit CRADA Status and Initial Observations of Drilling Damage/Wear," DWD & Drag-Bit CRADA Review, Sandia National Laboratories, Albuquerque, NM, October 15, 2002.
- Wise, J. L., "Overview of Drag Cutter and Bit Research Activities at Sandia," Technical Exchange Meeting, Hughes Christensen, The Woodlands, TX, December 10, 2002.
- DOE Geothermal Technologies Program Peer Review, NREL, Golden, CO, July 31, 2003: (1) J.L. Wise, "PDC Cutter Development & Testing;" (2) D.W. Raymond, "Self-Induced Bit Vibrations;" (3) J. L. Wise, "PDC Bit Development & Testing;" and (4) D.W. Raymond, "Mudjet-Augmented PDC Bit."

Planned FY 2004 Milestones:

Task 1. PDC Cutter Development and Testing:

Complete testing on PDC cutter lots #13 – 18 for fundamental parameter study	Mar 04
Document merged parameter-study results for cutter lots #1 – 18	Jul 04

Task 2. Self-Induced Bit Vibrations:

Evaluate baseline configurations using coupled PDCWEAR/drill string code	May 04
Evaluate baseline configurations with active damping at the bit	Jun 04
Complete MR Module characterization	Aug 04
Release CBD announcement for CRADA development of field ready damper	Sep 04

Task 3. PDC Bit Development and Testing:

Complete final public-release report on CRADA Phase 3 drilling results for "best effort" bits	Jun 04

Task 4. Mudjet-Augmented PDC Bit:

Complete nozzle/cutter interaction testing	Oct 03
Complete final report on Phase 1 and 2 developments	Jan 04

Diagnostics While Drilling (DWD)

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: Douglas A. Blankenship
Phone: (505) 284-1230
E-Mail: dablank@sandia.gov

Collaborating Researchers: A. J. Mansure, ajmansu@sandia.gov
S. D. Knudsen, sdknuds@sandia.gov
R. D. Jacobson, rdjacob@sandia.gov
D. S. Drumheller, dsdrumh@sandia.gov
J. A. Henfling, jahenfl@sandia.gov

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $2,052K

Cost Share Funding: $100K, in-kind participation of operators and service companies in providing technical advice, conference facilities, data-reduction consultation, and drill bits for field testing.

Project Objective: The principal cost barriers to meeting DOE Geothermal Program goals are three: exploration for new geothermal resources, well construction for access to them, and power-plant operating and maintenance costs (including remedial treatment of production and injection wells). Reduced drilling cost is a critical component in breaking each of these barriers. When exploration is limited by drilling cost, for example, it not only means that fewer potential reservoirs can be identified but it places a heavy expense at the front end of a project, years before it can be amortized by the revenue stream. The objective of the Diagnostics-While-Drilling (DWD) program is to provide a dramatic impact on the cost of geothermal drilling. Specifically, the DWD program is directed toward providing real-time information of downhole drilling conditions, thus adding capabilities to the drilling system and enabling a reduction of drilling flat-time and increased performance while drilling.

Background/Approach: DWD addresses drilling improvement both by reducing the cost of conventional drilling processes and by providing a revolutionary new capability – a closed feedback loop that carries data up and, eventually, control signals down between the driller and tools at the bottom of the hole. Upcoming data will give a real-time report on drilling conditions, bit and tool performance, and imminent problems. DWD will reduce costs, even in the short-term, by improving drilling performance, increasing tool life, and avoiding trouble. Cost analyses have shown that DWD technology can potentially reduce the bus-bar cost of geothermally generated electricity by 5% to 25%, depending on well depth, well productivity, and the type of geothermal reservoir.

The industry data transmission standard now is mud pulse telemetry, but this technology only communicates one way from the bit to the surface, has a very slow data transfer rate, and will not work in geothermal conditions – high-temperature regimes, vapor-dominated wells, or underbalanced drilling operations. The principal criterion that will shape design of the DWD data transmission system is the data rate that we wish to transmit. Real-time drilling control that considers a number of downhole measurements requires a data rate higher than mud pulse, so we can either choose a technology that provides a higher data rate or we can perform much of the data processing downhole and just transmit a "status report" signal at a low data rate. Downhole data-processing has three major disadvantages: reaction time is too long to respond to down hole conditions that can damage bits in seconds; there is a risk to expensive, sometimes fragile tools in a high-shock, high-pressure, high-temperature environment; and processing algorithms must be chosen before the tool goes in the hole, losing the flexibility of changing data processing on the fly as drilling conditions change. In order to support the goals of the DWD program, it is for these reasons, we have chosen a high data-rate system.

Status/Accomplishments: The principal accomplishments in FY03 included the support of field operations (the CRADA bit testing), redesign of the DWD sub, improvements in the data transmission link and investigation into alternatives, and advancements in data displays and analyses.

In support of a CRADA drag bit testing program (detailed data are proprietary) the DWD system was employed on four different occasions and was used in over 2,100' of drilling. Significantly better drilling results were obtained in the CRADA testing than the previously reported initial Proof-of-Concept tests. One reason for the improved performance was that the bit companies' drilling engineers were able to drill at substantially higher dynamic levels without destroying the bits. Although this gave improved bit performance, it also imposed considerably higher loads on the measurement sub, leading to tool failures during two of the tests. In third CRADA test, the bolts holding one of the clamshells (exterior shells on the measurement sub that isolate strain-gage sensor packages) backed out or broke, and both clamshells came off the tool in the hole. In both the second and third CRADA tests, a leak developed around the bolts that hold the upper spider (supports that hold the electronics package concentric with the tool centerline), resulting in a washout that required tool repair. Following the third CRADA test, the sub was redesigned and modified to correct these problems. The DWD sub performed well during the fourth and final CRADA test.

As part of the DWD sub redesign, the clamshell attachments were reinforced with pins in addition to the bolts, and the bolts are larger and made from a stronger grade of stainless steel. Thread-locking compounds were also investigated to assure that we were getting effective chemistry with the new material. The principal reason for the washouts was the spider geometry and tolerance problems that led to the spider being held in place by three bolts in tension with clearance between the spider legs and the inside diameter of the outer barrel. This meant that if one bolt loosened, then all three bolts in that spider would be loose. This allowed fluid passage from inside the tool to the annulus past the now-loose O-ring under the bolt head. New spiders were designed and manufactured that included threaded attachment holes that do not go all the way through to the electronics housing, eliminating a potential leak path. In addition, instead of suspending the spiders with three uniformly offset bolts, the new design allows two of the three spider legs to be held fast against the inside of the tool body with the third leg floating. The spider legs held against the tool body also have face seals in the ends of the spider legs that will add redundancy to the O-rings under the heads of the attachment bolts.

The data transmission link of choice between the sub and the surface continues to be the wet-connect wireline system. The wireline is a conventional single-conductor cable with connections that can be made and broken while immersed in drilling fluid and with an electrical swivel that allows the lower part of the cable to rotate relative to the upper part while maintaining electrical continuity. This wireline system has at least two major advantages in addition to its commercial status: the downhole electronics can be powered from the surface, obviating the need for downhole batteries, and the wireline can be quickly extracted from the drill string for any required maintenance or repair. During the drilling tests to date, performance of the wireline system has been adequate. Although there was an early difficulty with fatigue failure in the center conductor at the stab-in wet connection, this was solved quickly. Most subsequent problems, whether data dropouts or complete loss of signal, have been associated with the electrical swivel. However, Sandia worked with the company that manufactures the swivels, and the latest version used had significantly better longevity than earlier models. In addition to improvement of the current wireline system, Sandia continued to evaluate other options for data transmission. Nondisclosure agreements were negotiated with three companies that have announced wired pipe development efforts. While not yet available for field testing, this technology shows promise as a future replacement of the current wireline system.

Results to date have demonstrated that high-speed data collected downhole and displayed in real time allow recognition of, and reaction to, bit dysfunctions not seen in surface data alone, thereby improving bit performance. Currently, real-time displays include strip charts of signals (weight-on-bit, bending, torque, acceleration, etc.) vs. time, Fast Fourier Transforms displayed as magnitude vs. frequency, and cross plots of X- vs. Y-acceleration or X- vs. Y- bending The downhole data display systems were continually improved to allow CRADA partners real-time observation of downhole events during the testing of their representative bits. These displays provided valuable feedback to the CRADA partners. Following each of the CRADA tests, the partners were provided with full data sets and a special purpose data browser to allow engineers from the representative bit companies the opportunity to peruse the data.

Reports & Articles Published in FY 2003:

- Finger, J.T., Mansure, A. J., Knudsen, S. D., and Jacobson, R. D., *Development of a System for Diagnostics-While-Drilling,* paper SPE/IADC 79884 presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands, February, 2003.
- Finger, J.T., Mansure, A. J., Wise, J. L., Knudsen, S. D., and Jacobson, R. D., *Development of a System to Provide Diagnostics-While-Drilling,* Report SAND2003-2069, Sandia National Laboratories, Albuquerque, NM, June 2003.
- Minutes of DWD Technical Advisory Committee meetings (June, 2003).
- Mansure, A. J., Finger, J. T., Knudsen, S. D., and Wise, J. L., *Interpretation of diagnostics while drilling data***,** paper SPE 84244 presented at the SPE Annual Technical Conference, Denver, October, 2003.
- Finger, J.T., Mansure, A. J., Henfling, J. A., Jacobson, R. D., and Blankenship, D. A., *DWD: second-generation data link (2.2.4a)*, Report SAND 2003-3174C, Sandia National Laboratories, Albuquerque, NM, August, 2003.
- Finger, J.T., Mansure, A. J., Jacobson, R. D., Henfling, J. A., and Blankenship, D. A., *DWD: Downhole Measurement Sub (2.2.4b)*, Report SAND 2003-3190C, Sandia National Laboratories, Albuquerque, NM, August, 2003.
- Mansure, A. J., Finger, J. T., and Blankenship, D. A., *DWD: Field Test & Analysis (2.2.4c)*, Report SAND 2003-3189C, Sandia National Laboratories, Albuquerque, NM, August, 2003.

Presentations Made in FY 2003:

- Finger J. T., Mansure A. J., Knudsen, S. D., and Jacobson, R. D , *DWD Status Update*, Meeting of the DWD Technical Advisory Committee, BP Facilities, Houston, TX, June 2003.
- Finger, J.T., *DWD: second-generation data link (2.2.4a)*, U.S. Department of Energy Geothermal Technologies Program Peer Review held July 29-August 1, 2003 in Golden, CO.
- Finger, J.T., *DWD: Downhole Measurement Sub (2.2.4b)*, U.S. Department of Energy Geothermal Technologies Program Peer Review held July 29-August 1, 2003 in Golden, CO.
- Mansure, A. J., *DWD: Field Test & Analysis (2.2.4c)*, U.S. Department of Energy Geothermal Technologies Program Peer Review held July 29-August 1, 2003 in Golden, CO.
- SPE and SPE/IADC Presentations as Noted Above.

Planned FY 2004 Milestones:

Hard rock drilling test with industrial partner at Catoosa	Oct 03
Complete conceptual design of the second-generation DWD sub	Feb 04
Reassess the status of commercially available wired pipe	Mar 04
Repair and recalibrate existing low-temperature DWD subs	Mar 04
Component requirements analysis for second-generation sub	Apr 04
Complete refined data display system	July 04
Complete working design of second-generation DWD sub	Aug 04

Cost Database and Analysis

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: S. J. Bauer
Phone: (505) 844-9116
E-Mail: sjbauer@sandia.gov

Collaborating Researchers: John Finger, SNL

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $130K

Cost Share Funding: Well data contributed by operators is critical to this project, but value is difficult to quantify.

Project Objective: This project has three purposes.

1. Develop baseline data for geothermal drilling cost in different reservoirs.
2. Identify and rank the cost drivers in geothermal drilling.
3. Define opportunities for, and assess the impact of, technology improvements in the drilling process.

Cost database analysis contributes directly to Sandia's mission of reducing drilling cost. These cost reductions directly benefit each of the DOE Geothermal Programmatic goals. Creating a database of drilling costs in different geothermal fields will also provide baseline data so that we can judge the effect of technology improvements. This task is being closed out.

Background/Approach: There are three principal cost barriers to meeting DOE Geothermal Program goals, these include exploration for new geothermal resources, well construction for access to them, and power-plant operating and maintenance costs, including remedial treatment of production and injection wells. Each of these tasks is expensive, to some degree, because of drilling cost. Reduced drilling cost will be a critical component in breaking each of these barriers.

The basic approach is to collect well-cost data from operators, to compile the data in a consistent format, and then to analyze the data in terms of deviation from "average" performance. The three major geothermal operators in the US have begun keeping drilling records in a cost-accounting software package called RIMBase, and much of the data collected to date is in that format. Because RIMBase incorporates a Microsoft Access database, it is relatively easy to make specific queries about different items of drilling cost. For example, RIMBase can immediately identify all the wells in the database in which cementing expense exceeded $200,000, or in which fishing was necessary, or both. Many records of workovers and remedial drilling are also included in the available data, so it will be possible to evaluate life-cycle costs for a given well. This is important, because in some wells (e.g., retrofitting titanium casing in the Imperial Valley) the workover costs are very significant relative to the original drilling costs. Analysis of life-cycle cost can guide drilling strategies by demonstrating that high initial cost may pay off over the well's lifetime.

More generally, however, our approach has been to construct a hypothetical "optimum" well in a given field, using the cost records for that field. An optimum well is defined as one with no trouble and with best demonstrated drilling performance in terms of rate-of-penetration and bit life. By examining the differences between the optimum well and the "average" well for that field, we can identify the principal cost drivers, which would be primary targets for drilling research.

Because the optimum wells are based on best demonstrated practice, it's also possible to model improved drilling performance (e.g., better drill bits, more effective lost circulation control) to define an "advanced" well that has even lower cost than the optimum well. This technique can also show the sensitivity of well cost to various kinds of technology improvement, which is another way of guiding drilling research.

Status/Accomplishments: We have developed several ways of visualizing well-cost data. Spreadsheets can be used to filter cost records for individual wells and seek unusually high cost items. Depth-time curves emphasize the impact of flat time (times when costs accumulate and no drilling is done) and bar charts with standard deviation bars show at a glance the variation in drilling efficiency between an average well and an optimum well. Although we have a significant amount of data from three geothermal fields, additional well records would improve statistical validation.

It is observed that the improvement between the average and optimal wells from 55.6 days to 41.1 days is based only on consistency of demonstrated performance. That is, we have not assumed that ROP is higher than rates already achieved, only that it is consistently high. It is also assumed that there is no non-productive time or problem time; these may require new technology. This same comparison could be extended by assuming advanced technology can be incorporated into the drilling program. Tools and techniques such as high-performance bits, drilling with casing, expandable bits that could drill and underream in one pass, or high-performance cementing with faster cure could all lead to improvement even in the "optimal" well. The cost impact of these developments can all be modeled using the cost data in hand.

In the same way, individual wells can be analyzed for specific cost drivers. Two wells in a geothermal field were drilled to approximately the same depths, with approximately the same hole configurations, but total well costs varied significantly from $823,000 to $1,189,000. Each of these wells was compared with the "optimum" well for that configuration, which cost $774,000. The less expensive well, identified as "moderate cost", only had two minor lost circulation incidents, but the "high-cost" well had six twist-offs and one lost-in-hole BHA. Variation in specific well cost items, serves to verify what might be intuitive – that primary cost savings would come from a remedy for drill string problems. This remedy might come from new technology, such as a downhole data system, but might also be affected by a better drill pipe inspection program. More importantly, this exercise also demonstrates that this technique can be applied to larger samples of many wells in a field, when the dominant cost drivers might not be obvious.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003:

Annex 7: The IEA's Role in Advanced Geothermal Drilling, John T. Finger and Eddie R. Hoover, Sandia National Laboratories, Geothermal Resource Council Meeting, Morelia, Mexico, October 12-15, 2003

Planned FY 2003 Milestones:

Develop a scaled-down costing model	Dec 03
Provide all non-proprietary cost and performance data to NEDO (Japan)	Mar 03

Advanced Drilling Concepts

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, PO Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: A. J. Mansure
Phone: (505) 844-9315
E-Mail: ajmansu@sandia.gov

Collaborating Researchers: Doug Drumheller

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $137K

Cost Share Funding: $65K

Project Objective: Achieve more than incremental reductions in geothermal drilling costs by investigating potentially "game changing" technologies. Focus will be on technologies needed for future geothermal drilling including wells for Engineered Geothermal Systems (EGS).

Background/Approach: Cost-effective well construction requires integrating various functions including casing the well, maintaining wellbore integrity, removing the cuttings, etc. By considering the overall drilling system, alternate methods for enhancing borehole construction can be identified. Many methods have been evaluated in the past, including lasers, water/mud jets, arcs, flame jets, explosives, hammers, projectiles, rock melters, and coiled tubing. In general, the evaluation has been done in the context of currently developed geothermal resources rather than the geothermal resources of the future.

Just as drilling must be evaluated as a system of functions, wellbore construction must be evaluated in its context: what is the lithology, what will be the completion, and what will be the lift mechanism? All of these must be known before the well can be designed. Without the well design, it is not possible to evaluate applicable technologies. Slim open holes and large diameter cased holes will require very different "game changing" technologies. Thus the approach of this project will be comprehensive including identification of lithologic targets, methods of completing the reservoir, and lift mechanism. Note: future geothermal resources will quite likely not be self pumping, requiring artificial lift.

A primary purpose of drilling is exploration. Drilling and exploration are already integrated in the sense that drilling provides temperature information and intercepts fractures. A "game changing" integration of exploration and drilling would be to steer drilling toward fractures detected by Look-Ahead Seismic Imaging.

Past evaluation of advanced drilling concepts has used a systems approach that considers benefits and limitations in performing essential functions of drilling (Pierce et al, Advanced Drilling Systems Study, SAND95-0331, Sandia National Laboratories 1996). One limitation of that study critical to future geothermal drilling is it includes no information on how drilling becomes more difficult with depth. Building on that study, the issue of depth needs to be investigated as well as new technologies currently emerging (casing drilling, particle impact drilling, chemical erosion of rock, etc.). The objective is to establish the baselines of what can be done using current and emerging drilling technologies.

Historically, completion of EGS systems has been envisioned as hydrofracturing of basement rocks. There are other rock units with geothermal potential, for example deep sedimentary rocks. A necessary first step to comprehensive plan for developing advanced drilling concepts is to evaluate lithologic targets considering how the heat exchanger would be constructed in each wellbore completion.

The effectiveness of any seismic method depends on the direct measurement of the source vibration. This is called the pilot signal. But drill bit noise is most economically measured at a remote location, the surface. This is possible because the drill string serves as a conduit channeling the vibrations to the surface; however, the resulting pilot signal is distorted by its trip up the drill string. Two factors have hindered Look-Ahead Seismic Imaging --an effective acquisition and signal processing method for the pilot signal, and the immediate processing of images in the field. The purpose of this task is to improve pilot signal technology and provide images in real time to the drilling operator.

Status/Accomplishments: In FY 2003, contracts were placed with Duke University and Subsurface Exploration Co., for rental of seismic field equipment and field acquisition and processing of seismic data. Mammoth Pacific anticipates drilling a well early in FY04 on which the field tests can be performed. Sandia's surface receiver will be used to acquire the pilot signal. Phase I of this work will be completed by a) demonstrating the acquisition and processing to remove distortion of the pilot signal and b) processing of the seismic data by Duke to demonstrate real-time methods for processing look-ahead seismic imaging.

Plans were made to initiate work in FY 2004 on projects to characterizing future drilling challenges and to determine initial lithologic and completion targets. While these plans were being developed, information was gathered on several emerging technologies including partial-impact drilling – a test was monitored at TerraTek. Also contacts were made with ExxonMobil for chemical-erosion drilling and Tesco for casing drilling. A review of the chemistry of chemical-erosion drilling was done and a previous analysis of the issues of applying LASAR drilling to geothermal drilling was updated.

Reports & Articles Published in FY 2003:

FY 2003 U.S. Department of Energy Geothermal Technologies Program Peer Review.

ProDril's Particle Impact Drilling System – Testing at TerraTek's Drilling Research Laboratory, Trip Report: September 13 2002.

Presentations Made in FY 2003:

FY 2003 U.S. Department of Energy Geothermal Technologies Program Peer Review.

Planned FY 2004 Milestones:

Compile initial list of potential "game changing" technologies	Mar 04
Draft deep well design and cost analyses	Aug 04
Draft lithology and completion methodology targets	Aug 04

Acid-Resistant Cements

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC02-98CH10866

Performing Organization: Brookhaven National Laboratory, Upton, N.Y. 11973

Principal Investigator: Toshifumi Sugama
Phone: (631) 344-4029
E-Mail: sugama@bnl.gov

Collaborating Researchers: Lance Brothers, Halliburton, Lawrence Weber, Unocal

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $150K

Cost Share Funding: $200K

Project Objective: The purpose of this work is threefold. Develop cost-competitive, yet highly durable new types of sodium phosphate- and sodium silicate-activated cements and composites. Investigate the resistance to acid of set-retarded calcium aluminate phosphate (CaP) cement. And finally, conduct post-field test analyses of CaP cement in collaboration with Halliburton Corp. and Unocal Corp. The primary goal of this program is to formulate commercial cements and composites with superior acid-resistant properties that show less than a 5wt% loss after 30 days immersion in 5,000 ppm CO_2-laden H_2SO_4 brine (pH < 1.2) at temperatures up to 200°C. A secondary goal is to design tough yet flexible CaP cement composites with fracture toughness of > 0.08 $MN/m^{3/2}$ and water permeability of < 0.1 millidacrys after exposure for 30 days in an autoclave containing a 40,000ppm CO_2-laden brine at 280°C. The highly concentrated CO_2 and H_2S environments encountered in the upper regions of the wells (~ 3,800 ft. below the well's surface) at temperatures up to 200°C occasioned the former research objective of acid resistance. The latter was related to the problem of stress cracking caused by a slight thermal expansion of the cements during the passage of superheated geothermal fluid through the cement-sheathed steel pipes in production wells, and also due to the brittleness of the cements. Severe acid erosion and the development of numerous cracks in the cement lead to downtime or even failure of the wells, and the requirement for expensive time-consuming remediation involving redrilling and recementing operations. Thus, the improved cements would not only significantly extend the useful lifetime of the well casing, but also would save in excess of $150,000 per well in avoided remedial operations. Wells completed with improved cement are projected to have service lifetimes of 20 years, thereby improving the efficiency and lowering the costs of energy-extracting operations at the plants.

Background/Approach: In 2001, the cementitious materials to be developed were required to meet the following criteria: 1) maintenance of pumpability for at least 3 hours; 2) compressive strength, > 1000 psi at 24 hours; 3) water permeability, < 0.1 millidarcy; 4) bond strength to steel casing, > 100 psi; 5) carbonation rate, < 5 % after 1 year in brine at 300°C containing 40,000 ppm CO_2; 6) fracture toughness, > 0.08 $MN/m^{3/2}$ at 24 hours; 7) resistance to acid, < 5 wt% loss after 30 days in 5,000 ppm CO_2-laden H_2SO_4 (pH, < 1.2) at temperatures up to 200°C; and 8) cost, < $15/bag. Halliburton's commercial CaP cement known as "ThermaLock®" was originally developed at BNL as CO_2-resistant material for cementing steel casing to geologic formations in mild acid (pH ~ 4.5), CO_2-rich (> 40,000 ppm CO_2) brine environments at temperatures up to 320°C. Over the past four years, Unocal Corp., Halliburton Corp., and Japan Petroleum Exploration Corp., have used this cement to complete nearly twenty-four geothermal wells in Japan, Indonesia, and the United States. In 2002, it was used in Coso geothermal wells containing a highly concentrated H_2S and CO_2 brine, and has become increasingly popular for completing geothermal, oil, and gas wells worldwide. Thus far, the original CaP cement met all criteria, except for items 6 and 7. So, in developing advanced CaP cement, we focused on improving the two properties, acid resistance and toughness.

Resistance to Acid:

In 2001, work on the acid-erosion mechanisms of CaP cement consisting of calcium aluminate cement (CAC), Class F fly ash, and sodium polyphosphate (NaP) focused on understanding the role of CAC with various mole ratios of CaO/Al_2O_3 and different mineralogical phase compositions in reducing the rates of acid erosion. One important factor in abating acid attack was to have a sufficiently low porosity of 25.5 % that diminishes the permeability of acid solutions through the cements. A serious problem was that the remaining non-reacted CA and CA_2 components underwent carbonation to form calcite that was very susceptible to reactions with H_2SO_4. This led to the deposition of gypsum scales as an acid corrosion product on the cement's surfaces. On the other hand, three crystalline phases as hydration products of cement, hydroxyapatite (HOAp), boehmite, and Na-P type zeolite, particularly boehmite and Na-P type zeolite, were relatively insensitive to acid attack, thereby protecting the cements against acid erosion. In contrast, although the HOAp phase played the pivotal role in protecting cement from CO_2 attack, it was susceptible to acid erosion. So in 2002, in efforts to look for ways to protect the HOAp phase and minimize its erosion by acid, we assessed the usefulness of the various high-temperature silicon emulsion additives. From among them, silanol-terminated polydimethlysiloxane (PDMS) was selected because of its excellent thermal stability, high water-repellency, great flexibility, and outstanding resistance to acid. PDMS protected the cement in two ways: it considerably reduced the formation of calcite, which was generated by the carbonation of the cement and it abated the rate of reaction of HOAp with acid. Consequently, there was a weight loss of only 7.8 % after 20-day exposure. However, the new concern in using the PDMS was the hike in the cement's cost, making it more than three times as expensive as the original cement.

Improvement of Toughness:

Our approach to increasing the toughness of the CaP cement was to incorporate strong fibrous materials into it. The following criteria were used for selecting the fibers: 1) good dispersiveness to achieve a uniform distribution in the cement slurry; 2) thermal resistance of > 300°C; 3) lack of susceptibility to reactions with brine solutions containing alkali metals, alkaline earth metals, CO_2, and H_2S; and, 4) moderate adherence to the cement matrix. In 2001, the plan was to assess the usefulness of two ceramic fibers, corundum (α-Al_2O_3) and a corundum/mullite ($3Al_2O_3.2SiO_2$) blend in improving the fracture toughness of the cement at a hydrothermal temperature of 280°C. The corundum fiber displayed a better performance in improving the cement's toughness, compared with that of the corundum/mullite blend fiber. Incorporating the corundum fibers raised fracture toughness to 0.059 $MN/m^{3/2}$, corresponding to an increment of 2.7-fold above than that of non-reinforced cements. In 2002, we tried to further improve its toughness by incorporating milled carbon micro fibers (~ 7.5 μm diam. x 100-200 μm long) into the cement. The chemical composition occupying the outermost surface sites of the fibers consisted of graphite as the principal component coexisting with functional oxidized carbon moieties, such as carbonyl and carboxyl. These functional moieties contributed significantly to improving the following three properties, deemed essential for good reinforcing fibers: (1) the extent of dispersiveness of the fibers in the cement slurry; (2) the minimization of air-trapping by fibers during mixing with the slurry; and, (3) their affinity for the chemical species present in the cement's pore solution. Integrating all these factors conferred a great fracture toughness of 0.068 $MN/m^{3/2}$ by incorporating 14 wt% (21.8 vol.%) fibers, corresponding to its increase by 3.1-fold over that of the non-reinforced cement. In early 2002, Halliburton applied this fiber-reinforced cement as the anti-corrosive internal lining material to the geothermal well-head pipe in CalEnergy Power Plant. BNL monitored the changes in both the mechanical and physical properties of the aged composites.

Status /Accomplishments: In 2003, two new potential cements were synthesized hydrothermally at BNL: One was cost-effective sodium silicate-activated slag (SSAS) cement, and the other was aluminum phosphate (AP) cement, a new type of phosphate-bonded cement. For the former, we used granulated blast furnace slag (BFC) cement, a by-product from steel manufacturing, as the solid reactant consisting of an amorphous CaO-SiO_2-Al_2O_3-MgO quaternary system: it was supplied by Lafarge North America Corp. Although the hydrated BFC cement possessed great resistance to sulfate and brine, its low hydration heat was the major concern in using it in geothermal wells because it only developed a low strength during the early hydration period, and it had a long setting time. Despite such disadvantages, the inexpensiveness of BFC cement, ~ 25 % less than that of the conventional well cements, was very attractive. Thus, these two important factors, its low material cost and abundance, urged us to develop a technology to promote the rate of hydration of the BFC cement. For this work, we modified the cement using sodium silicates with SiO_2 /Na_2O ratios of 3.22, supplied by the PQ Corporation, as alkali activators. With a 20 wt% sodium silicate solution, the sodium silicate-activated slag (SSAS) cements autoclaved at temperatures up to 200°C displayed an outstanding compressive strength of more than 80 MPa, and a minimum water permeability of less than 3.0×10^{-5} darcy. The combination of calcium silicate hydrate (CSH) and tobermorite phases was responsible for strengthening and densifying the autoclaved cement. Although all the phases formed in the autoclaved cements were vulnerable to reactions with H_2SO_4, thereby depositing bassanite scales as a corrosion product over the cement's surfaces, the CSH phase played an important role in retarding the rate of acid erosion. Thus, after the uptake of Ca by H_2SO_4, the Ca-destitute CSH preferentially reacted with Mg from the slag to form the lizardite phase that not only slowed the rate of acid erosion, but also retained the integrity of the cementitious structure. Consequently, there was only a 6.6% loss in weight of SSAS cement after a 15-day exposure to hot CO_2-laden acid. After dissolving sodium silicate in water, its hydrolysis led to the formation of two hydrolysates, monosilicic acid and sodium hydroxide. The hydroxyl anion in the sodium hydroxide hydrolysate acted as an alkali activator for slag, and the monosilicic acid hydrothermally reacted with Ca in the activated slag to form calcium silicate hydrate. Thus, the free Na ions appear to remain in this cementitious structure. In attempting to transform non-reacted Na ions into a Na-intercalated crystal hydration product such as the zeolite phase that is relatively inert with reactions with acid, our attention will be concentrated on incorporating the Class F fly ash generated from the coal-combustion power plants into the sodium silicate-activated slag cement system. The mullite phase in the fly ash will react with Na to form zeolite. We developed aluminum phosphate (AP) cements derived from three major starting materials; ammonium polyphosphate, $Al(OH)_3$, and water. The AP cement showed a great resistance to hot acid. However, one concern was that this cement failed to develop strength. Even though the two crystalline phases formed in the 300°C-autoclaved cement, boehmite and augelite, played an essential role in developing compressive strength, the maximum value obtained was only a 19.2 MPa (2787 psi). Among the setting retarders of CaP cement, the citric acid significantly contributed to enhancing the setting temperature and to extending the thickening time of CaP cement slurry. The set-retarding activity of citric acid was due to the uptake of Ca^{2+} ions from the CAC by carboxylic acid groups within the citric acid. This uptake led to the precipitation of a Ca-complexed carboxylate compound as a set-retarding barrier layer on the CAC grains' surfaces. Concerning the resistance of this retarded cement to acid, two of the crystalline reaction products formed in the cement, HOAp and hydrogrossular, were susceptible to reactions with sulfuric acid. Based upon our previous information on the effectiveness of milled carbon microfibers (7.5 μm diam. x 100 μm length) in improving the toughness of CaP cement, Halliburton formulated a microfiber-reinforced CaP cement composite suitable for use as an anti-corrosion liner for well head pipes in CalEnergy power plant. In September 2002, the formulated cement composite containing 5wt% fiber was successfully lined on the pipe's internal surfaces (24-in. diam. and 40-ft.-long), and the field-performance test of ~ ½ in. thick-lined pipe was begun in October 2002, under conditions of ~ 240°C brine flowing through pipe at a velocity of ~ 3 m/sec. In collaboration with Halliburton, we analyzed this 6-month-old liner. From our results, the following conclusions can be drawn. Although the ability of the cement composite to protect the steel against corrosion under a very harsh, hostile brine environment at 250°C was enhanced during the six-month exposure, one concern raised was the conversion of the ductile composites into the brittle ones. Brittle liners may allow development of micro cracks in the liners, which can cause their failure as anti-corrosion barriers, when they undergo shrinkage and sustain impact-caused damage. In October, 2002, nitrogen-formed CaP cement was successfully pumped down into the upper region (~ 3,800 ft. depth from surface) of Coso geothermal wells, where the steam zone contains high concentrations of CO_2 and H_2S at ~ 160°C. Halliburton's post placement assessments of this cement after 13 months revealed that it remained intact. One major advantage for using foamed lightweight cement was that it eliminated the lost-circulation problem frequently incurred by the high pressure needed when cement slurry with high density is pumped down into deep wells. However, there are no detailed studies on the ability of such foamed cement to protect the casing against brine-induced corrosion, the adherence of cement to pipe's surfaces, and the durability of interfacial bonding thus far. Thus, these studies will be required to ensure that foamed cement retains the integrity of well casings.

Reports & Articles Published in FY 2003:

T. Sugama, L.E. Brothers, and L. Weber, "Acid-resistant Polydimethylsiloxane Additive for Calcium Aluminate/Fly Ash Phosphate Geothermal Well Cement in 150°C H_2SO_4 Solution", Advances in Cement Research, 15 (2003) 35-44.

T. Sugama and L.E. Brothers, "Sodium Silicate-activated Slag for Acid-resistant Geothermal Well Cements", Advances in Cement Research, (in press).

T. Sugama, L.E. Brothers, and L. Weber, "Citric Acid as a Set Retarder for Calcium Aluminate Phosphate Cements", February 2003.

Presentations Made in FY 2003:

Planned FY 2004 Milestones:

Formulate activated slag cement modified with fly ash	Feb 04
Formulate foamed lightweight phosphate-based cement	Mar04
Investigate acid and CO2 resistance of modified cements	May04
Complete report describing the results from acid and CO2 resistance tests	Jun 04
Deliver modified cements to Halliburton for their independent evaluation	July 04
Report results of field monitoring test for CaP cements placed in Coso well and lined in CalEnergy's well head pipe	Aug 04

Structural Response Analysis of Well Cements

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC02-98CH10886

Performing Organization: Brookhaven National Laboratory
Energy Resources Division, Building 526
Upton, New York 11973-5000

Principal Investigator: A. J. Philippacopoulos
Phone: (631) 344-6090
E-Mail: ajph@bnl.gov

Collaborating Researchers: M. L. Berndt
Phone: (631) 344-3060
E-Mail: allan@bnl.gov

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $60K

Cost Share Funding: None

Project Objective: The objective of this program is to investigate the mechanical behavior of well cements using material testing confirmed by structural modeling of the response behavior of geothermal wells. These investigations address ways of improving the performance of geothermal wells through material characterization and modeling of well response due to pressure and temperature loads occurring in steady-state or transient forms. As such, this program contributes to ensuring long-term mechanical strength of geothermal wells and consequently impacts the DOE programmatic goals with respect to reducing cost of generating geothermal power to 3-5 cents/kWh by 2007.

Background/Approach: Previous investigations of geothermal well cements under this project and discussions with geothermal operators led to the conclusion that traditional guidelines for well cements are deficient, especially when it comes to their mechanical property requirements. On-going research by the oil and gas industries is reaching similar conclusions. All of these studies are pointing out that adequate materials characterization and selection of cements used for the completion of all types of energy producing wells must be based on rigorous engineering analysis. Our approach is to utilize refined models that take into account interactions between the casing, cement annulus and the surrounding formation in order to investigate the response of the complete well system to various loads such as pressure and temperature. Furthermore, previous research has also demonstrated that the tensile strength of the cement is also critical for the performance of a geothermal well. With regards to improving the tensile strength, our approach is to investigate the use of fibre reinforcement. Our experimental materials program is also supported by extensive finite element analysis of geothermal wells that incorporate the materials tested. Engineering analysis of the well response to pressure and thermal conditions, allows us to study the type and magnitude of stresses and deformations developed at the cement annulus of a geothermal well. In general, two types of failures are of interest, namely, tensile failure for weak far-field stresses and shear failure in the presence of compressive far-field stresses. Also, stresses due to local tectonic regimes can lead to debonding of the cement annulus from the surrounding formation. These fundamental failure modes need to be investigated to see their relevance to cement mechanical properties. Finally, there is a need to design and verify optimum formulations for all operating conditions and any transient loadings experienced by the well during its design life. The expected outcome of the research is the development of performance-based approach for selection of geothermal well cements and this will ultimately lead to reduced failures and greater service life of wells.

Status/Accomplishments: Owing to reduced funding and work scope in FY03, research concentrated on characterization of well cements under tensile loads. Instrumentation necessary for performing direct tensile tests on well cements was developed. Different cement formulations were then tested to compare the tensile behaviour and then relate this to expected in-situ performance. The materials tested included conventional, latex-modified, fibre reinforced and lightweight formulations. The fibres studied were carbon microfibres, steel microfibres and steel macrofibres. Durability tests on steel fibre reinforced cements were performed to examine corrosion characteristics and determine whether tensile strength was maintained. Finally, the rate of strength development in fibre reinforced well cements was investigated.

The load-displacement curves obtained in direct tension for the different cements indicated that unreinforced and microfibre-reinforced cements exhibited brittle behaviour. Different degrees of linear elasticity were evident. Both lightweight (perlite- and microsphere-modified) cements had small displacement at failure. For the unreinforced cements the greatest displacements and peak loads were associated with the latex-modified cement. Some strain hardening type behaviour was associated with the steel microfibres in addition to a minor amount strain softening. Peak load was improved by addition of either type of microfibre. Ductility was most influenced by inclusion of 13 mm steel fibres. In the latter case, following initial crack formation the steel fibre reinforced cements continued to bear load as multiple matrix cracking, fibre alignment, disbondment and pullout occurred. The load-displacement curves were similar in form for the standard and latex-modified cements containing 13 mm fibres. Addition of latex had some benefit in terms of peak load. However, ductility and post-peak residual strength were not significantly affected by latex. The microsphere-modified cement reinforced with the 13 mm fibres also exhibited some post-peak load bearing capacity, thereby indicating potential improvement in this type of lightweight cement if fibres are incorporated.

Studies on the rate of splitting tensile strength development for cements with 0, 0.5 and 1% volume fraction 13 mm steel fibres showed that the material strength was not significantly different after 24 hours. At seven days the fibres clearly enhanced the tensile strength. The improvement provided by the fibres became greater after 14 days and strength continues to increase thereafter. The lack of influence of fibres on tensile strength at 24 hours suggests that interfacial bonding between the fibres and cement matrix has not progressed sufficiently at that time. The benefits of the fibres become apparent after a few days and this could be beneficial in situations where tensile loads are experienced in the cement annulus at such ages. Except for the results at 14 days, increasing the volume fraction from 0.5 to 1% only gave a relatively small improvement in tensile strength. Therefore, a volume fraction of 0.5% would appear most appropriate and economic for use in well cements.

Cements reinforced with 0.5% 13 mm steel fibres and 5% steel microfibres were examined for visual indications of deterioration after exposure to carbonated 1M NaCl at 90^{o}C for six months. Slight rust stains were evident on 13 mm steel fibres close to the surface. No staining was observed for the steel microfibres. The specimens were then tested for splitting tensile strength. The results indicated that there was no loss of strength over the test period. Examination of the fractured specimens did not reveal any corrosion of the internal fibres. The residual tensile strength of specimens that had 4% NaCl by weight of Class G cement added at the time of mixing did not show any significant decrease. Fractured specimens were also devoid of fibre corrosion. These observations are consistent with the requirement for chloride ions to initiated corrosion and for oxygen and water to sustain the cathodic reaction of the corrosion process. When the specimens were saturated in simulated brine the availability of oxygen within the cement matrix was limited and corrosion was suppressed. Under such conditions tensile strength is maintained and this is important if the fibres are to continue to provide benefits throughout the well life.

Reports & Articles Published in FY 2003:

- A.J. Philippacopoulos and M.L. Berndt, Mechanical Response and Characterization of Well Cements *SPE Annual Technical Conference*, Paper: SPE-75930, October 2002.
- M.L. Berndt, A.J. Philippacopoulos and C.E. Mancini, Properties and Thermoelastic Response of Conventional and Fibre Reinforced Well Cements, Geothermal Resources Council Transactions, Vol. 27, 125-129, 2003
- M.L. Berndt and C.E. Mancini, Tensile Tests on Plain and Fibre Reinforced Geothermal Cements, accepted for publication in Journal of Materials Science, 2003

Presentations Made in FY 2003:

- SPE Annual Technical Conference and Exhibition, San Antonio, October 2002

Planned FY 2004 Milestones:

Obtain well data for analysis of pressure transients	May 04
Document results	Sept 04

Prior Year Solicitations

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: Allan R. Sattler
Phone: (505) 844-1019
E-Mail: arsattl@sandia.gov

Collaborating Researchers: Doug Jung (Two Phase Engineering), Tom Champness (Drill Cool)
Louis Capuano (Thermasource) Marty Coburn (APS Technology)
Jack Wise, Steve Knudsen, John Finger, Ron Jacobson, and
Gary Whitlow - SNL

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: None

Cost Share Funding: Thermasource, $ 115K (over life of contract),
APS Technology > $ 300K to date
Two Phase Engineering, $ 75K (over life of contract)

Project Objective: Reduce geothermal drilling, well maintenance and related costs by commercializing new tools, materials, and by developing drilling and well maintenance techniques in cost-shared (50 % DOE, 50% industry or greater) projects. Complete the outstanding projects from the 00 and 01 solicitations.

Background/Approach: This project funded minimum 50:50 cost-shared, near-term, broadly applicable technology development projects for reducing drilling, well maintenance, and related costs. This support to industry is vital, largely because the geothermal industry is small and represents a limited, specialized market and the technical well construction challenges it faces are among the toughest. The approach was to solicit jointly funded projects addressing near term drilling and well maintenance related needs of industry. The projects from the solicitations were selected using a best-value process and the following criteria: (1) meeting current needs of industry and being broadly applicable, (2) ability of proposing team to perform work, (3) strength of approach, (4) schedule clarity, and (5) the proposal bearing a strong link to increasing or maintaining geothermal production. All projects included a geothermal operator as a major participant. Sandia provided support for each project (instrumentation, analyses, etc) as needed.

Status/Accomplishments: Three projects from the FY 00 and the FY 01 solicitation were still active in FY 03, the hybrid Drill Bit (Thermasource, FY 00 solicitation), the Turbine Alternator for Geothermal Drilling (APS Technology, FY 01 Solicitation) and the LEAMS (Low Emissions Atmospheric Metering Separator, Two Phase Engineering, Drill Cool, and Calpine). The hybrid drill bit project was concluded in FY 03 after a field test. A prototype Turbine Alternator was constructed (save the power conditioning circuit) and was featured at the 1993 SPE Trade Show in Denver. This Turbine Alternator project is continuing. The LEAMS with Two Phase Engineering (designer), Drill Cool (Fabricator), and Sandia won an RD 100 award. Moreover, a new version of the LEAMS functioned successfully at Glass Mountain. DOE/Sandia support of LEAMS was through the FY 01 solicitation and earlier DOE/GDO grants. Much LEAMS technology, developed with DOE/Sandia support, was employed in the LEAMS used on Glass Mountain. Drill Cool worked under the FY 01 solicitation as well as earlier DOE/Sandia Geothermal Drilling Organization grants.

Hybrid Drill Bit -- Thermasource

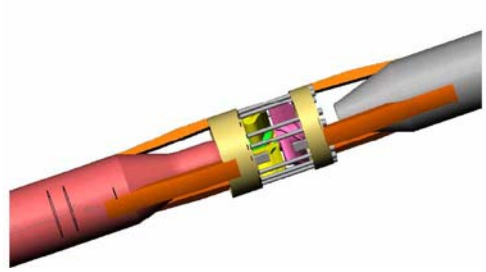
A hybrid drill bit was built that uses both PDC and thermally stable polycrystalline (TSP) diamond cutters hopefully to improve bit life and expand the range of formations that can be drilled with drag bits. TSP cutters do not have the cobalt binder used in PDC cutters. This was to make them more thermally stable and they were thought to be more wear resistant. TSP cutters have shown the ability to cut hard rock in a number of single-cutter laboratory tests. Conventional PDC bits cannot drill, or are severely damaged by, conditions found in geothermal drilling environments. If the hybrid bit can drill through hard zones while maintaining performance in softer formations, then drilling costs could be substantially reduced by decreasing the down time to replace worn out roller bits. The hybrid drill bits were constructed in previous fiscal years.

The project was concluded in a field test in FY 03. A hybrid bit was tested during drilling of an injection well (N-7) for the Northern California Power Agency (NCPA) steam field in The Geysers Known Geothermal Resource Area. Measured bottom hole temperatures exceeded 300^{o} F while drilling at depths in the vicinity of 5,000 ft. The test for the bit utilized a downhole motor that was driven by a circulating medium consisting of air (2,000 – 2,800 cfm) plus injected water (~65 gpm). The hole was advanced by adding single joints of drill pipe and running to the "Kelly down" position respectively with, then without, surface rotation on alternate joints to directionally drill the hole so as to build inclination toward the target angle of 80^{o} from vertical.

For this hybrid drill bit run, the Sandia team (1) tracked rig operating conditions, (2) obtained time-resolved measurements of drill string axial acceleration using a surface receiver sub clamped to the Kelly above the rotating table, (3) monitored bit performance, and (4) made post-run assessments of bit damage and wear.

Unfortunately, the hybrid drill bit ($8^1/_2$-in diameter) ran only 46 ft and sustained severe damage and wear that precluded further drilling. This result is attributable to the combination of hard rock, high temperatures, and inadequate cooling and lubrication by the air/mist circulating medium. Another unfortunate factor contributing to poor drag-bit performance was most likely an episode of motor stall that occurred as the weight on bit (WOB) was increased to explore the operational envelope for the bit. Prior to this event, the drag bit exhibited a rate of penetration (ROP) exceeding 10 ft/hr; afterwards, the ROP dropped to only a few feet per hour. Bit damage and drill string dynamics are to be analyzed later to identify potential improvements for drag-bit design and/or operating procedures.

High Temperature Turbine Alternator for Geothermal Drilling -- APS Technology



A durable Turbine Alternator is being developed to take the place of expensive, short-lived disposable batteries in both measurement-while-drilling (MWD) and logging-while drilling (LWD) applications. The APS High-temperature Turbine Alternator reliably outputs 150 W of power at temperatures of up to 200°C. The entire unit measures 60" in length, with a housing diameter of 2.06" and a turbine-housing diameter of 3.13".

Construction of the high temperature turbine alternator is complete save the circuit boards in the power conditioning circuit. Gyrodata, a service company contributing to the construction of this component, stated it would provide a test bed. Gyrodata has become a partner in this project and is preparing circuit boards and a test bed at no cost to DOE. (Note added in proof: The long awaited circuit boards in the latter part of FY 03 arrived early in FY04 and were integrated into the turbine alternator. The turbine alternator was successfully tested in a flow loop tested in the laboratory and is awaiting a field test from Gyrodata).

LEAMS, Low Emissions Atmospheric Metering Separator – Two Phase Engineering

The LEAMS Technology, was developed by Two-Phase Engineering and Research, with most fabrication accomplished by Drill Cool Systems, Inc., and support from the U.S. Department of Energy and Sandia National Laboratories. LEAMS has been selected by the independent judging panel and editors of R&D 100 Magazine as one of the 100 most technologically significant products introduced into the marketplace over the past year.

The LEAMS is a family of atmospheric geothermal separators used in the development of geothermal power. The primary function of the LEAMS is to safely contain and clean the atmospheric vented steam of polluting solids, liquids and noxious gasses. This novel system is designed to be environmentally friendly, intrinsically safe and relatively easy to transport and assemble. LEAMS has a wide operating range and can be used in drilling, well testing and plant start-up. Currently, no atmospheric cyclone separator can perform all of these functions under a single system as well as the LEAMS can. In the development of geothermal power, well fluids produced, along with drill cuttings, must be safely brought up to the surface to be measured and cleaned prior to being discharged into the environment. LEAMS is designed to reduce the solid and liquid pollution of the drilling process by up to 99 percent over current atmospheric discharged cyclone separator technology. This reduction in polluting liquids vastly reduced, indeed virtually eliminates environmental pollution. The vented steam is cleaned of formation cuttings, abatement chemicals, and toxic waste. LEAMS has the ability to internally abate hydrogen sulfide gas for secondary treatment, can meter two-phase flow without unnecessary drilling-rig down-time, and can be shipped in containerized components and erector set assembled. Due to its unique design, the system is also capable of dissipating high-energy slugs that might otherwise launch conventional equipment off the location.

A variety of LEAMS configurations are available. The latest improvements (see below) include a diffuser stack that ejects vapors high into the sky to dissipate residual hydrogen sulfide and protect personnel against injury or death from a potential gas excursion during startup. LEAMS incorporates many novel ideas to accomplish its versatility and high performance. Two-Phase Engineering developed much of the LEAMS technology under cooperative agreements with DOE/Sandia including recent solicitations. Drill Cool has fabricated different versions of the LEAMS under cooperative agreements with DOE/Sandia.

LEAMS III Separator at California Geothermal Field

Two Phase Engineering and Research, in conjunction with Calpine, has developed relatively new separator technology centered about their designed Low Emissions Atmospheric Metering Separators (LEAMS). In the winter of FY 03, an evolved version of the LEAMS successfully operated during production testing. This compact version of the LEAMS separator (called LEAMS III for simplicity) has functioned successfully at Glass Mountain.

As expected, the LEAMS eliminated virtually all brine and entrained solids from the vented steam given the lower than expected flow rate. During the unloading of phase the well, the LEAMS remained quite stable, easily handling all the effluent from the well. Stability was a safety issue with older cyclone technology.

In a geothermal well, residue gasses are released along with the steam. Perhaps the most exciting aspect of the operation of the LEAMS III separator was the addition of hydrogen sulfide abatement to the system. Part of the LEAMS technology is to mitigate off gasses entrained in the steam. Additionally, in conventional blooie mufflers (cyclones), the steam plume breaks up at the stack discharge and drifts near the ground. This can be both a personnel and an environmental hazard. However, with LEAMS III, the residue gases were ejected up to 300 feet into the sky for dispersion. In essence, the steam plume with its gasses was not an issue during this operation.

Two-Phase Engineering developed much of the earlier LEAMS technology under cooperative agreements with DOE/Sandia. Prominent new aspects of this particular LEAMS separator, LEAMS III, include a design for small-to- moderate size wells, and a stack to disperse residue gasses. These are important environmental and safety features not found on the conventional blooie muffler. Moreover the "standard" H_2S abatement feature on the LEAMS unit is applied more efficiently than on the conventional blooie muffler.

Reports & Articles Published in FY 2003:

A DOE/GRC insert was devoted to the LEAMS in light of the R&D 100 award. APS Technology has issued a news release featuring this turbine alternator and did show a model of this component at the SPE meeting, September 03, in Denver.

Planned FY 2004 Milestones:

Turbine Alternator

Completion of Fabrication and test in Flow Loop	Nov 03
Completion of Temperature Tests	Mar 04
Completion of Field Tests	Apr 04
Publication of Results in GRC or SPE Journal	Sep 04

LEAMS

Acceptance of RD 100 award and plaques	Oct 04

IV. ENERGY SYSTEMS RESEARCH

Field Demonstration and Evaluation of Lined Heat Exchanger Tubes

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC02-98CH10866

Performing Organization: Brookhaven National Laboratory, Upton, N.Y. 11973

Principal Investigator: Toshifumi Sugama
Phone: (631) 344-4029
E-Mail: sugama@bnl.gov

Collaborating Researchers: Keith Gawlik, National Renewable Energy Laboratory
Paul Hirtz, Thermochem, Inc.
Ed Curran, Bob Curran & Sons Corp.
Bob Sullivan, Mammoth Pacific, Inc.

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $165K

Cost Share Funding: $250K

Project Objective: The objective of this program is to fabricate cost-effective, tough polymer composite liners with excellent thermal conductivity for 40-ft.-long carbon steel heat exchanger (HX) tubes using the state-of-the-art lining apparatus, and to subject these lined exchanger tubes to a field performance test at a geothermal power plant. The program also includes post-test analyses for long-term (more than two years) and short-term (less than two years) exposures of 20-ft.-long HX liners at a power plant. Additionally, we are evaluating whether films made by an organic solvent-free electrostatic powder coating technology would adequately protect carbon steel against corrosion. The economic utilization of binary working fluids in geothermal energy conversion cycles would dramatically increase the size of the exploitable portion of any hydrothermal resource. A significant cost in a binary plant is the components of the heat exchanger, such as tubes, shell, and sheet. The stainless steel and titanium alloy heat exchanger tubes presently used in such binary-cycle plants afford great protection against corrosion caused by hot brine. However, the corrosion-preventing passive oxide layers that form at the outermost surface sites of these tubes are detrimental in that the tubes become more susceptible to the deposition of silicate and silica scales, thereby developing a strong adherence to them. This strong bond not only requires using highly pressurized hydroblasting to remove the scale adhering to the tube's surfaces, but also entails a substantial amount of time to do so. If the carbon-steel tubes could be coated with a thermally conductive material that resists corrosion, oxidation, and fouling, then the capital and maintenance costs of the heat exchanger, containing on average 800 tubes, will be markedly reduced. Therefore, the goal of this program is to decrease carbon steel tube capital cost to ~ 100 %, compared to those of the titanium- and stainless steel-based heat exchangers, and provide a more robust generation capacity for power plants.

Background/Approach: Based upon data obtained before FY2003, the design criteria for the liner systems being developed in this program are as follows: 1) continuous operating hydrothermal temperature of 240°C; 2) thermal conductivity > 1.0 kcal/hr.m°C; 3) cost of liner <$ 1.00/ft; 4) ionic impedance of lining film after 15-day-exposure to 200°C brine: > 1 x 10^8 ohm-cm^2; 5) oxidation rate (O/C atomic ratio) of liner's surfaces after 15-day-exposure to 200°C brine: < 0.05; 6) abrasive wear rate by SiO_2 grit (particle size of 15 μm) under 150 m/s velocity and 0.6 MPa pressure for liner surfaces after 15-day-exposure to 200°C brine: < 0.1 μm/min; 7) bond strength of liner to tube: >5.0 MPa; 8) tensile strength of lining film before exposure: > 60.0 MPa; and, 9) low surface energy of liner: contact angle > 80° of water droplet on liner surfaces.

In FY 2001, emphasis was directed toward designing new thermal conductive PPS/SiC-based material systems possessing excellent abrasive wear and oxidation resistance, and also on developing a lining process technology suitable for the new PPS material systems. These new PPS systems contained two specific additives, Al_2O_3-rich refractory (ARR) to resist abrasive wear, and the anti-oxidant polytetrafluoroethylene (PTFE). Zinc phosphate (Zn.Ph)-primed 20-ft.-long heat exchanger tubes were lined with this new material. An eleven month field test of their performance was undertaken at the Mammoth Pacific power plant site operating at a brine temperature of 160 °C. After exposure, the results from the post-field test analyses showed that the anti-oxidation PTFE additive not only minimized the rate of the scale deposition, but also rendered the liner's surfaces inert to reactions with the scales. In addition, the PPS liner satisfactory withstood a 160 °C brine and displayed great resistance to the permeation of brine, thereby expressing outstanding performance in protecting the tubes against corrosion. The ARR added for resistance to abrasive wear abated the extent of wear damage during hydroblasting. In contrast, the surfaces of unlined stainless steel tubes were very sensitive to the deposition of calcium silicate hydrate and silica scales, which developed a strong adherence to the tubes. This new coating system also resolved the problem of highly concentrated hydrogen sulfide-induced corrosion of the carbon steel piping system in cooling towers at the geothermal flash steam power plant in Cove Fort, Utah. Although the temperature of the basin ranged from 5° to 20°C at most, bare carbon steel underwent severe corrosion and erosion during only two months of exposure. In contrast, blending the anti-oxidant PTFE into the PPS reduced conspicuously the degree of H_2S-caused oxidation of the coating's surfaces, and made them hydrophobic, lowering their susceptibility to moisture. Hence, the PTFE-blended PPS material system has great potential for use as an anti-oxidative and anti-corrosive coating in sulfur- and sulfate-containing geothermal environments. However, the field test revealed that one shortcoming of the ARR- and SiC-filled PPS/PTFE liners was their brittleness, thereby requiring the development of lines that were tough and flexible. Nevertheless, based upon these very promising results, Bob Curran & Son Corp., commercialized this PPS-based lining material system under the trade name "CurraLon". In FY 2002, in efforts to improve the toughness-related properties of the liners, BNL succeeded in formulating a carbon microfiber-reinforced PPS/PTFE composite material system and in developing its lining technology. The carbon microfibers used were 100 to 200 μm long, with a ~ 7.5 μm in diameter. The composite not only significantly improved the toughness of liner, but also raised its thermal conductivity to 1.0 Kcal/hr.m °C. Three 20-ft.-long heat exchanger tubes were lined with this composite material, and then were sent to NREL to undergo a year-long field test at the Mammoth power plant. Using this composite lining system which met all the material criteria, the capital costs of the heat exchanger, containing on average 800 tubes, would be strikingly reduced by ~ 83% and ~ 80%, compared to those of the titanium- and stainless steel-based heat exchangers, respectively. Consequently, this high-performance PPS composite lining system was selected for the prestigious "Research and Development (R&D) 100 Award" in 2002. Additionally, post-approval tests were undertaken to determine the technical feasibility of BNL's state-of-the-art apparatus specifically desinged for lining the horizontal 40-ft.-long tubes, and also the reproducibility of the liners deposited on these tubes. The factors to be assessed included the liner's thickness, surface roughness and its adherence to underlying tube surfaces.

Status/Accomplishments: In FY2003, almost one year after the state-of-the-art lining apparatus was installed, work was completed to establish its operation parameters, in particular, equipping it with an impedance heater to regulate heat flow and thermal distribution in the 40-ft.-long HX tubes. In addition, work was finished on modifying the original apparatus to arrive at a cost-effective, laborsaving operation. Now, with this modified apparatus (Figure 1), one person instead of two can complete the entire fabrication process including preparing the surface of the tube and depositing the zinc phosphate primer and polymer-based liner. It also is intended to serve as a test bed for techniques to line pipes and to repair damages on liners incurred in the filed. We successfully lined the internal surfaces of 0.97-in.-diameter x 40-ft.-long HXs with two PPS-based material systems, zinc phosphate primer/single PPS and zinc phosphate primer/carbon microfiber-reinforced PPS/PTFE. These lined HX tubes were sent to the Mammoth power plant where NREL is conducting a year-long field validation test.

Figure 1. The modified state-of-the-art apparatus for lining 40-ft.-long heat exchanger tubes using impedance heating system.

In November 2002, the field performance test at Mammoth Power Plant site was completed for four 0.9 in. diam. by 20-ft.-long HX tubes lined with four different coating systems. BNL performed the post-test analyses for these liners after exposure for 27 and 19 months. The following conclusions were drawn from the test results: The thermally conductive, wear-resistant lining system consisting of a ZnPh primer, a SiC-filled PPS intermediate layer, and a ARR-filled PPS top layer adequately protected the underlying carbon steel tubes against CO_2-laden brine-induced corrosion at 160°C during their 27-month exposure. Although the amount was negligible, the deposition of some scale was microscopically observed on this liner's surface. For thermally conductive, tough carbon fiber (3 mm long)-reinforced PPS composite lining systems, their carbon fiber content was the key to their successful fabrication on the internal tube's surfaces. The composite liners made by incorporating an excessive amount of fiber in the PPS matrix failed during their 17-month exposure. This failure was due primarily to the non-uniform distribution of fibers in the PPS matrix caused by the entanglement of fibers during fabrication. This generated two serious problems. One was the formation of a porous microstructure, allowing brine to permeate through the composite liner; the other was the poor adherence of the fibers to the primed surface, causing the delamination of the liner from the primer surface. Thus, if 3-mm-long fibers are used, the appropriate amount of fiber to incorporate into the PPS matrix would be around 0.1 wt%. In response to concern about the integrity of the PPS liner at the HX tube-to-tubesheet joint, a small-scale specimen of a PPS-lined tube/tubesheet joint was prepared and immersed in an 80°C ultrasonic brine bath with a vibration frequency of 40 kHz. A1500-hour-long exposure test was completed and no damage to the liner at the joint was reported. The result of analyses of small diameter HX tubes (less than ½- in. O.D.) being lined by Ed Curran Corp. after a field test at Puna raised concern about the uneven thickness of the liners that caused its localized delamination from the underlying steel during exposure. This strongly suggested the need to reformulate the PPS slurry for HX tubes that are less than ½-in. O.D. Also, an ASTM non-destructive inspection test for the liner's thickness will be required to ensure that its thickness is uniform before any field tests. For our (BNL and NREL) efforts to transfer PPS coating technology to the private sector, we won a prestigious "Federal Laboratory Consortium for Technology Transfer (FLC) Award" in 2003.

Additionally, using an advanced Nordson powder coating apparatus, we completed work to optimize the process technology involving electrostatic powder coating for PPS of < 20 microns size. From a spray gun-to-part distance of ~ 5 in., the PPS powders were projected onto the steel panels. We found that when the feedback current of this apparatus was set at an output voltage of 25 kV, the weight of PPS powders deposited on the very heavy zinc phosphate (~ 300 micron thick)-primed steel panels was almost the same as that deposited on bare steel panels. This finding strongly affirmed that this apparatus is capable of fabricating a desired thickness of coating on the electrically insulated primer surfaces. With this entire coating process, called "powder-spraying-melting-cooling", an adequate film thickness for PPS can be obtained by repeating the process only three times, underscoring that the organic-free powder coating technology not only alleviated any environmental concerns, but also saved substantial time consumed in completing the coatings. To ensure that the coatings fabricated by this technology adequately protected the carbon steel against corrosion, steel panels coated with the PPS, ~ 5 mil thick, were exposed for 20 days to brine at 250°C. No failure of the coatings was reported from analyses of exposed panels.

Reports & Articles Published in FY 2003:

T. Sugama and D. Elling "Completion of the State-of-the-art Lining Apparatus for 40-ft.-long Heat Exchanger", May 2003.

T. Sugama and K. Gawlik "Post-test Analyses for 27-mo.-old PPS/SiC Liner and 19-mo.-old Carbon Fiber-reinforced PPS Liners", March 2003.

Presentations Made in FY 2003:

Planned FY 2004 Milestones:

Develop modified ASTM non-destructive test for liners	Jan 04
Prepare two 40-ft.-long lined tubes for field test at Mammoth	Mar 04
Prepare two 20-ft.-long lined tubes for field test at Puna	Apr 04
Delivery 40- and 20-ft.-long lined tubes to NREL	May04
Complete post-test analyses of 1.5 year-long exposed 40-ft. HX liners	Aug 04
Report the results of the laboratory and field-test	Sep 04

Materials Field Testing

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:

Performing Organization: National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

Principal Investigator: Keith Gawlik
Phone: (303) 384-7515
E-Mail: keith_gawlik@nrel.gov

Collaborating Researchers: Toshi Sugama
Brookhaven National Laboratory
sugama@bnl.gov

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@hq.doe.gov

DOE Funding Allocation: $175K

Cost Share Funding: $200K in-kind estimated by Bob Curran & Sons, Mammoth Pacific LP, Puna Geothermal Venture

Project Objective: Corrosion, erosion, and fouling by scale deposits are major issues for geothermal-fluid-wetted heat exchanger tubes and other plant equipment in geothermal power plants at several reservoirs. In some cases, expensive corrosion-resistant alloys are used in shell and tube heat exchangers or other components because of the need for corrosion resistance. In other cases, frequent heat exchanger retubing or equipment replacement is required to repair corroded tube bundles. Capital and maintenance costs of geothermal equipment in these environments can be reduced considerably if inexpensive carbon steel tubes could be coated with a low-cost, thermally conductive coating that provides corrosion resistance equal to that of high-grade alloy steels, thus reducing the levelized cost of generating geothermal power. Corrosion-, erosion-, and fouling-resistant coatings for carbon steel tubes have been investigated at Brookhaven National Laboratory (BNL) and the National Renewable Energy Laboratory (NREL), in cooperation with industry partners CalEnergy Operating Company, Mammoth Pacific LP, Bonnett Geothermal, Calpine, Puna Geothermal Venture, Thermochem, and Bob Curran & Sons. These partners have hosted field tests of the coatings at geothermal power plants, assisted in field testing, or have commercialized the coatings.

Objectives in FY03 were to start field tests in new locations, maintain tests in current locations, and install another PPS-coated piece of equipment in operating service at a geothermal power plant. All objectives were met.

Background/Approach: The research program is developing coatings for high- and low-temperature applications. On the high-temperature side of the plant, the goal is to develop a coating less susceptible to high-temperature hydrothermal oxidation. We found that polyphenylenesulfide (PPS) is one polymeric material that meets these requirements. Although PPS coatings showed oxidation after exposure to acid brine at 390°F, they played a key role in successfully protecting inexpensive carbon steel heat exchanger tubes against corrosion in wet, harsh, geothermal environments. Our findings suggested that PPS-coated carbon steel tubes can be used in place of expensive titanium alloys, Inconel, and stainless steels, which are frequently used in geothermal power plants. Because of its semicrystalline polymer structure, PPS has good surface hardness and smoothness. Fillers are used to further improve the hardness, thermal conductivity, and surface energy characteristics of the PPS coating.

On the low-temperature side of the plant, we have begun to explore organometallic polymer (OMP) coatings to protect evaporative condensers and aluminum finned tubing sprayed with geothermal fluid or well water. Strategies to use geothermal fluid to augment heat transfer by evaporative means are being explored at a number of geothermal plants in new and retrofit applications. An approach considered by air-cooled plants is to spray geothermal fluid directly on the finned tubes of condensers during the summer. The finned tubing has been shown to experience severe pitting and scaling during short tests with relatively clean geothermal fluid. OMP coatings are being considered for these applications.

Status/Accomplishments: In FY03 field tests were conducted at a number of current and new sites (Figure 1). Field tests of internally coated heat exchanger tubes continued in two test skids installed at the Mammoth Pacific binary plant using side streams of production and injection fluids (Figure 2). At this facility tests have been ongoing since August 2000, and some test articles have been in the apparatus for over two years. These tests have yielded important data on long-term exposure of PPS to the highest temperatures at which it has been tested in the field. Other test articles were installed, periodically inspected, and removed over the course of the year with a variety of coating formulations. At the Cove Fort plant, a test site which used flash and binary technologies, the first installation of an operating piece of PPS-coated equipment occurred in the Spring of 2002. This installation consisted of coated steam vent pipelines that experienced severe corrosion in the past due to exposure to acidic condensing steam. The test ended in June 2003 when the plant was permanently shut down. The coated steam vent pipeline was inspected at that time and found to have completely resisted attack by acidic condensate. Fabrication and installation of a test apparatus were accomplished at the Puna Geothermal Venture plant, a new test site where especially aggressive fluids are encountered (Figure 3). Tests of coated and uncoated tubes exposed to injection fluids began in the late summer of 2003 with initial results expected at the beginning of FY04. A test also started in May 2003 at the Geysers of a PPS-coated caustic injection pipe spool (Figure 4). This installation was at the Aidlin plant and the pipe spool was reported to be performing well as FY04 began. OMP-coated finned tubing test articles were exposed to brine spray at Mammoth in a test continuing into FY04 (Figure 5). Plans were made to continue tests of OMP-coated aluminum finned tubing in an apparatus designed to spray samples in a cyclic wet-dry manner to accelerate the test.

This project, titled Smart High-Performance (PPS) Coating System, won a Federal Laboratory Consortium Award in May 2003.

Reports & Articles Published in FY 2003:

A report on FY03 activities, “Long-term Field Testing of Polyphenylenesulphide Composite Coatings,” was presented at the Geothermal Resources Council Annual Meeting and published in the transactions, but this meeting occurred in FY04.

Presentations Made in FY 2003: See above.

Planned FY 2004 Milestones:

Establish loan agreement with Puna for equipment required for long term testing, install equipment	Jan 04
Complete current exposure test at Mammoth, hydroblast selected tubes, cut and visually inspect samples, ship samples to BNL	Feb 04
Install new apparatus for testing OMP coatings at Mammoth	Mar 04
Complete current exposure tests at Puna, visually inspect tubes, perform heat transfer analysis, install new coated tubes for long term testing, ship samples to BNL	April 04
Evaluate PPS-coated caustic injection spool at Aidlin plant	July 04
Complete next exposure test at Mammoth, clean selected tubes, cut and visually inspect samples, ship samples to BNL	Aug 04

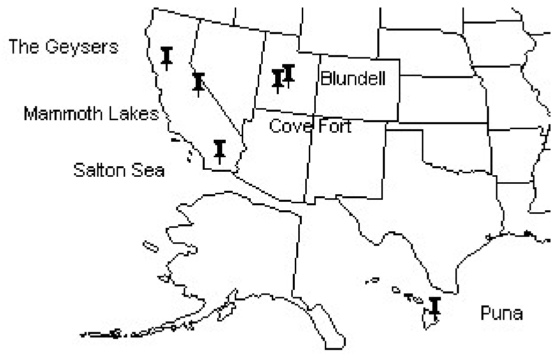


Figure 1. Map of current and past testing locations.

Figure 2. One of two sidestream skids used at Mammoth for testing coatings exposed to production and injection fluids.

Figure 3. Apparatus installed at Puna for testing coated tubes exposed to injection fluids.

Figure 4. PPS-coated caustic injection spool installed at the Aidlin plant at the Geysers.

Figure 5. OMP coatings exposed to brine spray at Mammoth.

High-Performance Coating Materials

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC02-98CH10866

Performing Organization: Brookhaven National Laboratory, Upton, N.Y. 11973

Principal Investigator: Toshifumi Sugama
Phone: (631) 344-4029
E-Mail: sugama@bnl.gov

Collaborating Researchers: Keith Gawlik, National Renewable Energy Laboratory
Bob Sullivan, Mammoth Pacific, Inc.
Douglas Jung, Two-Phase Engineering & Research Corp.
Paul Hirtz, Thermochem, Inc.

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $100K

Cost Share Funding: $70K

Project Objective: Corrosion, erosion, and fouling by scale deposits on carbon steel heat exchangers, well head pipes and aluminum-finned condensers at power plants has raised serious concerns in geothermal plants. These issues lead to a decrease in electrical generation, decline in the efficiency and profitability of plants, and an increase in the capital and operational costs, as well as environmental issues. In resolving these problems, the objectives of this project are to develop a 300°C-stable yet tough polyphenylenesulfide (PPS) and polybenzimidazole (PBI) composite coatings for heat exchangers and well head pipes, and to synthesize an organometallic polymer (OMP) for potential use as a thin hard coating for the condensers. The project also was designed to obtain a fundamental understanding of the characteristics of the developed coating systems before applying them to full-scale metal substrates. In collaboration with NREL, Mammoth Pacific Corp., Two-Phase Engineering & Research Corp., and Thermochem Corp., the ultimate goal of this program is to extend the useful lifetime of inexpensive carbon steel heat exchangers and well head pipes under a harsh, hostile environment with ≥ 250°C brine by lining them with such composite coatings, and similarly to enhance the efficacy of the condensers by applying a very thin hard coating film. The success of these coating systems will not only increase electric generation capacities, but will also substantially decrease capital costs because they will eliminate the need to use expensive stainless steel, titanium alloys, and inconel.

Background/Approach: In 2002, our efforts were devoted to developing innovative PPS composite coatings with advanced properties, in particular, thermal conductivity, toughness, and self-healing. For the first two properties, we assessed the effectiveness of the short milled carbon microfibers (7.5 μm diam. x 100-200 μm long) in improving these properties. After adding 5 wt% fibers, the thermal conductivity of the PPS coatings rose 2.6 fold to 3.7 kJ/h.m.°C. Furthermore, 3 wt% fiber-reinforced PPS coating films displayed a great tensile strength and elongation of 40.8 MPa and 5.8 %, respectively, corresponding to the improvement of 5.2 times and 2.6 times over those of the non-reinforced coatings. In attempting to develop a self-healing composite coating, we incorporated the hydraulic monocalcium aluminate ($CaO.Al_2O_3$) and calcium dialuminate ($CaO.2Al_2O_3$) reactants into the PPS matrix. The hydrothermal reactions of these reactants within the cracks led to the rapid growth of hard, strong boehmite (γ-AlOOH) crystals known as engineering ceramic. During exposure for 10 hours to 200°C CO_2-laden brine, the block-like boehmite crystals, ~ 4 μm in size, densely filled and sealed the open cracks, suggesting that the sealing of the cracks by the boehmite crystals played an essential role in reconstituting and restoring the function of the failed coatings as a corrosion-preventing barrier. Therefore, PPS coating films filled with these reactants are able to self-heal and –repair cracks generated on their surfaces in hydrothermal environments. The smart, multifunctional PPS coating systems described above were designed to withstand the hydrothermal temperatures up to 200°C. One important question remained unanswered. Will this coating adequately protect the underlying steel against a very harsh environment with an upgrade temperature of 300°C? Thus, work was initiated to develop 300°C-stable composite coating systems. A nanocomposite technology was used to further enhance the coating's hydrothermal stability.

Another concern facing geothermal binary power plants during the summer, the most profitable period for selling electricity is a decline in the efficiency of the air-cooled condensers, causing ~ 30 % reduction of the plant's net monthly energy delivery compared with that in the winter. In trying to augment power output in the summer, relatively clean geothermal brine or treated waste water is directly sprayed over the surfaces of aluminum-finned steel condenser tubes; this technology is becoming increasingly important. In fact, the plant's output of water-sprayed condensers in the summer was almost tantamount to that of wintertime conditions. However, two intriguing questions remained unanswered: One concerns the susceptibility of the two metal components of the condenser unit, the aluminum fins and the carbon steel tubes, to brine-initiated corrosion; the other concerns the deposition of scale adhering to the metal surfaces. To resolve these concerns, a new polyaminopropylsiloxan (PAPS) polymer developed at BNL is evaluated for use as a corrosion-and fouling-mitigating coating for the air-cooled condensers.

Status/Accomplishments: In FY 2003, the program was divided into the following three tasks. Our first task was to develop a hydrothermally stable PPS nanocomposite coating system that withstands hydrothermal temperatures of ≥ 250°C. The second was to evaluate the usefulness of NASA-developed room temperature-curable PBI polymer as a high temperature corrosion-preventing coating. Our third task was devoted to synthesizing a new OMP to coat the condensers. The OMP precursor was required to possess a very low surface tension so that it thoroughly wets both the carbon steel and aluminum surfaces, thereby forming a thin, continuous, uniform film of ~ 10 μm thickness over the substrates. For the first task, we designed nanoscale boehmite crystal-filled PPS composite coatings and exposed them to a very harsh, 300°C corrosive geothermal environment. The boehmite fillers dispersed uniformly into the PPS coating, conferring two advanced properties: First, they reduced markedly the rate of blasting wear (Figure 1); second, they increased the PPS's glass transition temperature and thermal decomposition temperature. The wear rate of PPS surfaces was reduced three-fold when 5wt% boehmite was incorporated into the PPS.

During exposure for 15 days at 300°C, the PPS underwent hydrothermal oxidation in which sulfide linkages were substituted by sulfite linkages. However, such molecular alteration did not significantly diminish the ability of the coating to protect the carbon steel against corrosion. In fact, PPS coating filled with boehmite of ≤ 5wt% adequately mitigated its corrosion in brine at 300°C. One concern in using this

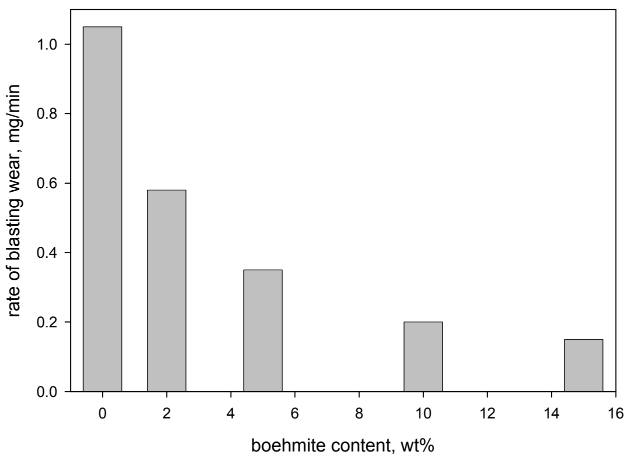


Figure 1. Changes in the rate of blasting wear for PPS coating's surface as a function of nano-scale boehmite filler content.

filler was that it absorbs brine. Thus, adding an excess amount of boehmite was detrimental to achieving maximum protection.

In the second task, the resulting data revealed that NASA-developed PBI displayed thermal stability at temperatures up to 600°C. However, when this film was exposed to 300°C brine, it underwent hydrolysis, causing the opening and breakage of imidazole rings in the PBI structure, followed by the formation of two hydrolysate derivatives, biphenyl tetra-amine and benzodicarboxylic acid. This shortcoming lowered the film's maximum effectiveness in minimizing the rate of transportation through it of corrosive electrolytes in hydrothermal environments. As a result, the PBI coating film was hydrothermally degraded, and it delaminated from the underlying steel substrates after a 14-day exposure. Based upon the above information, our work now will shift to developing PPS/ and polyetheretherketon (PEEK)/clay or graphite nanocomposite coating systems. PEEK has better thermal stability than PPS.

For our third task, polyaminoproplysiloxane (PAPS) synthesized by the condensation reaction of a water-based aminopropylsilane triol (APST) precursor solution at 175°C was evaluated for use as a corrosion-mitigating coating for air-cooled condensers consisting of two metal components, aluminum fins and carbon steel tube. For this assessment, a PAPS film of up to 2.2 μm thick was deposited on substrates of each metal through our dip-withdrawing-baking coating process. The effectiveness of the PAPS coating in mitigating corrosion depended on the species of metal; aluminum possessed better surface properties than steel, which aided in fabricating a void-free, uniform, continuous film. Among the factors governing the deposition of a satisfactory film over aluminum was the good wetting performance of the APST precursor, and the excellent adherence of the PAPS coating to the metal. Consequently, the useful lifetime of bare aluminum exposed in a 15 % salt-fog chamber at 35°C was considerably extended from only ~ 40 hours to more than 1400 hours by depositing the PAPS coating on its surfaces (Figure 2). By comparison, this coating extended the lifespan of bare steel from ~ 10 hours to ~ 216 hours. In trying to further improve the performance of this coating system, our attention will focus on modifying PAPS's molecular structure. Such modification will include increasing in the degree of cross-linking and enhancing the extent of coating's adherence to condensers, especially to the steel tube. The coated condensers will undergo a short-term (3-month) field-validation test at the Mammoth power plant. Additionally, BNL agreed to work with Two-Phase Engineering for developing a smoother, hydrophobic coating for steam separators at The Geysers.

Figure 2. Appearance of the condensers coated with 5wt% and 20wt% APST-derived PAPS after a 60-day slat-spray resistant test: Corroded condenser (left) and non-corroded one (right).

Reports & Articles Published in FY 2003:

T. Sugama and K. Gawlik, "Milled Carbon Microfiber-reinforced Poly(phenylenesulfide) Composite Coatings for Abating Corrosion of Carbon Steel at Brine Temperatures up to 250°C", Polymers & Polymer Composites, 11 (2003) 161-169.

T. Sugama and K. Gawlik, "Self-repairing Poly(phenylenesulfide) Coatings in Hydrothermal Environments at 200°C", Materials Letters, 57 (2003) 4282-4290.

T. Sugama, K. Gawlik, and D. Jung, "Polyaminopropylsiloxane Coatings for Geothermal Air-cooled Condensers", Recent Research Developments in Materials Science, (in press).

T. Sugama and K. Gawlik, "Nanoscale Boehmite Filler for Corrosion-and Wear-resistant Polyphenylenesulfide Coatings", Polymers & Polymer Composites, (in press).

T. Sugama "Hydrothermal Degradation of a Polybenzimidazole Coating" Journal Materials Science, (in press).

Presentations Made in FY 2003:

Planned FY 2004 Milestones:

Develop PPS- and PEEK-based nanocomposite coatings	Mar 04
Complete modification of PAPS coating	Apr 04
Develop Teflon-based coating	Jun 04
Deliver PPS-, PEEK -and PAPS-coated panels to Mammoth for field Tests	July 04
Deliver Teflon-coated panels to Two-Phase Engineering for field test	Aug 04
Report describing results of in-house work and field-evaluation tests	Sep 04

Internal Coatings for Geothermal Environment Applications

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: AC07-99ID13727

Performing Organization: Idaho National Engineering & Environmental Laboratory
Renewable Energy & Power Technologies
2525 Fremont Ave., P.O. Box 1625
Idaho Falls, ID 83415-3765

Principal Investigator: Karen A Moore
Phone: (208) 526-8852
E-Mail: gia@inel.gov

Collaborating Researchers: Ronald E Mizia

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $121K

Cost Share Funding: $5K

Project Objective: In extreme geothermal operating environments, operators are frequently forced to use exotic materials for piping and components, or to frequently replace these components. The intent of this project is to examine and validate the technology of spraying metallic coatings on the inside of pipes and other components to provide the same corrosion and scaling protection surfaces of the components as the exotic materials, but at a lower cost. Successful implementation of this technology will reduce the capital and maintenance cost for the geothermal fluid piping systems.

Coatings are considered a cost effective alternative to expensive alloys or the use of costly liners. The thermal spray process is a well established technique of propelling molten metal droplets through a trajectory onto a substrate where the freezing action allows for a mechanical bond between the metal substrate and the metal splats.

This project supports the DOE programmatic goals of reducing the levelized cost of power generated from geothermal energy. Validation of the technical feasibility of applying thermal spray coatings will lower capital costs relative to exotic material alternatives, or lower maintenance costs relative to the use of carbon steel as the material of construction.

Background/Approach: This project was initiated in response to inquiries by a geothermal operator as to how to properly specify the application of a thermal spray coating to ensure reliable performance. Investigators at the INEEL perform basic research on thermal spray coatings. In response to this inquiry and the receipt of DOE funding, INEEL investigators entered into a working agreement with a Salton Sea operator (CalEnergy), a Geysers operator (Calpine) and Zatorski Coating Company to focus on the issues related to applying thermal spray coatings to components in operating geothermal environments.

In cooperation with CalEnergy, a material-scoping test was conducted at a Salton Sea facility (coupons were exposed to geothermal fluid flow in the piping leaving a production well). Results were used to select a material for the internal coating of a carbon steel pipe that was then put in service and tested for a several month period. Coupons were then removed and examined to evaluate the integrity of the coating.

It is anticipated that this project will result in the development of a specification that can be used for the application of these coatings, as well as the identification of candidate materials for service with aggressive geothermal fluids.

Status/Accomplishments: A presentation of the results of the testing to-date and the cost analysis (relative to cement lined pipe) has been made to CalEnergy. The previously tested pipe will be grit blasted and recoated with the identified coating improvements. It is expected that these discussions will result in the installation of a second coated pipe that has the identified coating improvements. It is expected that the coating of this pipe will be done in the field by a company through a cost share with the INEEL. Test results will be incorporated into preparation of the fabrication specification and to the proposed revisions to the ASTM/NACE standards for thermal spray coatings to address those issues specific to geothermal applications.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003: None.

Planned FY 2004 Milestones:

Install recoated pipe at CalEnergy	February 2004

High-Temperature Polymeric Elastomers

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)	
DOE Grant/Contract No.:	DE-AC02-98CH10866
Performing Organization:	Brookhaven National Laboratory, Upton, N.Y. 11973
Principal Investigator:	Toshifumi Sugama
Phone:	(631) 344-4029
E-Mail:	sugama@bnl.gov
Collaborating Researchers:	Keith Gawlik, National Renewable Energy Laboratory Bob Sullivan, Mammoth-Pacific, L.P.
DOE HQ Program Manager:	Allen Jelacic
Phone:	(202) 586-6054
E-mail:	Allan.Jelacic@hq.doe.gov

DOE Funding Allocation:	$20K
Cost Share Funding:	$20K

Project Objective: The goal of this task is to replace the bronze oil-lubricated bearings in down-hole pumps extracting the geothermal energy resource from hot brine reservoirs (~ 160°C) for the brine-lubricated bearings made of the high-temperature stable polymeric elastomers. Success will eliminate the consumption of a substantial amount of oil and save the costs of maintenance brought about by mitigating damage to the shafting components in the pumps. In 2002, among the perfluorocarbon-related elastomers, our in-house work revealed that a cost-effective Viton®ETP-500 has a great potential as anti-swelling and anti-oxidation bearings in geothermal down-hole pumps. Thus, the objective is focused on conducting a long-term field-validation test at Mammoth power plant for this elastomer coupon to insure that the bearing made of this elastomer extends the useful service lifetime of line shaft pumps for at least ten years.

Background/Approach: Ogden Power Corp., owner/operator of three geothermal power plants at Mammoth Lakes, CA, was selected in 1998 to receive financial assistance for R&D of elastomeric, brine-lubricated bearings to replace the bronze oil-lubricated bearings installed on the Johnston line shaft production pumps. Brookhaven National Laboratory was brought into the project as a technical consultant on selecting and evaluating suitable elastomers, and has been involved in that capacity ever since. The initial bearings provided by Palmer Products did not perform well because of severe hardening of the bearing material and improper specification of clearances. Among the failed bearings were those made with acrylonitrile/butadiene copolymer (nitrile rubber) and fluorinated ethylene-propylene (fluoroelastomer, Viton®). The nitrile rubber underwent severe degradation shortly after exposure. Compared with that of the nitrile rubber, the Viton elastomer significantly extended its useful lifetime as a bearing. However, the chemical and physical analyses of the 1-year-old Viton bearing revealed that ~25%

of them already had been degraded by hydrothermal oxidation in this limited period. In contrast, the ethylene-propylene-diene-terpolymer (EPDM) bearing had far better resistance to oxidation, with the extent being 3.5 times less than that of Viton. In 2001, an additional problem arose in the field test at Mammoth when elastomers became swollen shortly after their being exposed to oil-contaminated brine. This was confirmed by BNL in a subsequent autoclave test with 160°C brine containing 82 wt% water, 13 wt% NaCl, 5 wt% steam cylinder oil, and 20,000 ppm CO_2, a composition considerably more extreme than that at Mammoth. The polymeric elastomers not only underwent hydrothermal oxidation under attack by the hot CO_2-laden brine, but also reacted with the steam cylinder oil, which caused them to swell. In 2002, in-house work evaluating the integrity of the various high-performance polymeric elastomers exposed in 5wt% steam cylinder oil-containing CO_2-laden brine at 160°C demonstrated that two perfluorocarbon-related elastomers, Kalrez® and Viton®ETP-500, have a great potential as anti-swelling and anti-oxidation bearings in geothermal down-hole pumps. Kalrez® showed an outstanding resistance to such an environment; for instance, there was no change in weight after exposure for five months. However, one concern about using this elastomer was its extremely high cost, estimated as $1500/lb. Although Viton®ETP-500 showed a slight gain in weight of 0.3 % after five-mo. exposure, its estimated cost $195/lb was considerably lower than that of Kalrez®. Based upon this material cost comparison, we selected Viton®ETP-500 for a 7-mo.-long field validation at Mammoth power plant. Keith Gawlik (NREL) performed this test, and BNL conducted the post-field test analyses to monitor its integrity during exposure. The factors to be monitored included alternations in microstructure, and change in elemental distribution on the surfaces and in the cross-sectional profiles, as well as changes in thermal stability and in physical properties, such as 100% modulus, tensile strength, and elongation.

Status/Accomplishments: When this Viton®ETP-500 coupon was exposed for 7 months, a specific characteristic of the SEM image was the appearance of cavities created by dislodging the SiO_2 fillers, suggesting that some degradation of the polymeric elastomer, which binds the fillers together into coherent masses, took place on its surfaces over the 7-month exposure. The EDX spectrum at the cavity indicated the incorporation of addition Na element into the top surfaces. Our attention next centered on exploring the cross sectional area of the 7-month-exposed coupon by SEM-EDX (Figure 1). The SEM image revealed two distinctive microstructures; namely, a superficial rim layer of ~ 4 μm thick with a relatively smooth surface texture, and beneath it, a layer with a rough texture. The EDX spectrum for the rim layer denoted as site “A” contained the undesirable element Na that represented the penetration of brine through the elastomer during exposure. In contrast, no Na was detected in area “B” at a distance of ~ 8 μm away from the top surface. Hence, the smooth rim structure can be categorized as degraded areas that allowed the brine to permeate into the elastomer, suggesting that a superficial layer of ~ 4 μm thick underwent degradation during the 7-month-long exposure. The analysis now shifted to assessing thermal stability before and after exposure. With a diamond-edged scrubber, we collected the samples from a subsurface layer at a depth of 1-2 mm. Figure 2 illustrates the TGA curves for these samples. For all samples, the onset of their major decomposition occurred around 400°C, demonstrating that although the elastomer was exposed over a long-term period of 7 months, its excellent thermal stability remained unchanged. The weight loss of ~1.9 % occurring between 140°C and 190°C for the 7-mo.-exposed samples was due primarily to the elimination of brine adsorbed in the degraded superficial layer of ~ 4 μm thick. All the information obtained above was correlated directly with the coupons’ physical properties (Table 1). Unexposed elastomers had a 100 % modulus of 1166 psi, a tensile strength at break of 1742, and elongation at break of 149 %. After 3-mo. exposure, the modulus and tensile strength fell ~19 % and ~ 10 % to 946 psi and 1577 psi, respectively. In contrast, this exposure time had increased elongation by 19 % to 177 %, meaning that the elastomer had become more elastic compared with the unexposed one. A further retrogression of modulus and tensile strength was reported from 7-month exposed specimens, while elongation increased somewhat. However, the rate of reduction of these properties was only 5 %

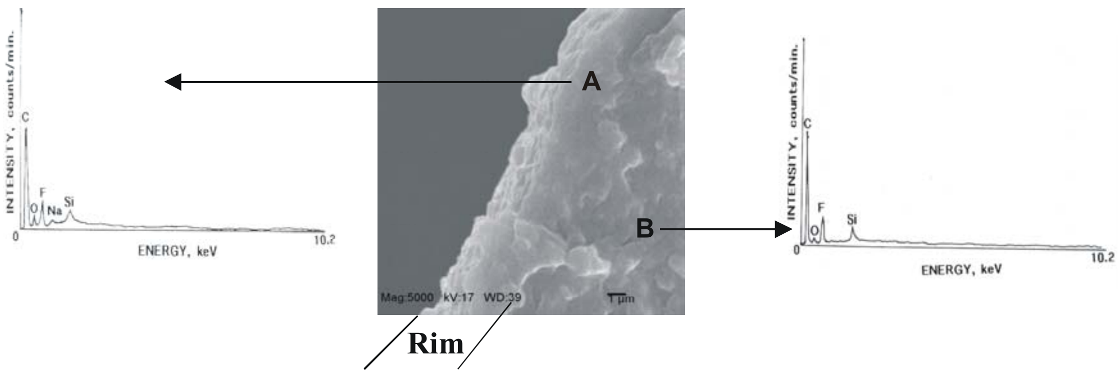


Figure 1. SEM-EDX data for the cross sectional profile of 7-mo.-exposed elastomer.

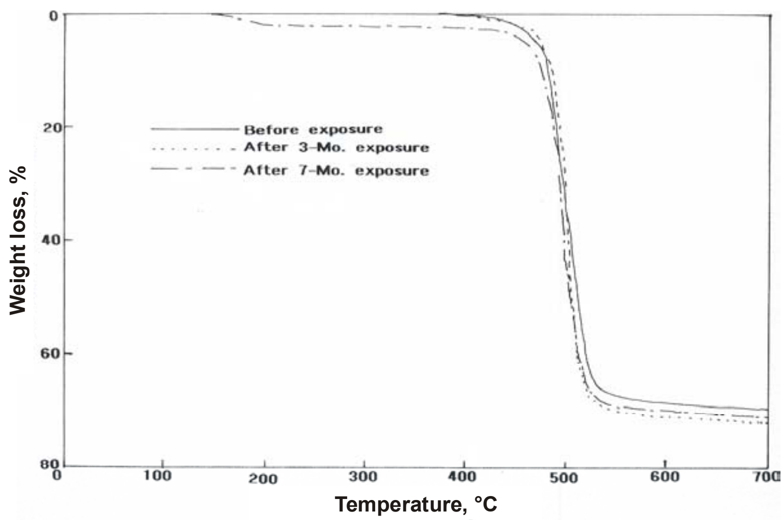


Figure 2. TGA curves for the unexposed and exposed elastomers.

and 3 % for the modulus and tensile strength, respectively, compared with those of 3-month exposure, while the increased rate of elongation was as little as 5 %. These findings demonstrated that the major changes in these physical properties occurred in the first 3 months of exposure; beyond that time, the changes occurred gradually as a function of exposure time, suggesting that such short-term retrogression may reflect a thermal shock. Despite these decrements, the elastomer exposed for 7 months still displayed great physical properties, such as 898 psi 100% modulus,1528 psi tensile strength, and 186 % elongation. Since the elastomer bearing was designed to be 8000 µm thick, this depth of degradation means that only 0.05 % of the bearing had deteriorated during this 7 months exposure. Assuming that degradation to a depth of 4 µm occurs progressively over every seven months of exposure, we estimated that for a 30-year used elastomer, the depth of degradation is as little as 206 µm, meaning that the damage to the elastomer is less than 3.0 % after 30 years use. As a result, we recommend the use of this elastomer as an anti-swelling and anti-oxidation bearing in geothermal down-hole pumps. BNL will assist Mammoth Pacific in its fabrication of Viton®ETP bearings for line shaft pumps. The task will involve qualitative reevaluations of “as-received” Viton ®ETP to ensure that it is the right material before its assembly in the pump. BNL will also monitor certain properties of these bearings as a function of real using time although this will depend on how long it will take to complete the bearing’s fabrication in the pumps.

Table 1. Typical physical properties of unexposed and exposed Viton®ETP-500 elastomers

Exposure time, month	100% Modulus, psi	Tensile strength at break, psi	Elongation at break, %
0	1166	1742	149
3	946	1577	177
7	898	1528	186

Reports & Articles Published in FY 2003:

T. Sugama, K. Gawlik, and Bob Sullivan "Viton®ETP-500 Elastomer: Seven-month Field Tests", August 2003.

Presentations Made in FY 2003:

Planned FY 2004 Milestones:

The proposed program aimed at assisting the fabrication of full-scale bearing and at monitoring the integrity of bearing installed in down-hall pump at Mammoth is not being funded, so that no milestones was made.

Non-Destructive Testing and Piping Integrity Assessment

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC02-98CH10886

Performing Organization: Brookhaven National Laboratory
Energy Resources Division, Building 526
Upton, New York 11973-5000

Principal Investigator: M. L. Berndt
Phone: (631) 344-3060
E-Mail: allan@bnl.gov

Collaborating Researchers: A. J. Philippacopoulos
(631) 344-6090
ajph@bnl.gov

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $250K

Cost Share Funding: None

Project Objective: The objective of this project is to evaluate methods for long-range non-destructive testing, integrity assessment and repair of geothermal piping systems. The project will identify, validate and support industry-wide implementation of better Non-destrictive Testing (NDT) and piping repair methods and thereby reduce operating and maintenance costs. The DOE programmatic goals of reducing the overall cost of generating geothermal electric power are supported by this project.

Background/Approach: Our research involves: (a) evaluation of NDT methods as applied to specific problems encountered in geothermal piping with emphasis on on-line, long range techniques; (b) integration of the results from NDT with remaining strength assessment; and (c) development of in-situ repair/strengthening materials and methods. The research plan is to combine input from geothermal operators, existing knowledge from industry, experimental work and numerical modelling to meet the identified needs in the most effective manner.

The first part of the project has involved determination of the limitations of current practices used by the geothermal industry for assessing pipe condition and the desirable attributes of better inspection methods. From this information, alternative methods and the development of new methods have been considered. In order to evaluate the potential of alternative NDT methods, it has also been necessary to investigate the morphology and statistical aspects of corrosion and erosion-corrosion in geothermal piping through evaluation of samples removed from plants. For this purpose, ultrasonic wall thickness testing was performed as well as microstructural analysis and determination of statistical distributions to describe spatial and depth distributions of corrosion pits. In addition, numerical modelling of wave propagation in piping with the types of defects typically encountered was performed in support of improving NDT methods. These investigations have led to delineation of certain global inspection technologies as being most appropriate and are being used in development of recommendations to the geothermal industry.

In the second area of the project, methodologies and the level of detail required from NDT for remaining strength assessment of geothermal piping are being investigated so that inspection and maintenance programs can be optimized. Existing analytical and numerical methods have been reviewed and a systematic approach for integrity assessment of internally corroded geothermal piping is being developed.

Finally, the third part of the project deals with in-situ repair/strengthening of geothermal piping systems. Piping that exhibits corrosion can be replaced, repaired or operated at lower pressure. Permanent repair is the preferable option in order to restore strength and extend useful service life, thereby lowering plant operating and maintenance costs. Repair by welding has a limited life and permanent repairs are more efficient. The approach taken in this task is to start with a review and evaluation of different methods and materials related to the long term repair of geothermal piping. The work will involve experimental evaluation of the relevant material properties of candidate high temperature composites. It is also necessary to analyze the stresses in repaired corroded piping in support of determining suitability for repair and required properties and configuration of the repair material.

Status/Accomplishments: In FY03 discussions were held with the developers of both types of guided wave systems and the issues of high temperatures, internal liners and the types of defects encountered in geothermal systems were covered. We have interacted with Southwest Research Institute and observed a demonstration of the magnetostrictive system on significant lengths (>100 ft) of large diameter pipes containing bends and elbows. We also had technical exchanges with Pennsylvania State University, Plant Integrity Ltd., PetroChem Inc. and Guided Ultrasonics Ltd. and visited the Ultrasonics NDE Laboratory at PSU to view operation of the guided wave method and discuss its application. The demonstrations and discussions gave great confidence in applying this technology to geothermal piping. Furthermore, modeling studies were conducted to assist in the understanding of guided wave propagation in geothermal piping systems. In these studies SH-waves were considered and dispersion curves were developed.

An industry-wide survey was performed in FY03 to give geothermal operators the opportunity to have input into the program. Those surveyed were asked to identify specific needs and priorities in the areas of nondestructive testing, integrity assessment and life extension of piping and other equipment. Respondents indicated definite need for long range screening of defects in insulated pipes operating at elevated temperature. Ability to detect pitting corrosion and accuracy of defect location were rated as important attributes of an NDT method. The use of NDT to estimate thickness of internal scale was of interest to some operators. Guided wave testing meets the need for detection of pitting corrosion and can identify the longitudinal location of defects. Furthermore, circumferential location can be given by exciting antisymmetric modes of propagation. Some literature exists that suggests guided waves may also have potential for estimating scale thickness. Significant interest was expressed in methods for in-situ repair and strengthening of corroded piping. Improved methods for piping integrity assessment were also identified as being important by the majority of respondents. These areas have been incorporated in our on-going and future research plans.

Alternative and more effective in-situ repair methods than welded patches or sections are being investigated in order to strengthen corroded piping and extend service life. Different concepts include external clamps, epoxy-filled sleeves, composite wraps and internal liners. Of these, composite wraps appear to have the greatest potential for repair and strengthening of geothermal piping. Composite wraps are finding increasing use to repair a variety of piping, particularly in oil, gas and chemical applications.

These repair materials typically consist of glass or carbon fibre reinforcement in a matrix of polyester, vinyl ester or epoxy resin. Use of multi-directional fibres in the form of fabric or random mat leads to improvements of both axial and hoop strength. Composite wraps can strengthen relatively long lengths of piping and can be applied to any diameter. The thickness of the installed wrap is usually around 0.5 in. In addition to chemical bonding at the steel/composite interface, surface preparation by sandblasting to a near-white metal finish is required in order to achieve some degree of mechanical bonding of the composite. Other possible applications of composite wraps in geothermal power plants include repair of vessels, vents and other structures. Successful implementation of composite wraps requires development and testing of matrix materials that will withstand high temperature environments and also exhibit resistance to degradation by geothermal fluids in the event of leakage. Conventional polyesters, vinyl esters and epoxies do not have the required temperature resistance. Alternative thermosetting resins are currently being considered such as modified vinyl esters, cyanate esters, and bismaleimides.

Determination of whether a pipe is a candidate for repair firstly requires detailed quantification of existing corrosion damage by NDT and subsequent prediction of whether defect growth is probable. Once the damage is documented in terms of location and geometry, the suitability of different repair methods and materials for the prevailing temperature and pressure conditions is evaluated. This entails assessment of the ability of the repaired pipe to withstand operational stresses, particularly if corrosion continues. Accordingly, engineering evaluation of the repaired pipe with existing and growing defects needs to be performed. Therefore, our research on development of analytical and numerical models for remaining strength assessment can be applied to assessing whether corroded piping can be repaired and strengthened adequately.

Recommendations to the geothermal industry with respect to NDT, integrity assessment and piping repair were documented and submitted to the GRC Bulletin for dissemination.

Reports & Articles Published in FY 2003:

M.L. Berndt, Update on Non-Destructive Testing, Integrity Assessment and Repair of Corroded Geothermal Piping, BNL Report No. Pending, Submitted to GRC Bulletin, 2003.

Presentations Made in FY 2003:

U.S. Department of Energy Geothermal Energy Program, ESR&T Peer Review, July 2003.

Planned FY 2004 Milestones:

Complete preparation of high temperature composite specimens	May 04
Complete uniaxial tensile tests on composites at range of temperatures	Jul 04
Complete thermal property tests on composites	Aug 04
Complete report describing findings	Sept 04

Enhanced Heat Rejection Systems

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:

Performing Organization: National Renewable Energy Laboratory

Principal Investigator: Charles Kutscher
Phone: (303) 384-7521
E-Mail: chuck_kutscher@nrel.gov

Collaborating Researchers: Eric Kozubal, Keith Gawlik, Bethany Rotherham

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@hq.doe.gov

DOE Funding Allocation: $300K

Cost Share Funding: $30K

Project Objective: The project objectives are to identify and develop improvements in geothermal power plant heat rejection systems, including improved air-cooled condenser designs, evaporative pre-cooling of air-cooled condensers, and combinations of air and water-cooled condensers. Our goal is to reduce electricity cost by 0.5-cent per kWh.

Background/Approach: Because of the thermodynamics of operating power cycles at typical geothermal resource temperatures, approximately 85-90% of the heat extracted from the ground must be rejected to the environment. As a result, air-cooled condensers account for as much as 30% of total plant capital cost or 20% of electricity cost. Water-cooled condensers are preferable from a performance standpoint, although air-cooled condensers are widely used in geothermal power plants because of the lack of cooling water. The cost of geothermal electricity can be decreased significantly if performance of the heat rejection systems can be improved. This is especially true for air-cooled plants during summer operation when electric output can drop by more than 50% due to elevated air temperatures.

NREL has developed spreadsheets and other computer-based models to evaluate the impact of improved condenser designs and operation strategies. NREL has used the models to compare different fin designs for air-cooled condensers. In FY03 we developed the concept of using small tabs punched into the fin surface to enhance the heat transfer. We are building and testing prototypes in conjunction with our industry partner, Super Radiator Coils. We also examined the potential benefits of tube-side heat transfer enhancements.

NREL has developed a spreadsheet to compare the cost and performance of various options for using evaporative cooling in conjunction with air cooling. This work has shown that several different evaporative cooling alternatives can significantly improve summer performance. As part of this effort, we have provided analytical and measurement support to the Mammoth Lakes power plant in their efforts to implement evaporative cooling systems. We have also investigated ways to combine water-cooled condensers with air-cooled condensers.

Status/Accomplishments: Invented Tab Fin Concept. We identified a new higher-performance concept for fin enhancement that involves the use of tabs punched into the fin material. Heat transfer is enhanced because each tab begins a new thermal boundary layer and reaches out to the coolest free stream air. The pressure drop penalty is kept to a minimum because the tabs align with the flow direction and are oriented to direct some flow into the wakes behind the tubes. We submitted a provisional patent application on this concept.

Fluent Simulations and Factorial Analysis. To examine the range of possible tab geometries we conducted a series of Fluent computational fluid dynamics runs. Design Expert software was used to design a factorial experiment that allowed us to determine the effects of tab height and length.

Improved Transient Test Apparatus and Flow Visualization Experiment. We designed, built, and instrumented an improved transient test apparatus that allows us to measure the performance of the tab fin concept. We also designed and built a flow visualization apparatus that uses the hydrogen bubble technique to see the flow path lines between fins.

Experimental Determination of Tab Fin Performance. Using our Fluent and flow visualization results, we conducted preliminary tests on small heat exchangers using tab fins and found significant improvement in overall performance. Base on these results, we began design of a tool for making a larger quantity of tab fins.

Analysis of a Trim Condenser. We exercised our computer model of a trim water-cooled condenser downstream of an air-cooled condenser and found the optimum trim condenser size based on overall economics. We prepared a paper on this for the annual Geothermal Resources Council meeting.

Field Measurements at Mammoth Power Plant. We again took measurements of the evaporative pre-cooling systems at Mammoth Power Plant. We determined cooling effectiveness, pressure drops, and the impact on fan performance and provided a report to Mammoth.

Reports & Articles Published in FY 2003:

C. Kutscher and K. Gawlik, “Report on Measurements of the Mammoth Pacific Power Plant Evaporative Pre-Cooling Systems taken on September 26-27 and November 13, 2002,” January 31, 2003.

E. Kozubal and C. Kutscher, “Analysis of a Water-Cooled Condenser in Series with an Air-Cooled Condenser for a Proposed 1 MW Geothermal Power Plant,” submitted to Geothermal Resources Council, July 2003.

C. Kutscher, “Heat Transfer Enhancement Methods,” written report submitted to Geothermal Energy Program Peer Review, July 31, 2003.

C. Kutscher, “Evaporative Cooling Enhancements for Air-Cooled Power Plants,” written report submitted to Geothermal Energy Program Peer Review, July 31, 2003.

Presentations Made in FY 2003:

C. Kutscher, "Heat Transfer Enhancement Methods," presented at Geothermal Energy Program Peer Review, July 31, 2003.

C. Kutscher, "Evaporative Cooling Enhancements for Air-Cooled Power Plants," presented at Geothermal Energy Program Peer Review, July 31, 2003.

Planned FY 2004 Milestones:

Complete fabrication of tab fin prototypes and reference heat exchangers	January 15, 2004
Obtain test results at ITS	February 15, 2004
Convene panel of experts to review NREL and INEEL concepts	March 1, 2004
Transfer concepts developed to date to industry	May 1, 2004
Perform Fluent analysis of any design modifications recommended by panel	May 1, 2004
Fabricate next-generation tab or combined tab/winglet concept for circular fin tubes, if appropriate	July 1, 2004
Fabricate heat exchanger for testing at ITS, if appropriate	September 1, 2004
Test results	October 1, 2004

Enhancement of Air-Cooled Condensers

Reporting Period: FY 2002 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:

Performing Organization: Idaho National Engineering & Environmental Laboratory
2525 Fremont Ave, P.O. Box 1625, MS 3815
Idaho Falls, ID 83415-3815

Principal Investigator: Manohar S. Sohal
Phone: (208) 526-9412
E-Mail: sohalms@inel.gov

Collaborating Researchers:

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@hq.doe.gov

DOE Funding Allocation: $185K

Cost Share Funding: McElroy Manufacturing, Inc., cash $3K plus in-kind

Project Objective: This task supports the programmatic goal of reducing the levelized cost of power generated from geothermal energy. By improving air-cooled condenser heat transfer performance by ~15%, installed component cost will be lowered, reducing the cost of power.

Background/Approach: Geothermal resources utilizing binary power cycles are frequently located in regions lacking a sufficient supply of make-up water for evaporative heat rejection system. Thus, heat is rejected directly to the ambient air using air-cooled condensers. Because air is a poor heat transfer medium, a large surface area of the condenser tubes is required. An EPRI report "Next Generation Geothermal Power Plant" prepared by Ben Holt Co. indicates the air-cooled condenser cost can be up to ~25% of the total plant cost (including well field). Improving the performance of the condensers is expected to have a significant impact on reducing the cost of power generated from these plants. Investigators have identified and confirmed the potential of vortex generators on fins of air-cooled condensers to improve heat transfer performance. The vortex generators (on the fins) induce swirling flow, which disrupts the formation of the boundary layer and mixes the flow between the fins. It also reduces the stagnant wake region behind a tube. This concept can reduce condenser size and cost in binary geothermal plants. The work at INEEL parallels efforts at NREL, which is using a different technology/concept to enhance air-side heat transfer performance. To date INEEL investigators have completed laboratory scale experiments, numerical work, and limited small-scale tube bundle testing. During FY02, all the work was completed on a NEDO-Japan grant that was used to supplement DOE funding. Negotiations were initiated in FY02 with several manufacturing companies. One CRADA agreements with a manufacturing company was signed in FY03

Status/Accomplishments: Testing of tube bundles with winglet configurations at the Single Blow Test Facility was completed. This established the thermal and hydraulic performance of the enhanced bundle. Subsequent to completing this testing, INEEL's enhanced tube bundle was independently tested at conditions equivalent to those used to test the NREL bundle in FY02. Overall benefit of the proposed enhanced tube air-cooled condenser was quantified considering performance enhancement (increased heat transfer and pressure drop). The CRADA agreement(s) was signed, which will address both the manufacturing issues related to cost effective incorporation of the vortex generators on to fin surfaces.

Reports & Articles Published in FY 2003:

Two papers reports were presented FY 2003.

Presentations Made in FY 2003:

J. E. O'Brien, M. S. Sohal, and P. C. Wallstedt, "Heat Transfer Testing of Enhanced Finned-Bundles using the Single-Blow Technique," 2003 ASME Summer Heat Transfer Conference, Las Vegas, NV, July 21-23, 2003.

M. S. Sohal and G. L. Mines, "Enhancement of Air Cooled Condenser Performance," Geothermal Resources Council Annual Meeting, Morelia, Michoácan, Mexico, Reno, NV, October 12-15, 2003.

Planned FY 2004 Milestones:

Complete independent testing of a tube bundle	Feb 04
Develop a path forward based on the recommendations of an independent reviewers panel	Mar 04

Air-Cooled Fin-On-Plate Heat Exchanger

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:

Performing Organization: National Renewable Energy Laboratory (NREL)
Buildings and Thermal Systems Center
1617 Cole Blvd.
Golden, CO 80401

Principal Investigator: Dr. Vahab Hassani
Phone: (303) 275-4427
E-Mail: vahab_hassani@nrel.gov

Collaborating Researchers: James Dickens (NREL), Dr. Ken Bell (University of Oklahoma)

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $235K

Cost Share Funding: None

Project Objective: The objective of this work is to improve resource utilization and reduce the cost of electricity generation from low-to-medium temperature geothermal resources. The specific goal is to develop new components to improve the performance and reduce the cost of heat-rejection units in air-cooled binary geothermal power plants. The results of this study will facilitate the designing of efficient heat-rejection units by manufacturers in the United States

Background/Approach: Our focus at the National Renewable Energy Laboratory (NREL) has been on designing and testing an enhanced air-cooled condenser that has superior performance when compared to the conventional air-cooled heat exchangers. The working fluid of choice for this study is ammonia/water. The work conducted during FY03 has led NREL researchers to design a prototype air-cooled fin-on-plate heat exchanger (absorber/cooler) with specific design considerations for mixing of vapor with lean liquid, as well as enhanced air-side heat-transfer coefficient. This work has many potential benefits, for example, reducing the size and expense of the condenser unit by as much as 30%, and reducing the turbine back-pressure (hence, increased power generation).

NREL has recognized that fins on plates can significantly reduce the air-side pressure drop, while making it possible to force air through the heat exchanger at higher velocities. This, in turn, results in higher heat-transfer coefficients. In addition, NREL has identified that highly concentrated vapor exiting the turbine can be readily condensed through a mixed absorption/condensation process. This process is accomplished by mixing lean liquid extracted from the high-pressure side of the cycle with the turbine exhaust. NREL researchers have concluded that the best way to thoroughly mix the liquid and vapor, while removing heat from the mixture, is to use a plate heat exchanger, rather than a tube-fin configuration.

Therefore, our objective has been to design, build, and test an air-cooled fin-on-plate heat exchanger as an absorber/cooler for binary geothermal power plants. Currently, all the heat exchangers (condensers) on the market are of the shell-and-tube or tube-fin type. No heat exchanger manufacturer has designed or built an air-cooled condenser of the type we propose. NREL tested several fin-on-plate configurations with very encouraging results. The heat transfer coefficients on the air-side were more that 50% higher than the conventional tube-fin heat exchangers.

NREL's fin-on-plate heat exchanger (Figure 1) has two flat plates placed face-to-face and welded together to form passage for the process fluid. A number of short fins are attached (by welding, brazing, or cementing) in a staggered or offset pattern to each side of a flat plate. The flat plate has multiple short studs or other separators welded to it. The fin-on-plate assemblies are then stacked together to form the heat exchanger. Air flows through the finned passages in countercurrent flow to the process fluid, which is distributed into and flows through the passage between the plates.

This configuration has several advantages – for example, the air flow parallel to the fins practically eliminates the form drag that arises in flow across banks of tube. Because the form drag results in a loss of pressure without a commensurate contribution to the heat-transfer process, air velocity can be increased without exceeding the allowed pressure drop. This results in a reduced cross-sectional area required to accommodate the air flow and an increased heat-transfer coefficient.

Further, the countercurrent flow arrangement ensures that the maximum possible temperature difference for heat transfer is realized. The close spacing of the plates ensures that the phases in multi-component condensing situations remain in close contact and, hence, maintain high heat- and mass-transfer rates and near thermodynamic equilibrium between the phase compositions. The downward flow of the condensing vapor results in the two-phase frictional pressure loss being largely offset by the hydrostatic pressure increase. Air blowers or low-pressure compressors may be conveniently used with this configuration if higher pressure drops are required. Because of this design, the fin-on-plate heat exchanger has the potential to be an excellent air-cooled condenser. NREL's effort will significantly benefit the geothermal industry, as well as other industries that use air-cooled heat exchangers.

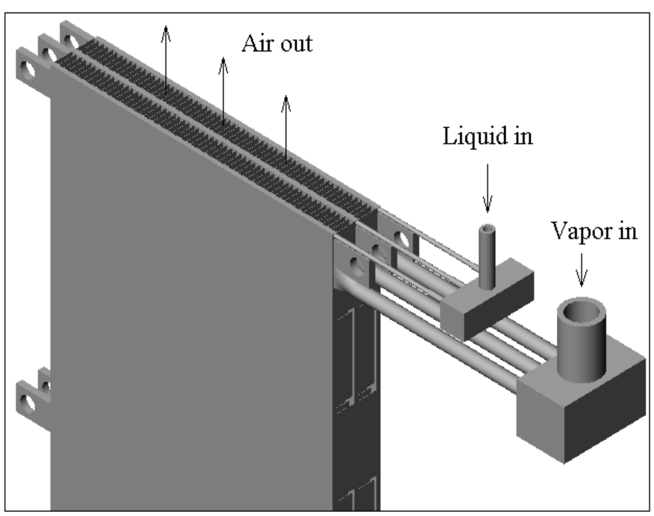


Figure 1. Fin-on-plate heat exchanger.

During FY03, NREL addressed several manufacturing issues related to the construction and assembly of the fin-on-plate heat exchangers. NREL developed a procedure for the design and fabrication of a fin-on-plate heat exchanger that can operate at high pressures. However, this procedure needs to be modified to be cost effective. It is also necessary to develop a commercialization plan for this type of heat exchanger. During this fiscal year, we addressed both the R&D and engineering design issues. NREL carried out tests to address issues such as development of the most effective air-side fin geometry, and development of heat transfer and pressure drop correlations for that fin arrangement. The engineering effort consisted of design of a liquid and vapor distribution system, plate and fin manufacturing and bonding techniques, and development of a cost-effective manufacturing procedure. The engineering design effort should be completed in collaboration with an industry partner. One of our major efforts during this year was to contact several heat-exchanger manufacturers in the United States and sign a collaborative agreement with one. We finally got the attention of Marley in that respect and we are still negotiating a collaborative agreement with them. We also had an independent testing facility (ITS) perform tests on our prototype fin-on-plate heat exchanger. The result showed an excellent agreement with those conducted at NREL.

Status/Accomplishments: During FY03 NREL completed testing of several fin-on-plate configurations. NREL had its prototype tested by ITS where the results compared very well to those conducted by NREL. NREL held collaborative work discussions with a major heat exchanger manufacturer. NREL developed a vapor distribution system for the fin-on-plate assembly. NREL developed a preliminary manufacturing technique for the fin-on-plate unit.

Reports & Articles Published in FY 2003:

We have written an NREL technical report on the performance of the fin-on-plate heat exchanger. Published a paper in the GRC 2003 meeting abstracts. Published a paper in The International Journal of Heat Transfer Engineering.

Presentations Made in FY 2003:

Technical presentations were made to Marley, and GEA Rainey.

Planned FY 2004 Milestones:

No activity planned for FY04

Continual Removal of Non-Condensable Gases for Binary Power Plant Condensers

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3625

Principal Investigator: Charles Mohr
Phone: (208) 526-9552
E-Mail: mohrcm@inel.gov

Collaborating Researchers: Greg Mines

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $167K

Cost Share Funding: In kind, only

Project Objective: Although not typically associated with binary geothermal power plants, non-condensable gases (NCGs) are present in these plants. Most of the commercial binary plants in operation have some provision for the periodic removal of these gases. This project is testing and evaluating the use of membrane separation technology to provide for the continual removal of the gases. The system being developed takes advantage of membranes developed for other industries that separate condensable organic vapors from air. This system is intended to minimize both the adverse effect these gases have on power output and the loss of working fluid to the ambient. This project is developing technology that will reduce the cost of generating electrical power by increasing the output of binary-cycle geothermal plants without requiring significant increases in operating or capital costs. In addition, the membrane system can be designed to minimize the release of working fluid, compared to the release associated with the current purge system. This will alleviate any associated public and institutional environmental and air-quality concerns.

Background/Approach: Once the concept was formulated, data from operating plants was evaluated to establish air introduction rates and estimate the probable benefit of the technology. Concurrently the membrane performance for the specific separations involving typical working fluids was established. This was done by subcontract to Membrane Technology and Research, Inc. (Menlo Park, CA), a developer of membranes suited for this application. A prototype pilot unit was then designed and built under subcontract by MTR. The front end of the system consists of a compressor and air condenser, similar to that of existing working fluid recovery systems. It differs in that membranes are installed on the discharge of the working fluid condenser to provide additional removal of the working fluid from the vent stream, allowing the plant condenser to be vented continuously with minimal working fluid loss.

Status/Accomplishments: The prototype system testing was completed at the Steamboat plant and is now undergoing testing at a second plant, Mammoth's MPI. Preliminary membrane tests results showed that the membranes were suitable for the separation of air from the working fluids at both plants. Separation factors of 12 to 15 were measured for air/working fluid mixtures at typical plant condenser compositions. Results of testing at Steamboat were reported at the September '02 GRC meeting, and showed excellent performance. The condenser of the test unit was reduced to 0.5% NCG over four days of pilot unit operation. The vented stream was typically 99+% air, demonstrating minimal working fluid loss. Some operational problems were observed; primarily associated with the return of liquid to the plant condenser. Operation of the condensate return pump was not completely reliable, resulting in system shut-downs from high liquid inventory. Modification to the control system improved performance, but it did not eliminate these shutdowns.

In March 2003, the unit was moved and testing started at the binary plant near Mammoth Lakes, CA. The unintended shutdowns that were encountered at Steamboat are more frequent at Mammoth and have thus far prevented continual unsupervised operation of the unit. Part of the issue with the more frequent shutdowns at this facility is due to the atypical air introduction rate to the plant; it is much higher than the removal rate for which the test unit is designed. Investigators and plant personnel are continuing to modify system's control logic and hardware configuration to provide a more reliable method to return liquid from the NCG skid to the plant condenser. When operating, the unit has proved beneficial to the Mammoth Lakes plant, effectively reducing the NCG content of the plant condenser despite the high introduction rate. Data also indicates that the working fluid losses have been reduced relative to the frequent condenser purges previously required.

Reports & Articles Published in FY 2003:

A patent for this process was issued in December, 2002.

Presentations Made in FY 2003:

Paper presented at the 2003 Geothermal Resources Council Annual Meeting.

Planned FY 2004 Milestones:

Complete modifications for extended operation.	(I)	Mar 04
Complete 4 month of continuous operation	(I)	Aug 04
Document test results and recommendations for further improvements.	(I)	Sep 04

Geothermal Plant Process Monitoring

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
Renewable Energy and Power Technologies
2525 North Fremont Drive, P.O. Box 1625
Idaho Falls, ID 83415-2211

Principal Investigator: Judy K. Partin
Phone: (208) 526-2822
E-Mail: jk6@inel.gov

Collaborating Researchers: None

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $189K

Cost Share Funding: $18K (Industry In-kind)

Project Objective: This project is directed toward DOE's goal of reducing the levelized cost of geothermal power to 3-5 cents/kWh by 2010 through the development and verification of low maintenance instrumentation for the real-time detection and control of abatement process parameters.

Background/Approach: Geothermal plants contain gaseous, liquid, and particulate species in process streams that require abatement to minimize equipment damage, maximize performance and/or meet regulatory requirements. These abatement processes involve the use of costly chemicals and/or the consumption of energy; and in addition, are conservatively applied, in part, because the targeted species are only measured periodically. Some examples of these processes include the over-application of iron chelate to ensure hydrogen sulfide emissions from cooling stacks remain within the regulated limits, and excessive steam washing to remove particulate and reduce chloride concentrations to levels that will not damage plant components. Continuous measurements could allow these abatement processes to be optimized and costs reduced. This project is applying new diode technologies that have been developed for the telecommunications industry in the design of robust instrumentation for the real-time monitoring of various stream parameters which impact operating cost and/or plant performance. Parameters targeted in prior year research included measurement of H_2S in the treated vent gas stream, and HCl and particulate in the steam line. Currently, the project is focusing on the development of a new on-line instrument for monitoring steam quality.

Measuring steam quality is important because of the impact that excessive moisture in the steam can have on the turbine performance and maintenance costs. Excessive moisture in the steam can lead to both erosion and scal-ing of turbine components. Both adversely impact turbine efficiency, which also decreases as the amount of moisture in the steam increases. Decreases in turbine efficiency reduce power output and lower revenue streams. In a 50 MW plant the revenue losses due to a 1 percentage point drop in efficiency is $175K per year or more (depending upon the cost of electricity). Over a year of operation, a typical (5%) efficiency degradation can reduce the annual revenues by as much as $850K for 3 cent power. Efficiency degradation due to erosion is not recovered by maintenance unless it includes costly repair or replacement. The cost to replace the turbine can exceed 5 million dollars. Development of a more sensitive, real-time instrument to detect the presence of moisture entering or leaving major steam plant components is expected to mitigate some of these costs.

Calorimeters are the most commonly used instruments for the measurement of steam quality, but difficulties with sensitivity, accuracy, and range limit their suitability for use in many applications. A number of factors can impact the sensitivity and accuracy of calorimeter data. The measurement of quality with this instrument is based upon the assumption of a constant enthalpy expansion from the process pressure to atmospheric pressure thus any heat loss from the measurement volume results in a deviation from this assumption and introduces error. The gases found in geothermal streams may also have different Joule-Thompson (dT/dP) coefficients; and consequently, a mixture of these gases and steam may not accurately correlate with the pressure/temperature curves used to interpret the data. In addition, calorimeter measurements are made with slipstream installations where the insertion of multi-port probes may disrupt the steam flow and result in measurement errors due to non-representative sampling. The calorimeter range is also restricted by its ability to produce a measurable superheat for determining steam quality. (For a 50 psig process stream, this limit is on the order of 3%.)

Since there is no commercially-available instrument that can produce real-time, *in-situ* data with high sensitivity over all the ranges of interest, a new optical steam quality monitor is being developed and tested. The measurement is based upon the selective absorption of infrared radiation for determining the water content of moist air and takes advantage of the strong rotational and vibrational absorption bands produced by water vapor (steam) and liquid water in the middle- and near-infrared ranges of the electromagnetic spectrum. Three wavelengths are used in the measurements: a wavelength that is strongly absorbed by water, a wavelength that is sensitive to water vapor (steam), and a reference wavelength that is minimally influenced by water and steam; and thereby, serves as the reference to correct for particulate or droplet scattering. The wavelengths are chosen to be as close as possible in order to more effectively correct for scattering effects.

While these techniques have been known for decades, they have not been widely used due to the cost and complexity of the instrumentation required. In general, large-scale, Nerst glowers were needed to provide sufficient infrared radiation for the measurements, which were typically performed in regions of the electromagnetic spectrum that were not compatible with remote sensing over optical fibers or the use of room temperature detectors. This instrument incorporates semiconductor emitter and detector technologies, developed by the telecommunications industry, that are sensitive, compact, relatively inexpensive, and compatible with standard low-loss optical fiber technology. All of these components operate at room temper-ature and can be packaged as devices that could be directly interfaced to steam lines and used to collect and transmit data from locations throughout the plant.

During FY00-01, laboratory testing was conducted to establish if the semiconductor devices would be sensitive enough to provide reliable signal changes in response to small ($\leq 0.05\%$) changes in steam quality. During FY-02, an initial evaluation of the concept was conducted at the Bonnett Geothermal Plant near Cove Fort, Utah. The purpose of this activity was to determine if a high sensitivity measurement could be obtained in an actual geothermal process steam. During the evaluation, steam from three locations including a well head, a steam line leaving a flash/separator vessel, and an ejector supply line was sampled and measured. In the experiments, the process steam was sampled into a well insulated, flow-through cell configured with three optical ports. Changes in the optical signals transmitted across the cell were digitized and transferred to a personal computer where they were displayed and logged. Since the process streams contained some unknown fraction of moisture the cell was configured with heaters so that the process steam could be dried. This capability allowed the researchers to introduce controlled changes in the process stream and observe the instrument response to these changes. The optical signals were compared with steam quality data collected with a throttling calorimeter installed in the sampling line near the exit port of the optical cell. The results of these experiments indicated that the optical technique was quite sensitive to change in the quality of these geothermal streams, detecting qualities as low as ± 0.03%. Building upon the success of these experiments, the FY03 goals were to develop optical interfaces for performing the measurement in an operating steam line, select a site for the installation and evaluation of the instrument, and then determine if a high-sensitivity can be maintained in an extended *in-situ* deployment application.

Status/Accomplishments: Guided by the results of the testing at Bonnett Plant, the instrument was modified for an *in-situ* deployment in a steam line. In particular, new window ports for interfacing the instrument to the line were designed and fabricated. The port design addresses some of the common problems encountered when optical probes are inserted into process streams, that is, preventing the build-up of condensate or particulate on the window and providing a capability to easily remove the probe for cleaning without impacting the process being monitored. The deployment and extended evaluation of the monitor is being conducted at the Brady Power Plant near Fernley, Nevada operated by ORMAT, Inc. The plant is well suited for the *in-situ* evaluation, since water washing is periodically used in the operation to reduce scale, providing known periodic changes in the steam quality for the instrument to track.

The optical window probes, shown in Figure 1, were installed on a turbine inlet line immediately upstream of the turbine and downstream from a series of throttling valves. The optical signals are fiber-optically-coupled from the optical windows, to the instrumentation box containing the emitters, detectors, controllers, and data acquisition system located in the control room.

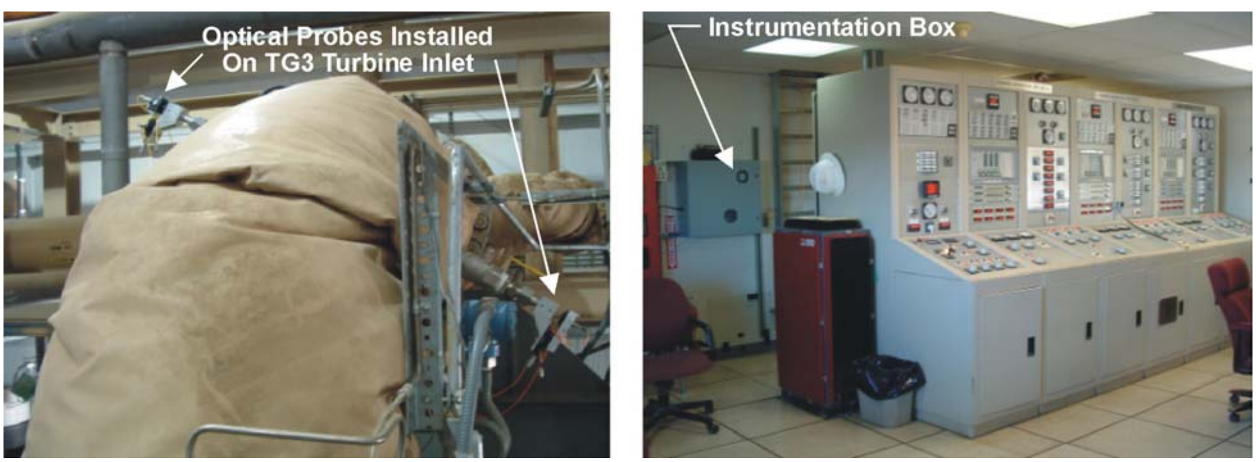


Figure 1. Optical steam quality monitor installation at the Brady Power Plant.

The optical steam quality monitor was installed at the plant on August 20, 2002 and is continuing to collect data. Figure 2 shows the response of the instrument to water introduced during a steam washing cycle performed at the plant. The plot shows the signal changes induced when small qualities of water

(1.0-1.5 gpm) are metered into the nominally 120,000 lb/hr steam flow. The monitor is seen to not only track these changes but also to return to its initial level prior to the initiation of the washing cycle.

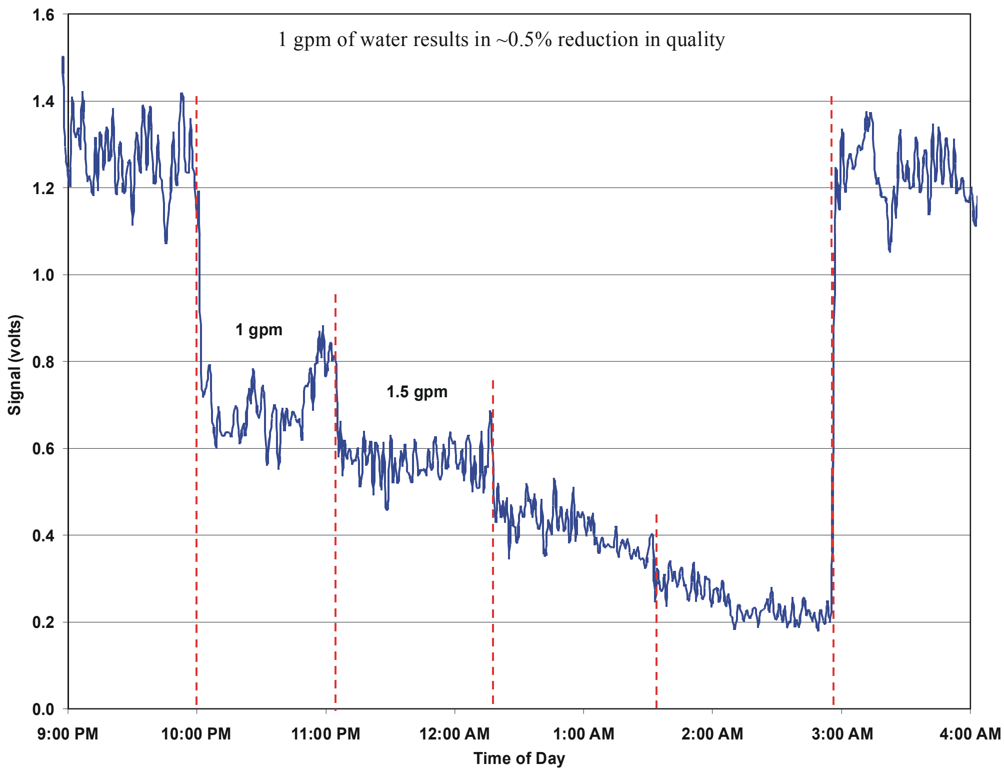


Figure 2. In-situ measurement of steam quality by optical monitor during a water wash at the Brady Plant.

In addition to verifying that the optical steam quality monitor can successfully detect changes in steam quality in an operating steam line, addition goals of the long-term deployment are to access the stability, reliability and to identify potential maintenance issues with the device.

In FY-04 the project will investigate the possibility of upgrading the instrument to include a particulate monitoring capability. This would allow operators to conduct on-line monitoring of both steam quality and purity with the same instrumentation for more efficient operation of their plants.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003:

J. K. Partin, "Geothermal Plant Gas Monitors," Department of Energy Geothermal Program Peer Review, Golden, CO, July 30, 2003.

Planned FY 2004 Milestones:

Results of the extended steam quality monitor testing at the Brady Plant reported	Apr 04
Design and cost estimate for particulate characterization system prepared	Aug 04

Microbiological Research

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
Renewable Energy and Power Technologies
2525 North Fremont Drive, P.O. Box 1625
Idaho Falls, ID 83415-2203

Principal Investigator: Peter A. Pryfogle
Phone: (208) 526-0373
E-Mail: wck2@inel.gov

Collaborating Researchers: Allen Sonneville, Calpine Corporation, asonneville@calpine.com
John Avery, Calpine Corporation, johna@calpine.com
Beth Kershaw, Calpine Corporation, bkershaw@calpine.com

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $125K

Cost Share Funding: $12,000 (Industry In-kind)

Project Objective: This activity is directed at investigating the impacts of microbiological activities on the efficient operation of geothermal power production facilities and developing techniques for mitigating the costs associated with these impacts. The specific objective of the 2003-04 work is to contribute to the DOE goal to reduce the levelized cost of geothermal power to 3-5 cents/kW-h by 2010 through the demonstration and validation of an on-line instrument for monitoring biofilm development. The project is developing and testing procedures for effectively using the instrument to minimize the impact of biofilm development in condenser and cooling tower systems in geothermal plants. The project goal is reduce the estimated cost of $500,000 for 100MWe plant due to lost revenue, cleaning, and chemical abatement by 50%.

Background/Approach: Microbial activity is an operational issue in power plants utilizing evaporative heat rejection systems. INEEL sampling studies at steam and flash-steam plants in California, Nevada and Utah have shown that cooling waters in their heat rejection systems contain significant densities of bacteria. The steam condensate utilized as cooling water make-up in these plants contains impurities such as hydrogen sulfide, ammonia, carbon dioxide, and dissolved solids that provide nutrition for microbial growth. Microbial organisms can adhere to the surfaces of critical components in geothermal heat rejection systems and develop complex structures called biofilms. The development of biofilms can impact plant performance in a number of ways. Their development on heat transfer surfaces retards the exchange of heat. The biofilms can damage equipment by direct corrosion processes, or by accelerating chemical corrosion activity. Microbial growth can also impact the effectiveness of plant chemical abatement systems. Investigations at the INEEL showed increased microbial activity after exposure to the iron chelate compound used in hydrogen sulfide abatement systems, indicating the compound served as a feedstock. Biofilms may also interfere with corrosion inhibitors by preventing their contact with the metallic surface.

The impediment to heat transfer due to biofilm development has the potential to significantly impact plant performance, and consequently plant revenues. Condenser temperature and pressure rise in response to this increased resistance to heat transfer, and power output declines as the associated turbine exhaust pressure rises. Experience at The Geysers indicates that the condensing pressure drops by ~ 0.5 inch-Hg after cleaning (on a two-year maintenance cycle). Examination of fouled condensers and deployed coupons indicate the fouling is dominated by biofilm development. Assuming the fouling is linear with time and a cost of power of $0.03 per kW-h, the associated lost revenues approach $400,000 annually in a 100 MWe plant. When the power revenues associated with cleaning both the condenser and cooling tower and with tube failures are included, the impact of microbial activity on the operation of a 100 MWe plant can exceed $500,000 annually.

Plant operators are well aware of the impact of microbial activity, which they attempt to control and mitigate with costly chemical applications. (An operator of a small 10 MWe, flash plant has indicated that their annual expenses for biocides approach $100,000.) In spite of the high costs, few geothermal plants have biological monitoring programs in place to detect growth problems. Most apply treatments on a predefined schedule, or in response to growth as evidenced by changes in flow parameters or film formation on coupons or other structures. In either case the operating efficiency has been impacted to some extent and larger doses of biocides may be required to eliminate the film. In addition, treatments are typically designed by the vendors selling the chemicals, who have little incentive to reduce their costs. Most biological control strategies are also geared toward reducing the number density (cells per unit volume) of the bacteria present. Work conducted by INEEL and other researchers indicate that it is possible to dramatically reduce the numbers of bacteria present without having any significant impact on biofilm development. Furthermore, not all the bacteria found in process streams may be detrimental. For example, species of sulfur oxidizing bacteria are found in geothermal cooling basins that are capable of metabolizing sulfide compounds and converting them to less toxic sulfate compounds, potentially reducing the amount of chemicals required for abatement. The ideal monitoring program would allow operators to identify, track and control the “activities”, such as biofilm development or sulfur oxidation/reduction, of the microorganisms for the most cost effective mitigation of these problems in their plants.

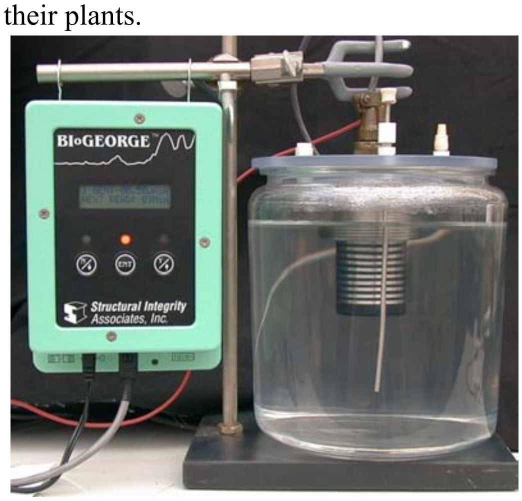


Figure 1. BIoGEORGE™ Monitor.

INEEL investigators have been evaluating analytical techniques for the detection and characterization of biological growth in geothermal plant cooling water systems. In particular, the utility of a commercially-available electrochemical probe, the BIoGEORGE ™ Biofilm Activity Monitor, that has been specifically tailored for the detection of biofilm formation, has been investigated. The monitor, pictured in Figure 1, consists of a stack of stainless steel discs comprising two identical electrodes. The electrodes are electrically isolated from each other and from the stainless steel plug that serves as the body of the probe. One electrode is polarized relative to the other for a short period of time each day to a preset DC potential. The polarization cycle creates an environment that encourages biological growth on the discs; and therefore, growth occurs on the instrument as a pre-cursor to fouling on plant components. Biofilm formation is then detected as an increase in the applied current required for achieving the preset potential. The instrument also monitors the current generated between the two electrodes when no external potential is applied. This current can also provide an indication of biofilm formation. The electronics for the control, data acquisition and data analyses are housed in the electronic box picture at the left of the probe.

During FY2001-02, the monitor was installed in a cooling water circulation line at the Bonnett Geothermal Plant (Cove Fort, UT) operated by Utah Municipal Power, for extended testing and evaluation. The goal of this testing was to determine if the probe, which had typically been installed in static environments, could be deployed in a flowing process stream and successfully used to collect data that could be correlated with other plant parameters, including visual observations, indicating growth problems. The results of this extended field evaluation concluded that the instrument did show promise as a real-time indicator of biofilm in geothermal plant cooling water systems. However, the operators at the Bonnett plant had some issues with its mode of operation. In particular they felt that instrument would be more valuable if the software could be modified to automatically update and display trend information on a daily basis. (Data had to be downloaded and manipulated in a spreadsheet to provide this trending information.) They also wanted to be able to determine the minimum reliable signal change, or trend, that indicated growth in their system, since that would provide the optimal control. They felt if these changes could be incorporated then they would be more confident about using the instrument for controlling chemical applications.

The FY-03 project work scope was developed to address these issues and complete the in-plant validation. This scope was developed under the assumption that this work would be accomplished at the Bonnett plant. How-ever with the sale and closure of this plant in early 2003, it was necessary to find another location for this testing. Calpine Corporation subsequently agreed to host this testing at its Aidlin Power Plant located near Middletown, CA.

Status/Accomplishments: Using input from the Bonnett plant investigation the BIoGEORGE ™ Biofilm Activity Monitor vendor, Structural Integrity (San Jose, CA), has modified the data acquisition software allowing the data to be automatically updated and displayed for real-time trending. In addition, the system has also been configured so that data can also be accessed via a modem for remote monitoring and analyses of plant stream conditions. The monitor probe was installed in a sampling line at the Aidlin cooling tower July 12, 2003. The installation, shown in Figure 2, provides access to the condenser circulation, is designed to simulate flow velocity through the condenser tubes, and contains coupon holder for the placement of metal substrates to be used for biofilm calibration and verification purposes. The real-time display was placed just outside the control room at the facility in a location that can be easily viewed by operations personnel.

Figure 2. BIoGEORGE ™ Biofilm Activity Monitor installed at the Aidlin cooling tower.

Baseline data is being collected to establish the monitor performance in this new process stream prior to attempting to use the readings for chemical control at the facility. This data is presented in Figure 3.

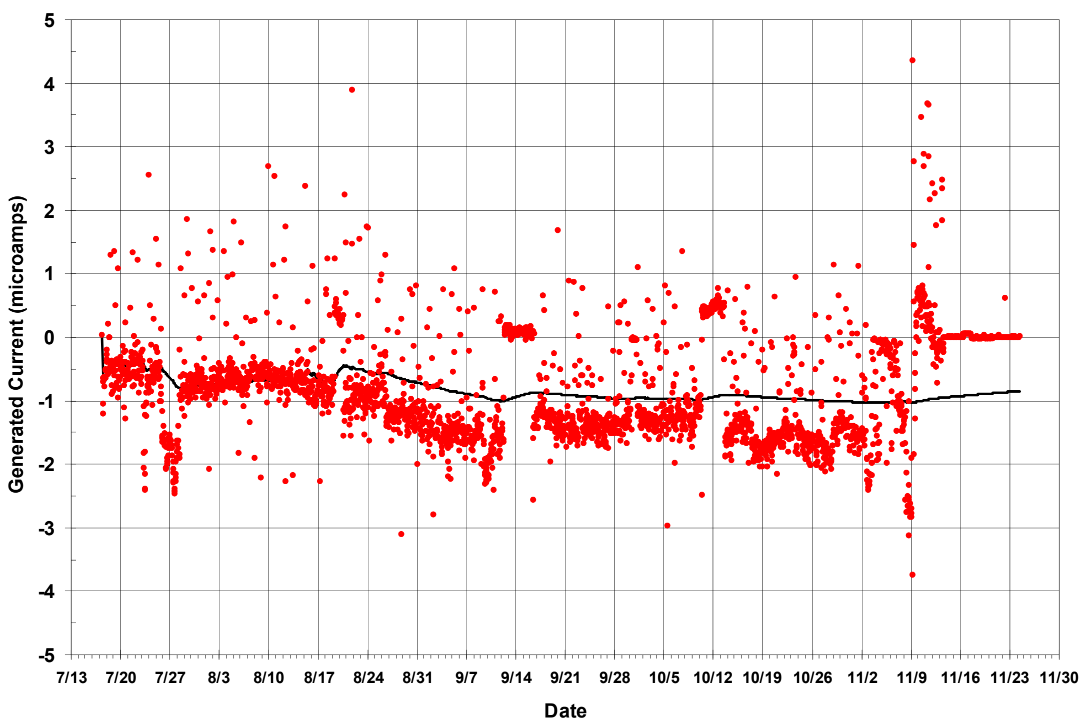


Figure 3. BIoGEORGE ™ Biofilm Monitor baseline data collected from Aidlin installation.

The applied current data collected to date exhibits significantly more noise than from the previous deployment at the Bonnett Plant; although, some trending is still evident. Investigators are working with plant operators and the instrument vendor to better understand the variances in the instrument readings before proceeding with the calibration and chemical application tasks at the plant scheduled to be completed in 2004.

Other geothermal operators have expressed an interest in using the procedures for installing and calibrating the monitor developed during this activity for optimizing chemical treatments at their facilities. In particular, operators at the Caithness Dixie Valley Plant and their chemical vendor, NALCO, are interested in implementing a system at their plant. They have a particular interest in the possibility of conducting remote monitoring of the on-set of fouling at the facility in order to reduce travel costs

Reports & Articles Published in FY 2003:

P. A. Pryfogle, "Monitoring Biological Activity In Cooling Towers and Condenser Circulation Systems at Geothermal Power Plants," Industrial Water Conference Proceedings, December 9-11, 2003, Las Vegas, N.V.

Presentations Made in FY 2003:

P. A. Pryfogle, "Monitoring Biological Activity In Cooling Towers and Condenser Circulation Systems at Geothermal Power Plants," Industrial Water Conference, December 9-11, 2003, Las Vegas, N.V.

Planned FY 2004 Milestones:

Procedures for the installation, calibration, and operation of the biofilm monitor reported	Jul 04

Investigation of Microbial Sulfur Oxidation for the Natural Abatement of Sulfides in Geothermal Cooling Tower Basins

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
Renewable Energy and Power Technologies
2525 North Fremont Drive, P.O. Box 1625
Idaho Falls, ID 83415-2203

Principal Investigator: Peter A. Pryfogle
Phone: (208) 526-0373
E-Mail: wck2@inel.gov

Collaborating Researchers: Allen Sonneville, Calpine Corporation, asonneville@calpine.com
Beth Kershaw, Calpine Corporation, bkershaw@calpine.com

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $45K

Cost Share Funding: $5K (Industry In-kind)

Project Objective: The goal of this project, initiated in May 2003, is to assist in lowering the levelized costs of generating geothermal power to 3-5 cents/kWh by 2010 by reducing the cost of hydrogen sulfide abatement in geothermal process streams through the optimization of natural abatement processes.

Background/Approach: The natural abatement of hydrogen sulfide that occurs in the cooling towers has always been considered to be purely inorganic oxidation by oxygen. However, operators have observed changes in the degree of abatement that occur for unknown reasons and cannot be explained by changes in oxygen solubility or activity. Since populations of sulfur-oxidizing bacteria, including various strains of *Thiobacillus*, are known to exist in these process streams it is reasonable to assume that some component of this abatement is due to microbiological activity. Operators, including those at the Calpine plants at the Geysers', are interested in investigating the ability of microorganisms found in the cooling basin to metabolize and cycle sulfides to less toxic sulfur compounds. If the role of these organisms were better understood, then it might be possible to take steps, such as adding nutrients to selectively enhance growth, to increase natural abatement in the cooling tower. This could result in substantial cost savings by reducing the quantity of expensive chemicals that are currently used for sulfide abatement.

A key element of this work is to develop techniques for tracking and manipulating the microbial communities found in cooling tower basins in order to enhance sulfide-oxidation without increasing fouling or acid production in the systems. The hypothesis to be tested is that by performing nutrient enrichments in an oxygenated environment, such as the cooling tower, the growth of sulfur-oxidizing bacteria will be favored over other organisms that may be detrimental to the plant performance.

Status/Accomplishments: The Sonoma facility at CALPINE was selected as the test site for this work since this plant will be using Santa Rosa wastewater as tower make-up during the summer months. The use of the Santa Rosa wastewater as make-up is expected alter the water chemistry of the cooling tower basin by introducing phosphates and nitrates, which are expected in turn to increase some types of microbial activity. (These nutrients may also impact the addition of chemicals used for sulfide abatement.)

A series of experiments, based upon respirometry, have been designed to investigate the ability of micro-organisms found in cooling tower basins to metabolize and cycle sulfides. Respirometry is a manometric measurement of dissolved gases that are in equilibrium in a confined volume. Since microbes expire varying amounts of carbon dioxide or oxygen as they metabolize nutrients, this technique can be used to evaluate their activities in process streams. Respirometry is a well-established tool for process control in the biological treatment of wastewater. And, while it is most commonly performed on samples in a laboratory environment, it is also possible to implement as an on-line measurement.

Scoping experiments have been performed in the laboratory using water samples from the Sonoma facility cooling basin and bacterial isolates cultured from geothermal fluids to determine if the respirometric technique could track changes in activity induced by changing the nutrient concentrations under various conditions. Data from one of these experiments using a Gibson Differential Respirometer is shown in Figure 1.

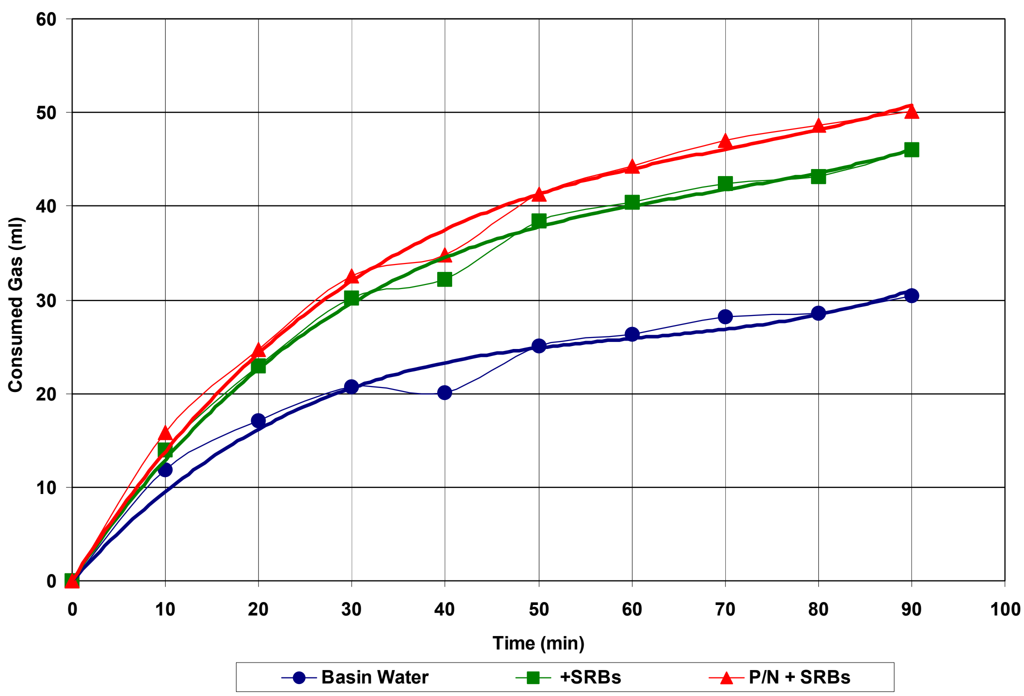


Figure 1. Microbial respirometric activity as a function of increased bacterial and nutrient concentrations.

The plot shows increased microbial activity, as evidenced from increased gas consumption, when a cell pellet containing sulfate-reducing bacteria (SRBs) is added to the water basin sample. This activity is seen to increase at a larger rate when small (20 ppm) concentrations of phosphorus (P) and nitrogen (N) are added. (It should be noted that some activity is also measured in the water sample since it also contains microorganisms.)

During 2004 the respirometric studies will be expanded using different mixing ratios between the wastewater and steam condensate to determine the subsequent effects on this activity. Changes in the chemical balance will also be monitored using standard colorimetric reactions for measuring phosphates, nitrites, sulfates, and sulfides. Bench-scale test results will be compared to actual conditions in the tower when the Santa Rosa wastewater is added as cooling water make up. This work will provide data for optimizing the enrichment concentration and exposure conditions to be used in the plant study and will also allow the development of analytical procedures to be used for in-plant tracking of the cycling activity.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003: None.

Planned FY 2004 Milestones:

Procedures developed and validated for in-plant tracking of microbial sulfur cycling for natural abatement. Aug 04

Improving Existing Plant Performance

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)	
DOE Grant/Contract No.:	AC07-99ID13727
Performing Organization:	Idaho National Engineering & Environmental Laboratory Renewable Energy & Power Technologies 2525 Fremont Ave, P.O. Box 1625 Idaho Falls, ID 83415-3830
Principal Investigator:	Greg Mines
Phone:	(208) 526-0260
E-Mail:	minesgl@inel.gov
Collaborating Researchers:	
DOE HQ Program Manager:	Raymond LaSala
Phone:	(202) 586-4198
E-mail:	Raymond.LaSala@ee.doe.gov

DOE Funding Allocation:	$65K (FY03)
Cost Share Funding:	None (No value assigned to data received from plant operators)

Project Objective: This task supports DOE's programmatic goals of reducing the levelized cost of power generated from geothermal energy and increasing the number of homes/business for which geothermal supplies the energy needs. Efforts focus on identifying methods of improving existing plant performance or reducing plant operating costs. The increased revenue streams and/or lower operating costs will result in lower power generating costs for plant operators. While the emphasis is on improvement to existing plants, technologies identified will also likely have benefit to new power plants and their economic feasibility. In addition, increasing the viability of existing power plants will contribute to the growth of the generating capacity by minimizing the likelihood that these plants will be retired as new generating capacity comes on line.

Background/Approach: Previous research efforts have focused on developing technologies that can be incorporated into new plant designs to improve plant performance. Where these technologies may have applicability to existing plants, their application may be limited because the plants are not designed to best utilize the potential benefit. In this task researchers will examine performance issues associated with existing operating plants and work with plant operators to resolve these issues using the best available technologies (including those being developed by ESR&T researchers). Two factors that have a major impact on existing plant performance are resource decline and off-design ambient conditions (especially with air-cooled condensers). Though investigators continue to assess technologies that mitigate the impact of these factors, this work will also examine other issues that also adversely impact performance and cost.

Analytical tools previously developed, will provide the basis for evaluating resolutions. These tools include process simulation software, as well as cost databases. Investigators work with power plant operators to identify issues. Investigators will then work to identify technologies and methods that mitigate these issues, drawing in part on access to work done by others. Analytical tools will be used to evaluate the impact of these technologies on performance and/or cost. Those having potential benefit will be presented to industry. Follow-on support will be provided, as required, to facilitate the commercial use of those determined to have economic benefit.

Status/Accomplishments: Prior year efforts focused on the effect of resource decline and off-design ambient conditions on the performance of air-cooled binary power plants, and the identification of methods of mitigating these adverse affects. During the past year, this work was expanded to evaluate costs of incorporating these various methods.

The off-design conditions evaluated adversely affect power generation. The decrease in power output corresponds to a decrease in the available energy of the brine entering the power plant. Available energy represents the work that could be done by an ideal conversion system that brings the geothermal fluid into equilibrium with the ambient. For the resource conditions used in this study, a decline of 30˚F in the resource temperature resulted in a 20% decrease in the available energy of the geothermal fluid entering the plant, while a 50˚F rise in the ambient temperature decreased this available energy by 33%. The second law efficiency is the fraction of this ideal work, or available energy, that is converted into actual work by the energy conversion system, or power plant. The analytical studies showed that this conversion efficiency, or second law efficiency, does not remain constant in an actual plant; it decreases as the resource and ambient conditions deviate from those used to size components and design the power plant. As a consequence, the adverse impact of these off-design conditions on plant performance is larger than would be indicated by the associated decrease in available energy. Different methods of off-setting the impact of resource decline and elevated ambient conditions were evaluated for a 15 MW air-cooled, binary power plant. Some of the methods were found to provide a relative improvement in plant performance. The level of the improvement depended upon both the off-design condition and the degree to which that condition deviated from the design.

One method considered for reducing the impact of off-design operation was an operational change that involved removal of constraints on the turbine inlet conditions (minimum superheat). This change produced an increase in power of up to 3%. The costs associated with this operation modification would be minimal; primarily associated with upgrades to the turbine inlet and outlet instrumentation (both pressure and temperature), as well as some initial technical support. The total cost is estimated to be less than $15K per turbine (or <$45K in the modeled plant).

Another method of increasing plant output involved the management of “house loads”, or plant parasitics, using variable frequency drives (VFD’s). These devices were evaluated for use with both the fan motors in the air-cooled condensers and the motors for the working fluid circulating pumps. Under a worst case scenario (both resource decline and high ambient temperatures), the use of the VFD’s with both motor applications increased power output by up to 18%. As the resource declined in productivity, the VFD’s had a larger impact on the plant performance when used with the working fluid pumps than with the condenser fans. With less resource decline, the impact on performance with either the working fluid pumps or condenser fans was comparable. An estimate was made of the cost to incorporate VFD’s in these two applications. When VFD’s were used on each of the three working fluid pumps in the modeled plant, the estimated installed cost was ~$570K total. However, it is probable that VFD’s would not be required for each of the three motors; if only required for one pump, the cost would decrease to ~$190K. Because of the number of motors used with the air-cooled condenser fans (there were 120 fans in the modeled plant), it is unlikely that the VFD’s would be installed with each fan motor (using the VFD’s with all the fans resulted in an estimated cost in excess of two million dollars). It is more likely that the

VFD's would be used to drive groups of fans. The estimated cost for VFD's to separately drive 4 groups of fans (30 in each group) was ~$560K. Except in applications where the degradation in resource productivity is significant, it is not clear that there would be an advantage using the VFD's in one application or the other. However, if as suggested, the VFD's were not used on all of the working fluid pump motors, there would be a cost advantage to using them with the working fluid pumps instead of just the condenser fans. It was postulated that a similar benefit could be achieved by shutting off fan motors. This will not occur as the associated heat transfer surface area will be lost to the condensing process.

As part of this effort, the impact that additional heat exchanger and condenser area could have on plant performance and cost was also examined. Increasing the heat exchanger area for either process by 25% increased the plant performance by 3 to 5%, depending upon the off-design scenario considered . Though there is no performance advantage, there is a significant cost difference. The cost of increasing brine heat exchanger size by 25% was much less than a similar relative increase in the condenser size ($460K vs $2,275K). This cost difference occurs in part because the condenser area is so much greater than the heat exchanger area. However, because of the impact on performance is about the same for the same relative increase in size, there would be more of an economic benefit in doing so with the brine heat exchangers.

In response to discussions of the results of this work with a plant operator, work was expanded on the impact of using VFD's on both brine production and injection pumps. There is continued interest in this activity because the higher brine injection temperatures in the summer can limit the ability to inject all of the produced geothermal fluid. If this occurs, brine flow must be curtailed. There is also interest as to whether the VFD's could be used to increase flow during times when a premium price is paid for power delivered. As part of this effort, the effect of pump/motor size on performance and cost is being evaluated. This work has not yet been completed.

A limited evaluation was made of the performance of a flash-steam plant to identify areas having the most significant impact on the plant performance. This effort has been hampered by difficulties using the process simulator software to adequately model evaporative cooling towers and steam ejectors.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003: None.

Planned FY 2004 Milestones:

This activity is being combined with another task in FY2004. There are no specific milestones for the new activity that are related to this work.

Advanced Processes for Geothermal Brines Multiple Resources

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: EB-4001000

Performing Organization: Brookhaven National Laboratory

Principal Investigator: Devinder Mahajan
Phone: (631) 344-4985
E-Mail: dmahjana@bnl.gov

Collaborating Researchers:
Bin Dong, Advanced Fuels Group, Energy Sciences & Technology Department, BNL
Stuart D. Johnson, Caithness Operating Company, LLC, Reno, NV; Tel.: (775) 850-2248.
Ted DeRocher, Coso Operating Company, CA

DOE HQ Program Manager: Allan Jelacic
Phone: (202) 586-6054
E-mail: Allan.Jelacic@hq.doe.gov

DOE Funding Allocation: $100K

Cost Share Funding: $50K (In-kind-contribution from the industrial partners listed above)

Project Objective: In FY 2003, the objective of this project was to optimize the high-purity amorphous silica recovery process from low-salinity geothermal brines. These data will be used to design a silica production plant and evaluate its contribution to offset geothermal power production cost in collaboration with industrial partners. The project is aimed at addressing the goals of the DOE geothermal program, i.e., to reduce the levelized cost of generating geothermal power to 3 - 5 cents/kWh by 2007.

Background/Approach: Geothermal resources can be rich energy and/or mineral sources. The co-production of silica has gained considerable interest in offsetting cost of power production via geothermal resources. Published data have shown that geothermal silica co-production can lower cost of power production in two ways: (1) high quality recovered silica can generate a significant secondary income stream, and (2) the removal of silica minimizes scale formation and thus allows for more cost-efficient energy production capabilities.

Silica exists as a dissolved monomer in all liquid dominated geothermal resources. Silica concentration determines silica recovery rate per volume of processed brine. However, concentration alone neither determines the quality of silica nor the economic justification of a silica recovery process. The salinity range found in geothermal systems has proven to be a significant factor in determining the quality of recovered silica. While high salinity systems promote diverse ion interactions and incorporation of a wide range of ionic species into silica precipitates, the chemical simplicity of low salinity systems promotes precipitation of high purity silica. The physical quality of this high purity silica is also enhanced by high effective surface area and porosity as a consequence of a lack of interfering and competing ions in the low-salinity brine systems.

Silica is a very versatile material whose market value varies greatly and depends on the purity and physical properties of the final product, which includes surface area, pore structure and particle size. Low priced silica is used as filler to improve hardness, wear resistance and tensile strength of rubber products and polymers. Similarly, such silica is used in the production of desiccants, food and animal feed, filler in paints, coatings and inks. Depending on the methods of preparation involving few or many processing steps which influence the cost, the application of silica products with an increasing product value is found in the production of catalysts, optoelectronics, chromatographic plates and columns and commercial separation applications in the pharmaceutical and fine chemical industries. The properties desired in these applications include specific porosity size and distribution (for size-exclusion-chromatography), and high active surfaces (for thin-layer and column liquid chromatography).

In the last few years, we have been evaluating the silica-power co-production route to offset the cost of power generation from geothermal sources. In this respect, we initially designed and explored various methods to synthesize high-purity silica from low salinity geothermal brines, samples of which were obtained from our industrial partner. This work was followed by our emphasis on producing high-purity silica for which various methods were evaluated. The outcome of these trails was the development of a simple method of silica production. The preferred method involves precipitation of colloidal silica under controlled conditions followed by aging, acid washing and sintering. In the last step, the solid silica is obtained by centrifuging, filtering and finally drying the recovered solid at 393K.

Status/Accomplishments: It is well known that cost of silica can vary over a broad range depending upon the quality for a specific application. The work carried out during FY 2003 focused on synthesis of surface modified silica for various applications. The chronology of the completed tasks were as follows:

1. Samples were obtained from Steamboat, Beowawe and Coso geothermal reservoirs. Tested the nucleation process by adding group 1-2 ions, flocculent and seed silica at 366K. Several runs were conducted to optimize the rate of precipitation and microfiltration. These data were used to select the silica separation process.
2. Optimized the yield and quality of the product by varying pH, temperature, reaction rates and isolation methods.
3. Preliminary design study was conducted for processing low salinity geothermal brines at 200 gal/min to develop on a silica separation process in collaboration with our industrial partner.
4. The major focus was on studying bonding of surface-active compounds on the silica products. Under this task a procedure was developed to produce modified silica.
5. The modified silica products were evaluated for various applications. 1) Thin layer chromatography (TLC) plates were prepared and evaluated for the analysis of heavy crudes. Figure 1 shows the separation of saturates, aromatics, resin and asphaltene fractions. 2) Silica surface modification with silylation reagents included the use of dimethyloctylchlorosilane and octyltriethoxysilane to prepare the derivatives for chiral and other applications (Figure 2).

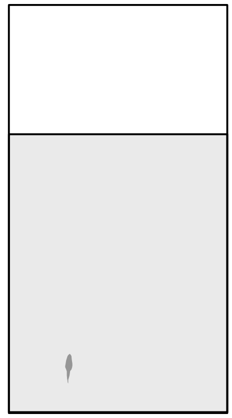


Figure 1. TLC analysis of a heavy crude oil (left), Aromatics standard (middle) and Saturates standard (right).

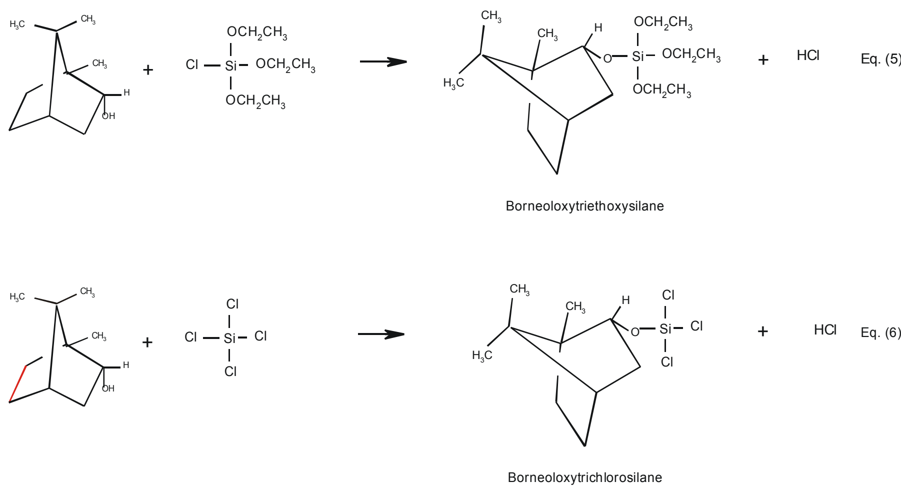


Figure 2. Synthesis of various modified silica surfaces

From the data collected in FY 2003, the following conclusions are noteworthy:

1. Current data indicate that production of high quality silica from geothermal brines is technically and economically feasible.
2. Quality of the starting materials e.g., brine source, influences the quality and the value of the end product.
3. Present batch and continuous process studies indicate that the emerging technology is highly promising and applicable in the near future.

Reports & Articles Published in FY 2003:

Lin, M.S., Premuzic, E.T., Dong, B., Zhou, W.M., and Johnson, S.D., " Recent Advances in the Development and Commercialization of Geothermal Silica Products" Geothermal Research Council Transactions, In press (2003).

Presentations Made in FY 2003:

2003 Geothermal Peer Review in Denver, Colorado, Mow Lin

2003 Geothermal Resources Council Annual Meeting Morelia, Mexico, S. D. Johnson (October, 2003)

Planned FY 2004 Milestones:

This project is scheduled to end in FY 2004. Should DOE continue funding, we wish to explore synthesis of nano-sized silica particles for various applications including catalysis. We have developed a scheme to synthesize nano-sized silica particles directly from low-salinity brines. The detailed milestones of the proposed task will be provided if funding is received from DOE.

Power Plant Costing Methods

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: AC07-99ID13727

Performing Organization: Idaho National Engineering & Environmental Laboratory
Renewable Energy & Power Technologies
2525 Fremont Ave., P.O. Box 1625
Idaho Falls, ID 83415-3830

Principal Investigator: Greg Mines
Phone: (208) 526-0260
E-Mail: minesgl@inel.gov

Collaborating Researchers: N/A

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $112K

Cost Share Funding: None

Project Objective: The goals of DOE's Geothermal Program include increasing the supply of electrical power produced by geothermal energy by reducing the levelized cost of power to 3 – 5 cents per KWh. The objective of this task is to develop methods to evaluate the impact of new power plant technologies that will improve plant performance and/or lower plant costs. The methodologies being developed provide representative capital costs for conventional types of power plants used with liquid-dominated, hydrothermal resources (binary and flash steam), and allow one to evaluate how innovative technologies will impact those costs. This effort will help direct research activities and priorities, and as such contribute to the goal of reducing the cost of electrical power from geothermal resources. In FY2003, the efforts in this activity were to focus on evaluating one or more on-going research activities, to apply the methodology to flash steam power plants, and to provide related technical support as requested by DOE supported researchers and program management.

Background/Approach: Sustaining the viability and future growth of the domestic geothermal industry is contingent upon reducing the costs associated with the generation of electrical power. To assess how technology advances in energy conversion systems impact these costs, one must be able to define conversion system component costs and the costs of the activities associated with the power generation. Although historical costs, in terms of $/KW installed, provide a valuable perspective on the capital costs of geothermal plants, they have limited use. Typically historical costs are not available in the detail required to assess the impact of a technology innovation on component costs. Obtaining historical costs in sufficient detail to provide this assessment requires one have access to information that is generally considered proprietary and has limited access. In addition, very few plants have been built domestically in the last decade; the costs that are available are dated and will not necessarily reflect true current costs. In order to account for the limitations of the historical data, INEEL investigators are working to establish methods of deriving current installed capital costs in sufficient detail to allow the impacts of technology advances on power production costs to be evaluated.

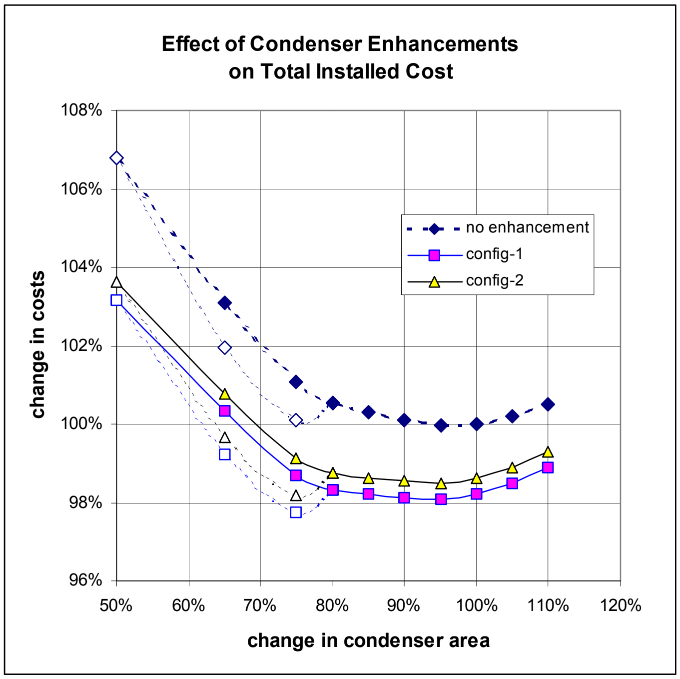
The methodology being developed utilizes a process simulator (ASPEN Plus) to both evaluate the impact of technology advances on conversion cycle performance and to size individual components. A cost estimating software (ICARUS Process Evaluator, or IPE) is then used to assess the impact on both component and plant capital costs (both equipment and installed costs). Plant operators have supplied equipment specifications and operating data from existing plants that investigators use to assure that the ASPEN plant performance models properly simulate both plant and component performance. The IPE derived cost estimates have been "calibrated" using both proprietary cost information from existing plants, as well as industry review for comment and concurrence. This process of model refinement and verification is an ongoing process that is done whenever new data becomes available. The emphasis in this activity to date has been on the performance and costs of binary power plants.

Status/Accomplishments: Previously investigators developed the methodology for using the ASPEN simulator models and the IPE software to derive the installed capital costs for binary power plants. This methodology has been "calibrated" using operating data from power plants and proprietary cost information. The methodology has subsequently been used to examine different scenarios for resource conditions.

In FY2003, the methodology developed was used to assess the impact that a DOE-funded research activity would have on the power plant costs. The activity selected was the work being done at INEEL to enhance the performance of air-cooled condensers by using "winglets" on the tube fin surfaces. This effort first examined the impact that these enhancements would have on the power production by using the ASPEN simulator models of a typical binary power plant. The models developed, accounted for the projected increases in heat transfer performance, as well as the impact the enhancements would have on the fan power. For this study the performance and configuration of all plant components were fixed, while the air-cooled condenser configuration was varied. Based upon modeling results, condenser operating conditions were defined that maximized the net power generation from the power plant. This information was then used to size the condensers both with and without the enhancements.

This work illustrated to investigators the importance of the air-side pressure drop on plant performance. Most enhancements to air-side heat transfer have an associated increase in this pressure drop. Heat transfer enhancements decrease condensing temperature and pressure (increasing power output) and/or allow condenser heat transfer area to be reduced. Increases in the air-side pressure drop require additional fan power (decreasing net power) to maintain the air flow rate, or requires that the air flow rate be reduced if the fan power is held constant (this tends to raise the condensing temperature, decreasing turbine output). The net effect is that a higher pressure drop will off-set in part, or in total, the power increase due to a heat transfer enhancements. The trade-off between enhancement and pressure drop is contingent upon the pinch point, or minimum temperature difference in the condenser. The larger the pinch point, the less sensitive the condenser will be to the air-side pressure drop. In binary power plants, the typical pinch point is not large and the performance benefit derived from an air-side enhancement is sensitive to its associated pressure drop. Two air side enhancement configurations proposed by INEEL investigators were evaluated. One enhancement would provide a 30% increase in the air-side heat transfer coefficient, with an associated 9% increase in the friction factor. The second enhancement increased the heat transfer coefficient by 40%, but had a 24% increase in the friction factor. Results indicated the two enhancements produced about the same impact on the modeled plant performance, with the enhancement having the lower pressure drop resulting in a slightly higher increase in power production.

ASPEN results were used to establish condenser sizes for different enhancement and operating scenarios. The IPE software was then used to develop installed capital costs for the condenser and power plant. Results, which are summarized in the figure below, indicate the enhancements would decrease the cost of the power plant by ~2% (which is similar to the predicted increase in plant power output). These estimates included an estimate of the cost to incorporate the enhancements into the manufacturing of the fin-tubes. This information was provided by McElroy Manufacturing, which is working with INEEL investigators to develop the tooling to manufacture tubes having these fin enhancements. It should be noted that these results do not represent an optimized condenser configuration. It is probable that once industry begins manufacturing condensers with these enhancements that an optimization will be done on the number of tube rows, tube size, fin spacing, pitch, etc., that will result in further cost reductions.



In FY2003, the methodology was expanded to include the costs of the surface gathering and injection systems. Work also continued on developing methods for estimating the capital costs of flash-steam power plants. This work is effectively completed though some of the sizing and performance evaluation must be accomplished using an EXCEL spreadsheet model. Investigators also used the ASPEN-IPE methodology to evaluate the effect of plant size and working fluid composition on plant cost. Arrangements have been made for industry to provide a review of the performance and cost projections for one of the scenarios that will provide additional refinement of the methodology.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003: None.

Planned FY 2004 Milestones:

This work scope of this task and another task (Improving Existing Plant Performance) have evolved to the point where they are overlapping, and in FY2004, the two tasks will be combined. The emphasis will be placed on evaluating the impact of both new technology innovations and on-going DOE research. The milestone for this combine task in FY2004 will be to complete the evaluation of a selected DOE-funded activity, similar to that done for the air-cooled condenser task in FY2003.

Geothermal Co-production of Silica and Other Commodities

Reporting Period: FY 2003 (October 1, 2001 to September 30, 2002)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA 94550-9234

Principal Investigator: William L. Bourcier
Phone: (925) 423-3745
E-Mail: bourcier1@llnl.gov

Collaborating Researchers: Adam Wallace, afw@vt.edu
Bill Ralph, ralph2@llnl.gov
Carol Bruton, bruton1@llnl.gov

Other Collaborators:
John Byers, Byers Rubber Consulting, byersrc@cs.com
Robert Sullivan, Mammoth Pacific LP, Bsullivan@ormat.com

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $100K

Cost Share Funding: $239K from the California Energy Commission (CEC)

Project Objective: Our objective is to develop extraction techniques for silica and other commodities from geothermal fluids such that marketable byproducts can be produced and sold. Our work this year is directed at optimizing the extraction methods to minimize cost and facilitate implementation in existing power plants. If successful, the results of this project would lower the cost of geothermal power by adding a new revenue stream from sale of byproducts. Project success would lower operations and maintenance costs by reducing silica scale formation in surface facilities and in re-injection wells.

Background/Approach: Produced geothermal brines contain large quantities of dissolved silica that often forms scale in power production facilities. During FY2003, we continued our collaboration with Mammoth Pacific LP to extract dissolved silica as a marketable byproduct. We are developing an understanding of how to produce silica with optimum properties for commercial use by varying the precipitation conditions and characterizing the resulting silica precipitates. We carry out these tests both in laboratory experiments with simulated fluids, and on-site in a mobile laboratory with real fluids.

The goal of our project is to develop working silica precipitation processes for geothermal sites such that it is possible to produce silicas with properties that match a targeted silica market, and are thus marketable. We are working with technical contacts from the rubber industry and colloidal silica distributors to help identify material properties and likely markets for our produced silicas. Once silica has been extracted from spent geothermal brines, it becomes technically feasible to extract additional metals such as lithium from the brines without interference from silica precipitates.

Status/Accomplishments:

- Completed a series of silica extraction tests at the Mammoth Lakes geothermal site
- Determined the composition and surface areas of geothermal silica precipitates
- Performed suitability tests of geothermal silicas as tire rubber binder (performed via contract with Byers Rubber Consulting of Wadsworth, Ohio)
- Upgraded our field equipment to include a larger (80 vs. 20 liter) custom designed stirred reactor and a 20 gpm reverse osmosis unit modified for use at elevated temperatures, and assembled a cross-flow filtration unit that uses ultra-filtration elements for solids capture (in progress)

We successfully extracted high-purity silica from the geothermal fluids at the Mammoth Lakes site (see table below). With a brief acid rinse, the purity is improved from 98 to 99.6% silica. The surface areas of the precipitates ranged from 40 to 130 m^2/g. Both the composition and surface areas of our silicas are in the range of existing commercial silicas.

Based on the results of our field tests, we determined that we needed to increase the silica concentration in the geothermal fluid prior to silica extraction in order to reduce the residence time for silica polymer growth and agglomeration. A shorter residence time reduces the volume of reactor needed and greatly reduces capital costs for a silica extraction plant. Without the concentration step, the process would not be economically favorable. We purchased a reverse osmosis unit for use in this project to replace the leased unit we had been using to test the process. We then modified the unit for use at elevated temperatures. The reverse osmosis unit produced a concentrate enriched in silica and other salts, and a low salinity permeate. The concentrate was used in subsequent silica removal tests. In production, the permeate would be used as feed for the evaporative cooler used to cool the isobutane working fluid at Mammoth (see figure below). The reverse osmosis unit rejected silica at 90-95% (the larger the number, the better), and showed no sign of silica fouling in about 3 weeks of use.

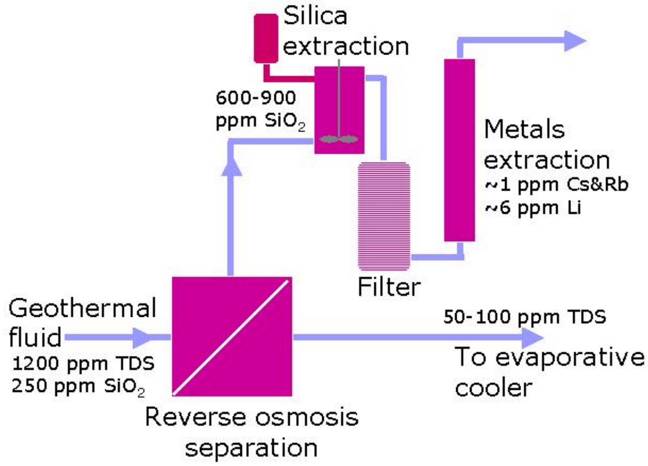
We determined that silica particle recovery using 200 nm cartridge filters was not satisfactory, and that a finer filter mesh size is needed. We believe a cross-flow filtration geometry will give us improved filter lifetime. We therefore purchased a tangential flow filtration device that uses commercially-available ultrafiltration membranes so we can test a variety of nominal pore sizes to determine the optimum filters for silica recovery.

We also designed and built a larger stirred reactor in order to increase the amount of silica precipitate that could be acquired in a given amount of time. We need to provide kilogram amounts for some marketing tests, and are currently generating less than 100 grams per day with our existing setup. Our new vessel volume is 80 liters, four times the size of the previous reactor.

We are in the process of modifying our field setup to incorporate the new reverse osmosis unit, reactor, and filtration device, and will be using this new equipment in our next set of field tests.

FY04 work will be targeted at using our new field equipment to recover larger masses of silica for marketing tests, improving silica yield using cross-flow filtration, and reducing the amounts of additives needed to lower operating costs.

Compositions of silica precipitates			
	Raw	DI Rinse	AcidRinse
Major components in wt %			
SiO2	**98.09**	**99.13**	**99.63**
Al2O3	0.33	0.31	0.31
Fe2O3	0.22	0.22	0.20
MnO	0.01	0.01	0.01
MgO	0.13	0.12	0.04
CaO	0.17	0.15	0.02
Na2O	1.15	0.08	0.02
K2O	0.15	0.05	0.00
TiO2	0.01	0.00	0.00
P2O5	0.03	0.03	0.02
Total	100.28	100.11	100.26
Minor components in ppm			
As	**450**	**304**	**162**
Au	0.07	0.06	0.05
Cs	21	18	5
Hg	4	4	1
Mo	20	18	10
Sb	**350**	**332**	**200**
Sc	0.3	0.3	0.2
W	31	26	15
Cu	14	13	10



Reports & Articles Published in FY 2003:

Bourcier, W.L., Nix, G. and Lin, M.S. (2003) Recovery of Minerals and Metals from Geothermal Fluids, Oral presentation and paper for Society of Mining and Metallurgical Engineers Annual Meeting, Cincinnati Ohio. Also Lawrence Livermore National Laboratory UCRL-JC-153033.

Burton, E.A., Bourcier, W.L, Wallace, A., Bruton, C.J. and Leif, R. (2003) Silica scale management: Lowering operating costs through improved scale control, and adding value by extracting marketable by-products. Geothermal Resources Council Transactions, v. 27, p. 519-522.

Presentations Made in FY 2003:

Burton, E.A., Bourcier, W.L, Wallace, A., Bruton, C.J. and Leif, R. (2003) Silica scale management: Lowering operating costs through improved scale control, and adding value by extracting marketable by-products.
Presentation at Geothermal Resources Council 2003 Annual Meeting in Mexico.

Planned FY 2004 Milestones:

Summary report to CEC (copy to DOE) on silica extraction process — Sept 04

Silica Scale Inhibition

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory
7000 East Ave.
Livermore, CA 94551

Principal Investigator: Elizabeth Burton
Phone: (925) 422-7330
E-Mail: burton14@llnl.gov

Collaborating Researchers: Carol Bruton, Bill Bourcier, Adam Wallace, Roald Leif, LLNL

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@ee.doe.gov

DOE Funding Allocation: $200K

Cost Share Funding: $20K in-kind, ChevronTexaco Energy Technology Company

Project Objective: This project aims to provide geothermal operators with technical information that will improve silica scaling prediction and mitigation techniques in facilities and injection wells. Tools presently available are incomplete and/or inappropriately framed for geothermal industry use. Conditions favoring silica scaling will become more common with the expansion to new resources and increasing maturity of existing geothermal resources. Declining reservoir pressure, spent brine reinjection, growth in use of lower grade geothermal resources, binary and hybrid plants, and lower pressure secondary flash or bottoming cycles will increase the need to improve silica scale management techniques and best-practice sharing across the industry.

Our project contributes to achieving two Program goals: reducing levelized costs by 3-5 cents/kWh, and doubling the number of states with geothermal power. Silica scaling negatively impacts plant operational costs, well performance and risk in a variety of ways that, in sum, may significantly reduce net income and curtail resource development. Improving silica scale control can reduce cost and risk by:

- Preventing declines in energy conversion efficiency due to scaling
- Expanding geothermal water usage to plant cooling operations
- Minimizing scale-related waste, use of scale inhibitor and dissolver chemicals, and their associated environmental impacts
- Decreasing frequency of facilities treatments and well workovers due to scaling
- Reducing operations upsets and downtime
- Reducing likelihood of injection well abandonment, wellbore and formation damage

Prior to FY2003, the project objectives were focused more on developing a fundamental understanding of inhibitor behavior. In FY2003, we have focused more on building a basis for the underlying effects of fluid chemistry on silica polymerization and how these effects relate to observed inhibitor performance variations, and in developing a way to deploy this information to the geothermal industry.

Background/Approach: Silica scaling commonly occurs in geothermal power plants. Silica scaling problems can be moderate, or so extreme that the power generation process must be specially designed to limit scaling. Even small amounts of scaling are deleterious to binary plants because of the effect on heat transfer. More efficient utilization of geothermal heat, and the use of geothermal and other water supplies for water make-up and cooling increases the risk of scaling. There are a number of chemical additives (inhibitors) that are commercially available for scale control. However, variations in fluid chemistry, different plant operating conditions, and the complex nature of silica reactions cause the effectiveness of an inhibitor to vary widely within and among geothermal fields. The growing use of brine acidification is promising with regard to scale control, but issues remain even with this technology. Scale management presently is done by qualitative case-by-case studies to test scaling potentials and inhibitor efficacy. Making scale management more systematic and predictable across the industry requires quantification of the effects of fluid chemistries and of inhibitor effectiveness for the full range of conditions found in geothermal operations.

The formation of silica scale can be broken down into four major steps: polymerization of monomeric silica, growth of polymeric silica to insoluble amorphous silica colloids, agglomeration of the colloids, and nucleation and growth of silica scale on solid substrates (e.g. piping). While thermodynamic models (e.g. TEQUIL) exist that predict the potential magnitude of scaling and qualitatively capture the overall dependence of reaction rates on the degree of disequilibrium, they do not capture the overall and step-specific rate effects of various other solution parameters, such as sodium and fluoride concentrations, and pH. Existing kinetic models are based on laboratory data alone, consider a limited number of chemical variables, do not explicitly include inhibitors, and are not field-validated. Thus, there is a critical need for a coupled kinetic-thermodynamic model specifically designed to address silica scaling in geothermal operations. Antiscalants, or inhibitors, intervene in the kinetics of one or more of these key steps leading to scale deposition. For example, threshold inhibitors delay the initial polymerization of monomeric silica in a supersaturated brine, and dispersive agents inhibit agglomeration of silica colloids.

In this project, we evaluated commercially available silica scale inhibitors from a variety of vendors for their application to geothermal brines of varying composition in both flash and binary plants. The approach used included laboratory testing to establish and model the polymerization rates of silica in a variety of geothermal brine chemistries as well as inhibitor testing. Laboratory tests were designed to quantify: (1) the effects of a matrix of aqueous chemical variables on silica polymerization and precipitation rates, and (2) the impact of commercial scale inhibitors on rates of specific steps in the silica precipitation reaction. In addition, we built a small database of geothermal water compositions, focusing on existing or potential geothermal sites in the western U.S., using existing databases at research centers (including Great Basin Research Center, USGS, Energy and Geoscience Institute) and published literature to define ranges for chemical variables for laboratory tests. We also sought to include data from field tests in order to compare our lab data to measures of chemical inhibitor effectiveness and silica precipitation in "real" geothermal fluids under plant conditions.

Status/Accomplishments: In laboratory tests, we have quantified the effects on silica polymerization of the following set of chemical variables: Na at 500 and 2000 ppm, pH values from 5 to 9, temperatures of 25 and 50^{o}C, and silica saturation values from 1.2 to 6. Total initial dissolved silica concentrations were kept constant at 600 ppm. Silica was added as sodium metasilicate. The pH was adjusted with hydrochloric acid or sodium hydroxide and monitored throughout each run. A circulating water bath held solutions at constant temperature to ±0.5^{o}C. Silica polymerization was followed over time by spectrophotometric measurements on solution aliquots using the silicomolybdate method as modified by Iler. We have recently purchased an automated system to control and maintain pH. Previous work identified appropriate laboratory testing protocols, and tested silica scale inhibitors from the geothermal and water treatment industry for the Dixie Valley and Coso geothermal fluids. Quantum mechanical modeling of silica polymerization and nuclear magnetic resonance measurements tracking the formation of oligomers were also conducted to better define the processes of early polymerization and predict the reactivity of aqueous silica. A technique for using hydrothermal atomic force microscopy to directly image silica deposition on metal surfaces was developed to study the influence of the substrate on silica precipitation. Work was also done to determine the effects of inhibitors on particle size and to identify the general molecular structures of inhibitors to develop an understanding of how they work. This work showed that inhibitor behavior could change dramatically with changes in fluid chemistry.

We decided to change our focus in the lab experiments in FY2003 from tests on site-specific brine chemistries to creating a baseline dataset that would allow us to isolate the specific effects of individual chemical parameters. We are using these data and applicable published data to find accurate equations for predicting silica scaling across the full range of fluid chemistries found in geothermal systems, and to provide a baseline for quantitative analysis of inhibitor performance. As an additional benefit, we can quantify the effects of pH-modification relative to other methods of silica scale control over a range of operating conditions. To insure coverage of the full matrix of chemistries, we have assembled a geothermal fluid chemistry database, including data from operations and sites in the western U.S., to establish the ion concentration matrix for our experiments (e.g., Fig. 1).

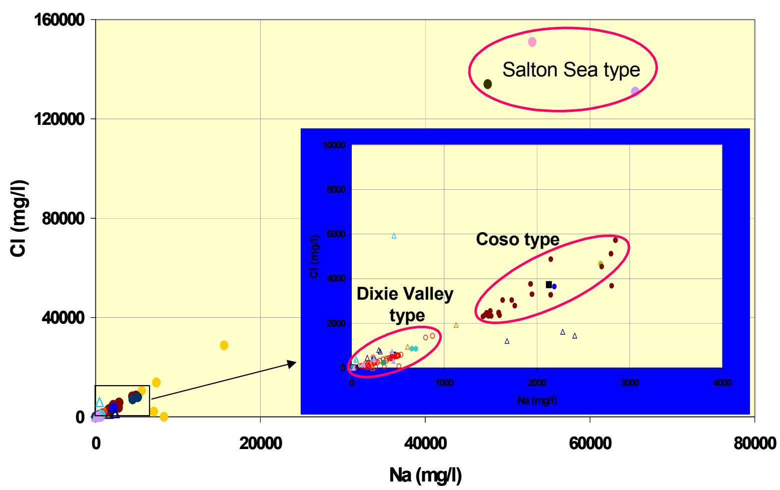
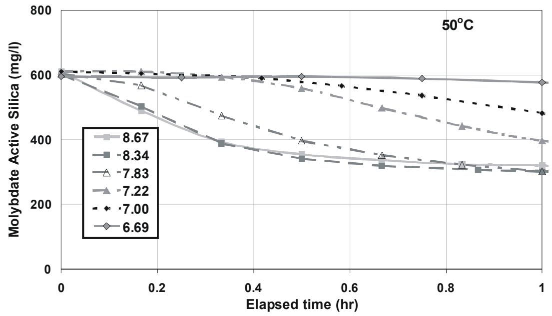
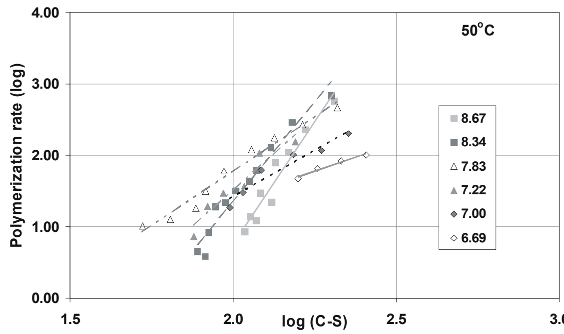


Figure 1: Geothermal brine compositions showing clusters of typical compositions with respect to Na and Cl.





Figures 2 and 3: Effect of pH on polymerization (low ionic strength, 600 mg/l total initial Si). Fig 2 shows monomer silica concentration vs. time. Fig 3 is derived from Fig 2, showing the rate of change in monomer concentration vs. log (C-S) where C is dissolved silica concentration and S is the equilibrium concentration with respect to amorphous silica at run temperature.

Figs. 2 and 3 show lab data quantifying fluid chemistry effects on the polymerization step. Lowering pH, as would occur by pH-modification, increases the induction time prior to polymerization and decreases polymerization rate. These results explain field experience where silica scaling has been effectively prevented by pH-modification. However, our results also show that the pH effects are interdependent on other aspects of fluid chemistry. For example, polymerization rate decline caused by decreasing silica concentration is faster at higher than at lower pH (as shown by varying slopes in Fig. 3).

We have used several approaches to begin the modeling. First, we used a multiple linear regression model to predict rates of polymerization as a function of chemical variables and elapsed time. This simple model appears to be a good predictor of polymerization rates for the intermediate range of rate measurements, but is less reliable for rates measured early or near the end of each run. We examined several data-fitting mathematical packages for use in developing more accurate nonlinear predictive equations for the model, but we decided a faster and more efficient approach would be to leverage off existing codes. We are now updating the Weres et al. SILNUC model for silica polymerization with our data.

Reports & Articles Published in FY 2003:

Burton, E.A., Bourcier, W.L., Wallace, A., Bruton, C.J., and Leif, R., 2003, Silica Scale Management: Lowering Operating Costs through Improved Scale Control and Adding Value by Extracting Marketable By-Products. Geothermal Resources Council Transactions v. 27, p. 519-522.

Presentations Made in FY 2003:

Burton, E.A., Bourcier, W.L., Wallace, A., Bruton, C.J., and Leif, R., 2003, Silica Scale Management: Lowering Operating Costs through Improved Scale Control and Adding Value by Extracting Marketable By-Products. Geothermal Resources Council Annual Meeting, Morelia, Mexico, Oct. 12-15, 2003.

Planned FY 2004 Milestones:

Finalize the predictive model. Incorporate updated SILNUC code, and use MatLab or other fitting tools to facilitate assembly and equation-fitting of lab and field data	Jul 04
Publish final model and report	Sep 04

Empire Energy Project

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:

Performing Organization: National Renewable Energy Laboratory

Principal Investigator: Charles Kutscher
Phone: (303) 384-7521
E-Mail: chuck_kutscher@nrel.gov

Collaborating Researchers: Gerry Nix

DOE HQ Program Manager: Raymond LaSala
Phone: (202) 586-4198
E-mail: Raymond.LaSala@hq.doe.gov

DOE Funding Allocation: $2400K

Cost Share Funding: $600K

Project Objective: The objective of this task is to manage and support the successful design and construction of small-scale geothermal power plant contracts awarded under the solicitation, “Small-Scale Geothermal Field Verification Projects.”

Background/Approach: Small-scale geothermal power plants are attractive because they offer a geothermal means to provide distributed power and expand geothermal use to states that have not been large users of geothermal energy. These plants are potentially more expensive on a per-kilowatt basis compared to larger plants because of the high fixed costs of exploration and drilling, and field verification of innovative designs is needed to show that costs can be reduced. An FY 2000 study by NREL revealed that with a government cost share, there was considerable opportunity for small-scale geothermal plants in several Western states. A solicitation was issued on March 23, 2000 requesting proposals for plants in the size range of 300 kW to 1 MW. Proposals were received on June 22, 2000, and 5 winners were announced. Each project consists of three or four phases: I) preliminary design, IA) well drilling (if necessary), II) detailed design, and III) construction, and operation and data collection for a 3-year period. Contracts were awarded to three projects: Exergy-AmeriCulture, Empire Energy, and Milgro-Newcastle. The Exergy project was transferred to the DOE Golden Field Office and eventually was canceled. Two slimhole wells were drilled for the Milgro-Newcastle project. Because adequate temperatures were not achieved and because of financial problems, Milgro-Newcastle decided against construction. The remaining project, Empire, conducted a preliminary design, but this project has since experienced a number of redirections, most recently associated with changes in the planned operations of the dehydration facility.

Status/Accomplishments: Under contract to Empire, Power Engineers performed a study on the potential advantages of using mixed working fluids. They concluded that the use of a mixed working fluid could lower the delivered electricity cost by approximately 6%, which is a significant savings. The final report was delivered in June 2003. NREL sent a revised statement of work to Empire in August 2003.

Reports & Articles Published in FY 2003:

"Mixed Fluid Binary Geothermal Plant Study-Empire LLC&NREL," Final Report, Power Engineers, June 5, 2003

Presentations Made in FY 2003:

"Mixed Fluid Binary Geothermal Plant Study-Empire LLC&NREL," Power Engineers, February 21, 2003.

Planned FY 2004 Milestones:

Select A&E firm to engineer-procure-construct plant	February 13, 2004
50% design review	April 15, 2004
100% design review	August 1, 2004
Order equipment	August 15, 2004

V. GEOPOWERING THE WEST (GPW)

Geothermal Energy Program: Leasing Information and Outreach

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG01-02EE35229

Performing Organization: Bob Lawrence & Associates, Inc. (BL&A)

Principal Investigator: Elizabeth C. Battocletti
Phone: (703) 836-3654
E-Mail: lbatto@att.net

Collaborating Researchers: Bob Lawrence, boblaw424@aol.com
David Reed, davereed@rcn.com
Jodi Hamrick, jodiha@erols.com

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $112K

Cost Share Funding: $1,065 in direct funding

Project Objective: The primary objective of the Geothermal Leasing Information and Outreach Project is to establish geothermal energy as an economically competitive contributor to the nation's energy supply by greatly broadening BL&A's existing and successful outreach and education program to engage electric utilities, state regulatory agencies, and consumer organizations. The project will also research, design, produce, and disseminate a Geothermal Leasing Workbook that will enable geothermal entrepreneurs and smaller developers to more easily work with state and Federal agencies to obtain geothermal leases, and consequently develop geothermal resources. The project supports the Geothermal Energy Program's goals of supplying the electrical power or heat energy needs of 7 million homes and businesses in the United States by 2010, and increasing the number of States with geothermal electric power facilities to eight by 2006. BL&A received authorization to begin work under the Leasing Information and Broadened Outreach Project in October 2002. Preliminary research was started in FY 2003.

Background/Approach: Education, outreach, local engagement, and participation are instrumental to GeoPowering the West's (GPW) success. In addition to reaching out to local and state stakeholders and geothermal entrepreneurs, an effort which is currently underway, active involvement by electric utilities, state regulatory agencies, and consumer organizations is essential to the increased deployment of geothermal energy. Outreach and education are needed to help decision makers in these critically important organizations understand the benefits and potential of geothermal energy in their states, and to remove barriers to its increased use.

One barrier to increased geothermal development is the complicated geothermal leasing process. Many geothermal resources are located on Federal or state lands. The Bureau of Land Management (BLM) is responsible for leasing Federal lands and reviewing permit applications for geothermal development. This authority encompasses about 570 million acres of BLM land, National Forest System lands (with concurrence of the Forest Service), and other Federal lands, as well as private lands where the Federal Government has retained mineral rights.

Small geothermal developers and entrepreneurs would benefit from a "one-stop shopping" approach to obtaining a geothermal lease. Navigating government bureaucracy, deciphering forms and processes, and determining "who's who" in U.S. Government and state agencies takes significant person-hours, persistence, and financial fortitude—resources which smaller developers and entrepreneurs often lack. A roadmap or flowchart that outlines how to work with the BLM and other relevant Federal and state agencies, and describes the procedures needed to obtain a lease by type of land (Federal, state, private) as well as by state, would be very useful in promoting the development of geothermal energy in the GPW states.

BL&A will provide information to electric utilities, state regulatory agencies, consumer organizations, and geothermal developers and entrepreneurs, resulting in:

- Increased understanding and awareness of geothermal energy in the 19 states of GPW as a possible source of electricity or for direct use,
- Better knowledge of the geothermal leasing process at the state level by smaller geothermal developers and entrepreneurs, and
- Increased use of geothermal energy for electricity generation and direct use in the 19 states of GPW.

Status/Accomplishments: In FY 2003, BL&A implemented three tasks: The firm:

1. Began collecting data on the appropriate contacts at electric utilities, state regulatory agencies, and consumer groups in the 19 GPW states to broaden the GPW contact database.
2. At the Geothermal Energy Program's request, BL&A contacted the Washington State University Energy Program to work together on the Geothermal Leasing Workbook.
3. Battocletti was trained on web design and other Internet-related technologies to best update the current Geothermal-biz.com website to add material specifically targeted towards the interests and issues of electric utilities, state regulatory agencies, and consumer groups.

Reports & Articles Published in FY 2003: None.

Presentations Made in FY 2003: None.

Planned FY 2004 Milestones:

Broaden GPW contact database	Ongoing
Re-design Geothermal-biz.com website to include sections on electric utilities, state regulatory agencies, and consumer groups	Ongoing
Research and design Geothermal Leasing Workbook	Ongoing
Facilitate web conference targeted towards utilities	Nov 03
Launch electric utility webpage on Geothermal-biz.com website	Feb 04
Launch state regulatory agency webpage on Geothermal-biz.com website	Apr 04
Launch consumer group webpage on Geothermal-biz.com website	Jun 04

Assistance to State Legislatures on Geothermal Energy Issues

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG03-01SF22367

Performing Organization: National Conference of State Legislatures (NCSL)
7700 East First Place
Denver, CO 80203

Principal Investigator: Matthew Brown, Energy Program Director
Phone: (303) 364-7700
E-Mail: matthew.brown@ncsl.org

Collaborating Researchers: Troy Gagliano, Energy Policy Specialist
Phone: (303) 364-7700
E-Mail: troy.gagliano@ncsl.org

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@hq.doe.gov

DOE Funding Allocation: $98K ($38K of this will be subcontracted to Washington State University Energy Program.)

Cost Share Funding: N/A All funding for this project came from DOE.

Project Objective: The purpose of this project is to educate state legislators and other policymakers about specific geothermal energy policies and technologies. There are some particular regulatory and technological barriers to developing geothermal energy that state legislatures must be aware of and address. This project will give policymakers the knowledge necessary to make informed decisions about ways to support the development of geothermal energy in their own states. NCSL will work jointly with the Washington State University Energy Program (WSUEP) to conduct some of the analysis for this project. This work will focus on eleven western states including: Alaska, Arizona, Hawaii, Kansas, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas and Wyoming.

Background/Approach: The potential of geothermal energy is receiving increased visibility in energy discussions as policymakers consider related issues of air quality, energy security, system reliability and economic development. Legislators need reliable information and assistance in order to make informed decisions about geothermal energy issues; however, it has been NCSL's experience that very few state policymakers have this information, or have devoted the time to acquire it. Consequently, NCSL will produce and provide the following reports and services on geothermal energy for state legislatures. Through their role as state policymakers, legislators have the ability to use this information to stimulate more widespread use of geothermal energy.

Written Reports (FY 2002)

Year 1

- State Legislative Report on Geothermal Electricity Generation

  This 10 to 15-page primer will focus on technology, costs and environmental issues related to generating electricity from geothermal sources. This primer will also outline the policy options that states can employ to further utilize this technology.

Year 2 (FY 2003)

- A Survey and Analysis of State Legislation and Regulation Regarding Geothermal Energy

  These activities will produce a comprehensive survey of geothermal energy legislation and governing law in eleven western states. This survey will serve as a basis for examining what states may wish to consider updating or changing laws affecting geothermal energy; many such laws have been in place for years and may not now reflect the vastly altered energy landscape.

  - Determine the utility commission's jurisdiction over the development, operation and rate regulation of geothermal-generated electricity.
  - Determine protocols and standards required for developing geothermal resources on state lands.
  - Determine the differences among states on how geothermal resources are defined and characterized.
  - Analyze issues involved with siting geothermal power plants.
  - Analyze laws applying to direct-use applications to determine where, and at what point, the utility commission has jurisdiction over such uses.
  - Determine a city or townships' ability, as specified in the state constitution, to develop geothermal direct use energy systems.

Year 3 (FY 2004)

- State Legislative Report: Analysis of State Legislative Policies for Geothermal Energy

  NCSL will analyze the effectiveness of these policies based on the survey of state legislative policies affecting geothermal energy that was developed in Year 2. In addition, as part of this task, NCSL will update the survey conducted in Year Two of state legislation affecting the use of geothermal energy.

Legislative Services

- Technical Assistance

  Technical assistance programs are available at no cost to state legislatures at their request. These formal, on-site assistance programs typically involve testimony, summaries of key issues, state and federal legislative and programmatic activities, and a review of policy issues and options up for consideration by the legislature. Often participating with NCSL staff are legislators from different states with expertise in renewable energy, other national experts, state energy officials and DOE officials. Technical assistance can also include Energy Project staff providing written testimony to a committee, in-depth research not available to a committee, and bill writing and analysis.

- Responsive Information Assistance and Outreach.

  NCSL will provide legislators and legislative staff with clear and reliable information regarding geothermal energy policies and programs, and act as a liaison between DOE and state legislatures. NCSL staff responds daily to information requests from state legislatures. This project will allow NCSL to provide the most current and comprehensive information available on geothermal issues.

Status/Accomplishments: This project allows NCSL to provide policy consultation on geothermal energy issues to the nation's 50 state legislatures; it is not a technical project and outcomes can not be measured in quantitative terms. However, NCSL is currently conducting research to analyze state laws and public utility commission jurisdiction to determine how this affects geothermal power plants. NCSL has completed the deliverables listed below.

Reports & Articles Published in FY 2003:

"Geothermal Energy: A Primer on State Policies and Technology"
National Conference of State Legislatures, State Legislative Report, January 2003

Presentations Made in FY 2003:

"State Policy Options for Renewable Energy"
GeoPowering the West State Summit, Boise, ID September 2003
Idaho House of Representatives, Renewable Energy Subcommittee, September 2003

"Renewable Energy Technologies and Policies"
Maryland Senate Finance Committee, January 2003
Maryland House Economic Matters Committee, January 2003

Planned FY 2004 Milestones:

- State Legislative Report: Analysis of State Legislative Policies for Geothermal Energy

  NCSL will analyze the effectiveness of these policies based on the survey of state legislative policies affecting geothermal energy that was developed in Year 2. In addition, as part of this task, NCSL will update the survey conducted in Year Two of state legislation affecting the use of geothermal energy.

Geothermal Energy Program: Information Dissemination and Outreach and Geothermal Direct Use Technical Support, Testing and Evaluation Support and Analytical Tools Development

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)	
DOE Grant/Contract No.:	DE-FG03-01SF22362 and DE-AC36-99GO10337/TAA-2-31490-10
Performing Organization:	Geo-Heat Center, Oregon Institute of Technology
Principal Investigator:	John W. Lund
Phone:	(541) 885-1750
E-Mail:	lundj@oit.edu
Collaborating Researchers:	Kevin Rafferty and Tonya "Toni" Boyd
DOE HQ Program Manager:	Ray Fortuna and Gerry Nix
Phone:	(202) 586-1711 and (303) 384-7566
E-Mail:	Raymond.Fortuna@ee.doe.gov and Gerald_nix@nrel.gov

DOE Funding Allocations:	$255K + $200K = $455K
Cost Share Funding:	$23K + in-kind contributions of $62K = $84K (required for DE-FG03-01SF22362 only)

Project Objective: To continue on-going work by the Geo-Heat Center to develop and disseminate information; provide educational materials; develop short course and workshops; maintain a comprehensive geothermal resource database; respond to inquires from the public, industry and government; provide engineering, economic and environmental information and analysis on geothermal technology to potential users and developers (technical assistance) and provide information on market opportunities for geothermal development. In addition, in order to increase the awareness of the potential of geothermal energy, efforts were directed towards documenting successful projects, and their operation and maintenance data; provide applied research and development, and revise and document relevant computer software.

Background/Approach: These efforts are directed towards increasing the utilization of geothermal energy in the United States and developing countries, by means of promoting electric power generation, direct-use and geothermal heat pumps. These objectives were achieved with the following general activities:

1. Providing information and training to potential developers, designers and users of geothermal energy.

2. Maintaining and updating the GHC technical library of 5,000 volumes; a website of over 1800 files (http://geoheat.oit.edu), and comprehensive databases of geothermal resources and utilization information with over 12,000 entries.

3. Developing and disseminating resource, engineering, economic and environmental information, analyses and project descriptions to potential developers and users.

4. Providing technical assistance to potential user and developers of geothermal projects.

5. Developing and distributing educational materials.

6. Analyzing and identifying opportunities in both domestic and international markets for potential industries, utilities, independent power producers, developers and government.

Status/Accomplishments: An indication of our activity level, the following statistics are cited:

1. GHC website with approximately 1900 files which includes over 69 technical papers and 31 issues of our Quarterly Bulletin, along with a western states direct-use database and list of consultants and equipment manufacturers.

2. The average number of hits per day on our website: 8,904

3. The average number of website users per day: 1,240. The percentage of international users is about 10%

4. The number of website downloaded files per day: 1,376

5. The number of technical assistance requests responded to: 1,732. These included responses to 47 states and the District of Columbia, and 47 difference countries.

6. Published four issues of the Quarterly Bulletin that included 32 articles. The March issues covered seven case studies.

7. The number of publications provided: 813

Examples of technical assistance include: lodge heating, pool heating and hot water system improvements at Belknap Hot Springs Resort, OR; modification to the Boise Warms Springs Water District, ID; Fountain of Youth Spa, CA corrosion problems; Industrial Park heating near Reno, NV; I'SOT district heating project, Canby, CA; City of Klamath Falls district heating improvements; hydrogeologic study near Whitehouse, Yukon Territory, Canada; visit to Lava Hot Springs, ID to evaluate a heating system; Lakeview Correctional Facility, OR well testing and heating system design; Klamath Brewing Co., OR retrofit and proposed connection to the city district heating system; Aircraft Hanger heating in UT; visit by Idaho greenhouse owner to evaluate the potential for geothermal heating; problem solving of the heating system for the Yakima Country Jail, WA, Oregon Institute of Technology heating system improvements; numerous geothermal (ground-source) heat pump projects, mainly in the mid-western and eastern states; and providing tours of the campus, Klamath Falls district heating project, and the local greenhouse and aquaculture installations to visitors from educational institutions, local civic groups and interested professionals.

Reports & Articles Published in FY 2003:

John W. Lund: papers published in the book: *Geothermal Energy Resources for Developing Countries,* A. A. Balkema Publishers, Lisse, The Netherlands (Oct. 2002)

"Direct Heat Utilization of Geothermal Resources"
"Introduction to Geothermal Greenhouse Design"
"Introduction to Geothermal Aquaculture Design"
"Introduction to Geothermal Heat Pumps"
"Agri-Business Uses of Geothermal Energy" (co-authored with Paul Lienau)

John W. Lund, *Proceedings* of the 2002 Beijing International Geothermal Symposium, China, "Worldwide Utilization of Geothermal Energy and Its Applications to the 2008 Olympic Games in Beijing, China." (December 2002)

John W. Lund, *Encyclopedia of Energy*, Elsevier, UK: "Geothermal Direct Use" (Sep. 2003).

John W. Lund, *Applied Energy*, Vol. 74, Elsevier Science Ltd., UK: "Direct-Use of Geothermal Energy in the USA," (Jan 2003).

John W. Lund, *Bulletin*, Geothermal Resources Council, 32/2, "U.S. Geothermal Update," (Mar/Apr 2003).

John W. Lund, Ladsi Rybach, Robin Curtis, Burkhard Sanner, and Goran Hellstrom, *Renewable Energy World,* 6/4, "Ground-Source Heat Pumps," (Jul-Aug 2003).

John W. Lund, *Proceedings*, International Geothermal Conference, Reykjavik, Iceland, "Examples of Industrial Use of Geothermal Energy in the United States," (Sep 2003)

Kevin Rafferty, *Ground Water Journal*, "Geothermal Heat Pumps," (Jun 2003)

Kevin Rafferty, *Water Well Journal*, "Geothermal Heat Pumps," (Jun 2003)

Kevin Rafferty, *Proceedings* of ASHRAE, "Water Chemistry Issues in GSHP Systems," (Jan 2003)

Kevin Rafferty, *Bulletin*, Geothermal Resources Council, 32/4, "Direct-Use a Reality Check," (Jul/Aug 2003).

Tonya Boyd, *Proceedings*, International Geothermal Conference, Reykjavik, Iceland, " Western States Geothermal Database CD," (Sep. 2003)

Tonya Boyd and John W. Lund, *Proceedings*, International Geothermal Conference, Reykjavik, Iceland, "Geothermal Heating of Greenhouses and Aquaculture Facilities," (Sep 2003).

John Lund, Kevin Rafferty and Tonya Boyd published 18 articles in the four issues of the Quarterly Bulletin issued in FY03.

The Geo-Heat Center staff published seven case studies in GHC Quarterly Bulletin 24/2 (Jun 03).

Presentations Made in FY 2003:

John W. Lund, training course on Geothermal Energy Resources for Developing Countries at Mar del Plata, Argentina on: " Direct Heat Utilization of Geothermal Resources", "Introduction to Geothermal Greenhouse Design," "Introduction to Geothermal Aquaculture Design," "Introduction to Geothermal Heat Pumps," and "Agri-Business Uses of Geothermal Energy," (Oct 2002)

John W. Lund, keynote speaker at the 2002 Beijing International Geothermal Symposium in Beijing, China: "Worldwide Utilization of Geothermal Energy and Its Applications to the 2008 Olympic Games in Beijing, China," (Dec 2002).

John W. Lund, invited speaker at the European Geothermal Conference, Szeged, Hungary: "The USA Geothermal Country Update," and "The Use of Downhole Heat Exchangers," (May 2003)

John W. Lund, invited speaker at the Irish Geothermal Association meeting, Dublin, Ireland: "Geothermal Direct Use" and "Geothermal Heat Pumps with Applications to Ireland," (Jun 2003)

John W. Lund, International Geothermal Conference, Reykjavik, Iceland: "Examples of Industrial Use of Geothermal Energy in the United States," (Sep 2003)

Kevin Rafferty, Harvesting Clean Energy Conference, Boise, ID: "Greenhouse and Aquaculture Applications," and "Geothermal Heat Pumps" (Nov 2002).

Kevin Rafferty, Industrial Renewable Energy Conference, Minneapolis, MN, "Direct-Uses and Economics of Geothermal Energy," (Apr 2003)

Kevin Rafferty, GeoPowering the West Conference, Boise, ID, "Geothermal Direct-Use Projects and the Use of Associated Equipment," (Sep 2003).

Tonya Boyd, International Geothermal Conference, Reykjavik, Iceland: "Western States Geothermal Database CD" and "Geothermal Heating of Greenhouses and Aquaculture Facilities," (Sep 2003).

Planned FY 2004 Milestones:

Continue providing technical assistance to potential developers and users	all year
Continue upgrading our various data bases and reference library	all year
Publish four issues of the GHC Quarterly Bulletin	all year
Provide seven case studies of geothermal use with O&M data	all year
Provide information and training as requested on the use of geothermal energy	all year
Provide tour of local geothermal installations in Klamath Falls, OR	all year
Investigate the feasibility of installing a 250 kW electric power generator at OIT	all year
Write papers promoting the use of geothermal energy as requested	all year
Participate in GRC Annual meeting committee activities	all year
Travel to several geothermal sites to assist developers/users with problems	all year
Attend GRC Board of Directors meeting as Past President of the GRC	Jan 04, Jun 04, Aug 04
Attend the GRC Annual Meeting in Morelia, Mexico and present two papers	Oct 03
Attend the Growing the Renewable Energy Industry in Central Oregon conference Redmond, OR and make a presentation of the direct-use of geothermal energy	Oct 03
Attend the GeoPowering the West Washington Working Group meeting in Seattle and make a presentation of the direct-uses of geothermal energy	Nov 03
Attend the GRC Pacific-Northwest section meeting in Portland, OR	Dec 03

Attend the California Aquaculture Conference, San Diego with our booth	Jan 04
Attend the GeoPowering the West meeting as a speaker, Honolulu, HI	Jan 04
Attend the GeoPowering the West Utah Working Group meeting, SLC and make a presentation on agri-business uses of geothermal energy	Jan 04
Attend the Harvesting Clean Energy Conference as speaker with our booth Portland, OR	Jan 04
Attend the Stanford Geothermal Reservoir Engineering Workshop, Palo Alto, CA	Jan 04
Attend the PowerGen Conference and participate in a panel discussion, Las Vegas	Mar 04
Attend the GRC Annual Meeting as part of the organizing committee, Palm Springs	Aug 04
Attend International Geothermal Board of Directors meeting (if elected)	Sep 04
Attend the International Summer School Workshop as speakers, Zakopane, Poland and participate in several training sessions with presentations	Sep 04

GRC – Geothermal Resources Council

Reporting Period: FY 2003 (Budget Period, September 1, 2002 to August 31, 2003)

DOE Grant/Contract No.: DE-FG03-01SF22364

Performing Organization: Geothermal Resources Council

Principal Investigator: Ted J. Clutter
Phone: (530) 758-2360
E-Mail: tclutter@geothermal.org

Collaborating Researchers: Geothermal Education Office (GEO)
Marilyn Nemzer
(415) 435-4574

DOE HQ Program Manager: Susan Norwood, National GPW Program Director
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $352K

Cost Share Funding: In-Kind Funding $481K

Project Objective: The project team consists of the Geothermal Resources Council (GRC - contractor) and the Geothermal Education Office (GEO - subcontractor to the GRC). The contract funded 10 tasks by both organizations. The objective of this project is to continue DOE-supported, on-going work by the GRC and the GEO to develop and disseminate information, provide educational materials, and enhance technology transfer for the geothermal industry. This work will assist both industry and government efforts to increase geothermal resource use in the United States and the world by means of electric power generation, and direct utilization. The GRC provided engineering, economic, environmental and topical information and analyses about geothermal resources and energy development to geothermal and other energy professionals on demand. In addition, the GRC and GEO provided educational materials and training on geothermal energy at a variety of comprehension levels; encouraged public and professional education through workshops and the GRC Annual Meeting; maintained a comprehensive technology database (both as a library of printed materials and as web-based resources); and responded to numerous public inquiries.

Background/Approach: The GRC and GEO have over 40 years of combined experience with geothermal information dissemination, public outreach, technical assistance, education and research. They have established reputations as major U.S. geothermal educational organizations, and have been active in all aspects of geothermal development and utilization.

The GRC was formed in 1970 as a tax-exempt, non-profit, professional education association; current membership is 850 individuals in more than 20 countries, with corporate membership representing major geothermal developers worldwide. The GRC organizes its Annual Meeting as a forum for participants to learn about the latest advances in geothermal technologies and discuss important development issues. The meeting features special sessions, technical sessions, poster session, public information workshop, field trips and a geothermal energy trade show. The GRC publishes an annual volume of *Transactions* containing approximately 150 papers presented at the Annual Meeting, and the GRC *Bulletin*, a magazine (six issues/yr., circulation 1,000 worldwide) which features geothermal resource and development issues and technical topics, news and commentary. The GRC also provides workshops on various aspects of geothermal resources, exploration and development.

The GEO develops and distributes public information and semi-technical materials about geothermal resources and uses. The GEO was formed in 1990 as a non-profit education organization to provide public information on geothermal energy and its benefits. It disseminates geothermal information worldwide, and fields about 2,000 requests and inquiries a year − most from the Internet. GEO has maintains a web site, and has produced a video, a slide show, student curricula, a world statistical map, encyclopedia articles and other outreach materials. The GEO also convenes an annual *Introduction to Geothermal Energy* Workshop in conjunction with GRC Annual Meetings.

GRC and GEO information materials are used by geothermal developers and other stakeholders to educate and collaborate with national, state and regional energy administrators, regulators, policymakers, educators, students, non-governmental energy and environmental advocacy groups and the media.

Status/Accomplishments:

GRC 2002 Annual Meeting. The GRC 2002 Annual Meeting was convened on Sept. 22-25, 2002 at the Reno Hilton in Reno, NV. The meeting attracted over 700 participants from more than 20 countries. The meeting featured a cooperative trade show with the (U.S.) Geothermal Energy Association (43 exhibitors), as well as over 150 technical papers in concurrent sessions, a poster session (37 papers), field trips (3) to local geothermal power and direct-use facilities, workshops on environmental considerations and optimization of field and power plant operations and maintenance, and social activities. The event attracted high-level officials to its Opening Session from DOE (Asst. Secretary. David Garman), the U.S. Navy (Asst. Secretary. Wayne Arny), the Mexican DOE and Comision Federal de Electricidad.

GRC 2003 Annual Meeting. The GRC 2003 Annual Meeting was convened on Oct. 12-15, 2003 with co-sponsorship by DOE and Mexico's Comision Federal de Electricidad at convention facilities in Morelia, Mexico. Most project work was completed prior to the end of fiscal year 2003. The meeting attracted over 600 participants from more than 20 nations. The meeting featured a cooperative trade show with the (U.S.) Geothermal Energy Association (32 exhibitors), as well as 160 technical papers in concurrent sessions, a poster session (32 papers), field trips (2) to geothermal facilities and features, workshops on geothermal exploration and development, and social activities. The event attracted high level officials to its opening plenary session from DOE, CFE, the Mexican DOE, and the governor and other officials of Michoacan State and the City of Morelia.

GRC *Transactions* (GRC). For Vol. 27 of the GRC *Transactions*, the GRC produced two *Calls for Papers*, which were posted on the GRC website (www.geothermal.org) and distributed worldwide to nearly 5,000 individuals. A total of 160 technical papers were reviewed and accepted by a volunteer committee of geothermal experts from DOE National Laboratories and the private sector. All papers were formatted for publication by an outsource designer for printing as a casebound volume of nearly 950 pgs. The volume was delivered in time for distribution at the GRC 2003 Annual Meeting in Morelia, Mexico (above). With DOE support, the volume is offered at an affordable price of $65.

***Geothermal Technologies* Newsletter (GRC).** During the fiscal year, the GRC received, printed, and bound 3 *Geothermal Technologies* newsletters within the GRC bi-monthly *Bulletin* (Sept/Oct and Nov/Dec 2002, May/June 2003). The GRC received disk copy from the National Renewable Energy Laboratory (NREL - Golden, CO) for each 8-page edition, which was distributed as an insert to the GRC *Bulletin* to 850 members in the United States and around the world. Three-hundred additional copies of each newsletter were also shipped to NREL for DOE internal distribution.

GRC On-Line Library (GRC). The GRC maintains the largest geothermal library in the world. A bibliography of citations is available through keyword search on the GRC web site (www.geothermal.org). During the fiscal year, the GRC maintained one full-time employee and one temporary employee (7 months) to perform cataloging of donated libraries, thus increasing the number of citations available on the GRC website. Entries were increased to 30,453, including 21,000 in the GRC database, 4,226 in the GRC *Bulletin* database, 407 in the industry vendor list, and 243 in the power plant database, for a GRC total of 25,296 entries. OIT Geo-Heat Center contributes an additional 4,577 entries from their *Bulletin* and library collections. GRC Library databases continued to be updated through the end of March 2002. An out-source consultant cataloged the donated B.C. McCabe Geothermal Library. An out-source designer provided new design to enhance information transfer and make the GRC website more attractive and user friendly. The number of GRC website "hits" is approximately 3,500 per month.

Distribution of Geothermal Education Materials (GEO). GEO distributed about 4,800 booklets, brochures, posters, fact sheets, curricula and bookmarks, and more than 100 Geothermal Energy videos and CDs in response to student, teacher, general public and organizational requests. During the fiscal year, there was also an unprecedented number of requests for use of graphics and/or photos from the GEO *Introduction to Geothermal Energy* Slide Show presentation on the GEO website.

Outreach, Collaboration and Consulting Services (GEO). The GEO assisted some 50 individuals and organizations with ideas, graphics and video footage for geothermal presentations. GEO continued to consult/collaborate with publishers, organizations and institutions inside and outside the geothermal industry, including numerous instructors (primarily university-level) and students of all ages. GEO is actively collaborating with Alameda Power and Light (AP&T - Alameda, CA) to manage a geothermal energy program in area schools, as well as collaborative field trips through the Northern California Power Agency to its Geysers power plants. GEO also collaborated with Calpine, NCPA and AP&T to develop a 3D, table-size geothermal power plant model that can be taken to community events, trade shows and other meetings.

Geothermal Public Information Workshop (GEO). The GEO convened a successful Geothermal Public Information Workshop on September 24, 2002, in conjunction with the GRC 2002 Annual Meeting in Reno, NV. The workshop attracted 45 participants, including teachers, non-technical staff from geothermal companies, and representatives from a utility, environmental organizations, a local newspaper, and a local radio station. Participants visited the Geothermal Energy Association Geothermal Trade Show and GRC Annual Meeting Poster Session following the workshop. During the period, GEO also organized a Geothermal Public Information Workshop (co-sponsored by the University of Michoacan) that was held on Oct. 14 in conjunction with the GRC 2003 Annual Meeting in Morelia, Mexico.

Geothermal Energy Exhibit Booth (GEO). The GEO booth at GRC 2002 Annual Meeting in Reno, NV was a highly visible and successful display, winning GEO it's second "Most Informative Booth" award from the Geothermal Energy Association. During the event, GEO offered a draft version of a 90-second video animation illustrating geothermal electricity production for comments and critique from members of the geothermal community. When completed, the animation will provide an easily displayed substitute for a demonstration model of geothermal energy. The animation will be used by GEO and provided to other exhibitors, web sites, and for video productions.

Maintain and Enhance GEO Geothermal Public Information Web Site (GEO). The GEO's website (http://geothermal.marin.org) continues to draw much attention from the geothermal industry, students and the public. The GEO receives many requests for permission to use images from the website, mostly from university level educators and graduate students, and from members of the geothermal industry for presentations. GEO is nearly finished with text updates for its *Introduction to Geothermal Slide Show* (available on the website), and is currently developing plans for other website upgrades.

Response to Internet Inquiries (GEO). GEO continues to answer questions submitted by e-mail, usually via the GEO website. Additional questions (mostly from students) are also forwarded to GEO from DOE, GRC, the International Geothermal Association and others. The GEO has individually responded to hundreds of e-mailed questions and requests for information during the period. GEO passes on some technical questions to expert volunteers, including those about low-temperature technology and installation of geothermal heat pumps, which are referred to the Geo-Heat Center (Oregon Institute of Technology).

Reports & Articles Published in FY 2003:

GRC *Transactions* Vol. 26
GRC *Bulletin*, Vol. 31 (Nos. 5 and 6)
GRC *Bulletin*, Vol. 32 (Nos. 1, 2, 3 and 4)
DOE *Geothermal Technologies*,

Presentations Made in FY 2003:

Not Applicable

Planned FY 2004 Milestones:

DOE Geothermal Technologies newsletter	Oct 03/Feb, June Aug 04
GRC 2004 Annual Meeting	Aug-Sep 04
GRC Transactions, Vol. 28	Aug 04
GEO Public Information Workshop	Aug. 04
GEO Booth Set-ups at various conferences	TBD

Geothermal Outreach and Project Financing

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG03-01SF22365

Performing Organization: Bob Lawrence & Associates, Inc. (BL&A)

Principal Investigator: Elizabeth C. Battocletti
Phone: (703) 836-3654
E-Mail: lbatto@att.net

Collaborating Researchers: Bob Lawrence, boblaw424@aol.com
Jodi Hamrick, jodiha@erols.com

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $122K

Cost Share Funding: $1K in direct funding

Project Objective: The primary objective of the Geothermal Outreach and Project Financing Project is to establish geothermal energy as an economically competitive contributor to the nation's energy supply. The project does this by bringing together local and state stakeholders, suppliers, users, and environmental groups; and providing project financing education to potential developers, entrepreneurs, and small businesses. It supports the Geothermal Energy Program's goals of supplying the electrical power or heat energy needs of 7 million homes and businesses in the United States by 2010, and increasing the number of States with geothermal electric power facilities to eight by 2006. In FY 2003, the three-year project, which began in August 2001, continued to build on the work done in previous years.

Background/Approach: Local engagement and participation are critical to the success of GeoPowering the West. Consequently, a core component of the Geothermal Outreach and Project Financing Project is a comprehensive and focused public education and outreach program that brings together and educates key local stakeholders and decision makers.

In addition, the majority of the geothermal sites identified by GeoPowering the West will be small projects (requiring a capital investment of $1 million or less), and developed by small businesses and entrepreneurs who may have limited or no experience in writing a business and financing plan and obtaining financing. Armed with a great idea but no business plan or access to capital, small project developers may get discouraged and give up. BL&A addresses the significant market barrier of limited access to finance for small project developers under the Geothermal Project Financing component of the project.

Status/Accomplishments: In FY 2003, BL&A implemented six specific tasks: The firm:

1. Maintained the Geothermal-biz.com website for geothermal entrepreneurs.

2. Maintained and grew its GeoPowering the West contact database from 847 in October 2002 to 983 in September 2003, representing a total increase of over 200% since the project began.

3. Held two web conferences—"The Geothermal Program: Appropriations and Authorizations" on 5 February 2003, and "Opportunities and Challenges to Expanding Geothermal Energy for Public Power" and "Barriers to Working with Public Power Utilities" on 24 June 2003.

4. Wrote and distributed via email and fax four issues of the Geothermal-biz.com newsletter in October of 2002, and January, April, and July of 2003. The newsletter has been highly successful; additional people subscribe via the convenient online form. Comments received to date include:

    - "Thanks for sending the October Newsletter. It is very informative."
    - "...very useful and informative, as usual."
    - "This e-newsletter is very informative and useful."
    - "An excellent newsletter! Many thanks! Please include me regularly."
    - "Your newsletter is fantastic ... a real step forward in communicating what is happening in respect to DOE, academic and commercial programs."
    - "I find this compact summary quite useful in keeping abreast of what is happening in the Geothermal arena. Thanks for sending it."
    - "Keep up the excellent work on letting us know about many of the happenings in the geothermal community.
    - "Thank you for the information. It is very helpful."
    - "I have once again found the Geothermal-biz newsletter very helpful, well put together, and fun to read. You do a great job of adding just enough text to keep it informative and quickly readable. Thanks for putting so much of your energy into keeping the Geothermal community knowledgeable."

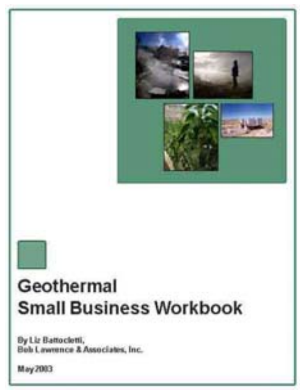


Figure 1. Geothermal Small Business Workbook

5. Published and distributed the Geothermal Small Business Workbook. In addition to sending hard copies to all GPW partners, BL&A posted the Workbook in PDF format on the Geothermal-biz.com website for immediate download. BL&A also provides the Workbook on CD-ROM. Using the online form, 43 people have received the Workbook on CD-ROM.

6. Researched and designed the Geothermal Small Business Financing Book.

Reports & Articles Published in FY 2003:

BL&A published the Geothermal Small Business Workbook in May 2003. In addition, presentations made by BL&A in FY 2003 were posted on the Geothermal-biz.com website in PDF format.

Presentations Made in FY 2003:

Elizabeth Battocletti made two presentations in FY 2003:

1. "Financing Geothermal Energy Development: Opportunities & Challenges" made at the National Tribal Sustainability Conference Council of Energy Resource Tribes on 15 April 2003.

2. "Making Geothermal Direct Use Applications Happen: Incentives, Funding & Proposals" made at the Geothermal Direct Use Workshop on 10 September 2003.

Planned FY 2004 Milestones:

Maintain Geothermal-biz.com website
Maintain and grow GeoPowering the West contact database
Write and distribute seventh Geothermal-biz.com newsletter
Hold seventh web conference
Write and distribute eighth Geothermal-biz.com newsletter
Deliver Geothermal Small Business Financing Book to DOE and reviewers
Finalize and distribute Geothermal Small Business Financing Book
Write and distribute ninth Geothermal-biz.com newsletter
Hold eighth web conference
Write and distribute tenth Geothermal-biz.com newsletter

Figure 2. Geothermal-biz.com website

Geothermal Regulatory Guides

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG01-02EE35226

Performing Organization: Washington State University Energy Program
Center for Distributed Generation and Thermal Distribution

Principal Investigator: R. Gordon Bloomquist, Ph.D
Phone: (360) 956-2016
E-Mail: bloomquistr@energy.wsu.edu

Collaborating Researchers: Kim Lyons, Research Specialist

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $70K

Cost Share Funding: Non required

Project Objective: To develop a set of regulatory guides to help developers of direct use projects navigate through the regulatory process required by federal, state, and local government. In addition to producing the guides, WSUEP staff will provide support and outreach to the geothermal community.

Background/Approach: The regulatory guides are to be produced as a result of an extensive state and federal regulatory search based on a web search of relevant state and federal statutes and implementing rules, and regulations and through interviews with key agency staff at state and federal agencies as it pertains to geothermal leasing, permitting, and licensing. The emphasis is on direct use projects and to a lesser extent on small scale (low temperature) binary power projects. The project takes existing, difficult to locate regulatory information and packages it in a user friendly format that, during the first year of the contract, covers the following ten western states: Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming.

Status/Accomplishments: Regulatory guides to the above ten states have been prepared and are now out for review. The guides provide links to all relevant agency provided forms, legislative references, and administrative codes. In addition to production of the ten state guides, WSUEP has begun to revise an already existing guide to the entire federal geothermal regulatory process and prepared a paper on U.S. Geothermal Policy.

Reports & Articles Published in FY 2003:

Ten regulatory guides were produced . See above for states covered. An article on U.S. geothermal policy was written and published as part of a course guide published by the United Nations geothermal school in Iceland.

Presentations Made in FY 2003:

A lecture on U.S. geothermal policy was given at the International Summer School on the Direct Use of Geothermal Energy. The course was held in September in Reykjavik, Iceland. Additional presentations on geothermal regulation were given at GeoPowering the West state working group meetings.

Planned FY 2004 Milestones:

Five additional regulatory guides will be prepared during FY2004 and the guide to the federal geothermal regulatory process will be finalized.

Geothermal Direct Use Technical Support

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC36-99G010337

Performing Organization: Washington State University Energy Program
Center for Distributed Generation and Thermal Distribution

Principal Investigator: R. Gordon Bloomquist, Ph.D
Phone: (360) 956-2016
E-Mail: bloomquistr@energy.wsu.edu

Collaborating Researchers: Robert O'Brien, PE

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $210K

Cost Share Funding: None required

Project Objective: The objectives of the project is to provide technical support, analytical tools development support, testing and evaluation support, and marketing conditioning support to the DOE/NREL Geothermal Energy Program users and potential user of geothermal direct use projects and project developers.

Background/Approach: The United States has a tremendous geothermal potential capable of providing the thermal requirements of industrial and agriculture process, space heating and for use in green housing and aquaculture. Unfortunately, technical information and direct technical assistance is often required to ensure that projects move forward. This project is designed to provide technical assistance directly to potential developers, develop tools required to reduce the time and cost of conducting technical and economic feasibility studies, and document the experience of those projects already on line so as to serve as a benchmark of lessons learned.

Washington State University Energy Program (WSUEP) has, together with the Oregon Institute of Technology GeoHeat Center, attempted to address the needs of the geothermal direct use developer through provision of advice and technical assistance to existing—as well as potential—developers of geothermal direct use projects, developed technical modeling tools to reduce cost and time involved in conducting feasibility and design studies, and documented lessons learned.

Status/Accomplishments: WSUEP has completed two case studies and is working on a third. The three include geothermally heated hotels in Ouray, Colorado and the VA Hospital in Boise, Idaho that is heated by a geothermal district energy system. The third case study under development is the Bonneville Hot Sprints Resort Hotel located in North Bonneville, Washington.

During the development of the case studies, WSUEP has collected and evaluated operation and maintenance information with the aim of identifying any specific O & M issues, problems, or needs. Based on the analysis of O & M data, it was determined that there was not an identified need for any further research and development relative to commercially employed equipment, but instead a serious need for better information and education relative to the proper selection , installation, and operation of commercially available equipment.

WSUEP has worked to expand the HEATMAP@GEO software model to adequately model geothermal based combined heat and power (CHP) application. This enhanced capability of the production module of DOE II into HEATMAP@GEO. The new HEATMAP@GEO/CHP MODEL will also allow for the incorporation of thermal storage and a complete accounting of utility rate information. Additionally (at no cost to this project), WSUEP is expanding the capability of the HEATMAP model to allow for the use of a broad array of CAD and GIS software products for geographic control, this greatly expanding the usability of the tool. Finally, the HEATMAP@GEO/CHP model libraries are being populated with technical specifications and cost information relative to equipment items required for modeling geothermal CHP opportunities.

WSUEP has also provided support to numerous potential and existing geothermal projects. These include Columbia Gorge Hot Springs Spa (Onsen), Conby, CA, Mammoth Lake, CA, Boise, ID, Elko, NV, Wells, NV, University of Nevada, Reno Campus, various hotels in Ouray, CO, and numerous geothermal heat pump projects. WSUEP has also provided technical assistance to state working group teams, including New Mexico, Arizona, Idaho, Utah, and Oregon.

Reports & Articles Published in FY 2003:

WSUEP has released three case studies during the present reporting period, including *Elko County School District Heating System, Empire Energy District Heating System,* and *Elko Heat Company District Heating System*. WSUEP has also prepared two technical papers, entitled *Geothermal Space Heating* and *Integrating Small Power Plants into Agricultural Projects*, that have been published by Geothermics.

Presentations Made in FY 2003:

WSUEP staff made presentations at the European Geothermal Conference held in Hungary in the spring of 2003 on Geothermal Space Heating and Integrating Small Power Plants into Agricultural Projects. WSUEP organized the GRC short course on geothermal project development held in Los Azufres, Mexico in October and made a presentation on geothermal project financing.

Planned FY 2004 Milestones:

It is unclear at this point due to funding cutback what the scope of activities for FY2004 will be.

Geothermal Industry Progress and Projects

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)	
DOE Grant/Contract No.:	DOEFG01-02EE35227
Performing Organization:	Geothermal Energy Association (GEA) 209 Pennsylvania Ave, SE Washington, D.C. 20003
Principal Investigator:	Karl Gawell
Phone:	(202) 454-5261
E-Mail:	Karl@geo-energy.org
Collaborating Researchers:	Diana Bates/Julia Watkins, research@geo-energy.org
DOE HQ Program Manager:	Susan Norwood
Phone:	(202) 586-4779
E-mail:	Susan.Norwood@ee.doe.gov

DOE Funding Allocation:	FY 2003: $27K
Cost Share Funding:	FY 2003: $4.5K

Project Objective: Develop or collect data on progress in the geothermal industry, including planned and operating projects, industry participants, and new technologies.

Background/Approach: GEA produced a preliminary listing of geothermal power plants by state as part of its updated directory. This listing was based upon the public databases available from state and federal agencies, but these sources were significantly out-of-date. The list incorporated updated and corrected information obtained by GEA's staff through individual contact with the companies in the industry and reflects significant changes in plant ownership. However, it still needed additional updating for the plants listed, outreach to ensure that small plants have been included accurately, and expansion to include other key data. All of these were proposed under this task.

GEA proposed to complete a full review of this list to ensure accuracy of the basic data: plant name, current capacity, year placed in service, location and owner/operator. GEA also surveyed industry participants, particularly power plant design and engineering firms, and state energy offices to determine whether any small power plants have been left off the listing and update the data as needed. Finally, GEA determined the current status of each plant and noted those that have been taken out of service or de-rated, which is another significant problem in the data used by both DOE and the state of California. Contact information for each owner/operator would also be provided. GEA staff would produce a revised survey and post it on GEA's web site for public use, with links to the company websites as available.

After completion of this basic task, GEA would work with DOE geothermal personnel and the Task Advisory Committee to determine what other baseline information GEA should seek as part of this survey, such as annual electricity production from each plant for the latest available year, and plans for capacity additions at the facility. GEA would seek to obtain information from existing sources wherever possible. For information not already available, and consistent with proprietary interests, GEA would conduct an industry-wide survey by mail and email. GEA would make follow-up calls to survey recipients to ensure full data collection, to the extent possible.

Further, GEA would assess the information available about the potential for new geothermal development in the US, and request information about potential new geothermal projects from a broad base of industry and state energy sources. GEA would develop a listing of estimated state-by-state geothermal resource potentials, with annotation or links to the sources for the estimates. These will be coupled with state listings of "potential projects." If such projects, or potential power sites, were sites developed by state or federal agencies, or other similar entities, the data will indicate the source for the information. For individual project developers responding to GEA's request for information, they would be contacted to verify the information provided and those who demonstrated that they reach some threshold of credibility, such as legal right to develop a project through a lease or property ownership, will have their "potential projects" listed on the database. The information about such projects will parallel the same baseline information for existing projects: name, potential capacity, expected start date or completion date, general location, and project developer. Contact information for the project developer would also be provided, and an appropriate "disclaimer" about these listings will be developed in consultation with GEA's legal counsel.

GEA would review and update this information on an annual basis.

Status/Accomplishments: GEA completed a final template for the information collected and reviewed as noted above, organized the information collected and posted it on GEA's web site (www.geo-energy.org). A layout was designed for the information using Front Page software.

Once the information for this web-site was edited and posted, GEA publicized the availability of this information through its newsletter and the web site. GEA also asked primary contact persons from each plant to check for accuracy of each posting. Reported errors were corrected on the web site.

The following information was collected, organized and posted under the "facilities" icon on GEA's web site:

Existing Plants in the US

This section of the web-site includes a comprehensive list of all geothermal power plants by state. By clicking on each state, the user can choose either to view individual pages for each plant or a running list of data for geothermal plants by state.

The individual pages include the following information:

A. Digitized Photo
B. Data Table (same as included in running list)
    1. Owner
    2. Location
    3. Name Plate Capacity
    4. Avg. Annual Gross MW
    5. Avg. Annual Net MW
    6. Zip Code

C. Unique Information-chosen to be included by individual plants
D. Tour Information
E. Up-dated Contact Information
F. Web-link for Owner, Company, or Plant.

The running data table pages for each state includes the following information:
A. Data Table (same as included on individual pages)
   1. Owner
   2. Location
   3. Name Plate Capacity
   4. Avg. Annual Gross MW
   5. Avg. Annual Net MW
   6. Zip Code

Developing Plants in the US*

The goal of this section of the web site is to maintain an up-to-date posting for owners, developers and financers of geothermal power plants.

In creating this site, GEA created a form to be filled out by interested developers and re-submitted to GEA for confirmation. Sites are currently posted on the site as either “confirmed” or “non-confirmed”. Non-confirmed postings are linked to the sources from which GEA discovered them.

Each plant is listed by state and has its own individual page. Confirmed postings include the following information:
A. Name and location of potential project
B. Type of project
C. Status of project
D. Contact information
E. Land status
F. Approximate date of completion/operation
G. Estimated capacity (MW) or other measure of energy production expected
H. Anticipated buyer of power or heat
I. Other information of interest

*Due to the nature of this section, it is continually being up-dated.

Resources*

The goal of this section of the web-site is to post geothermal resource information by state. Resource information includes maps and fact sheets highlighting areas with geothermal springs, geothermal wells, geothermal sources, as well as those areas with the potential for electric generation or direct use application.

* Due to the nature of this section, it is continually being up-dated.

Links

The goal of this section is to provide useful links to web sites, handbooks, photos, and reports related to geothermal energy. This section is divided into two groups:

A. Websites and Reports
B. Student Information

Reports & Articles Published in FY 2003:

As noted above, data collected is now available on GEA's web site. No separate reports or articles were published in FY 2003.

Presentations Made in FY 2003:

As noted above, data collected is now available on GEA's web site. No separate presentations were made in FY 2003.

Planned FY 2004 Milestones:

Updating of this data will be done on a regular basis throughout FY 2004.

Support of Geothermal Stakeholder Outreach and Information Dissemination

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-FG01-02EE35228

Performing Organization: Geothermal Education Office (GEO)

Principal Investigator: Marilyn L. Nemzer
Phone: (415) 435-4574
E-Mail: mnemzer@marin.org

Collaborating Researchers: N/A

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-Mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $67K

Cost Share Funding: $44K (includes value of in-kind contributions)

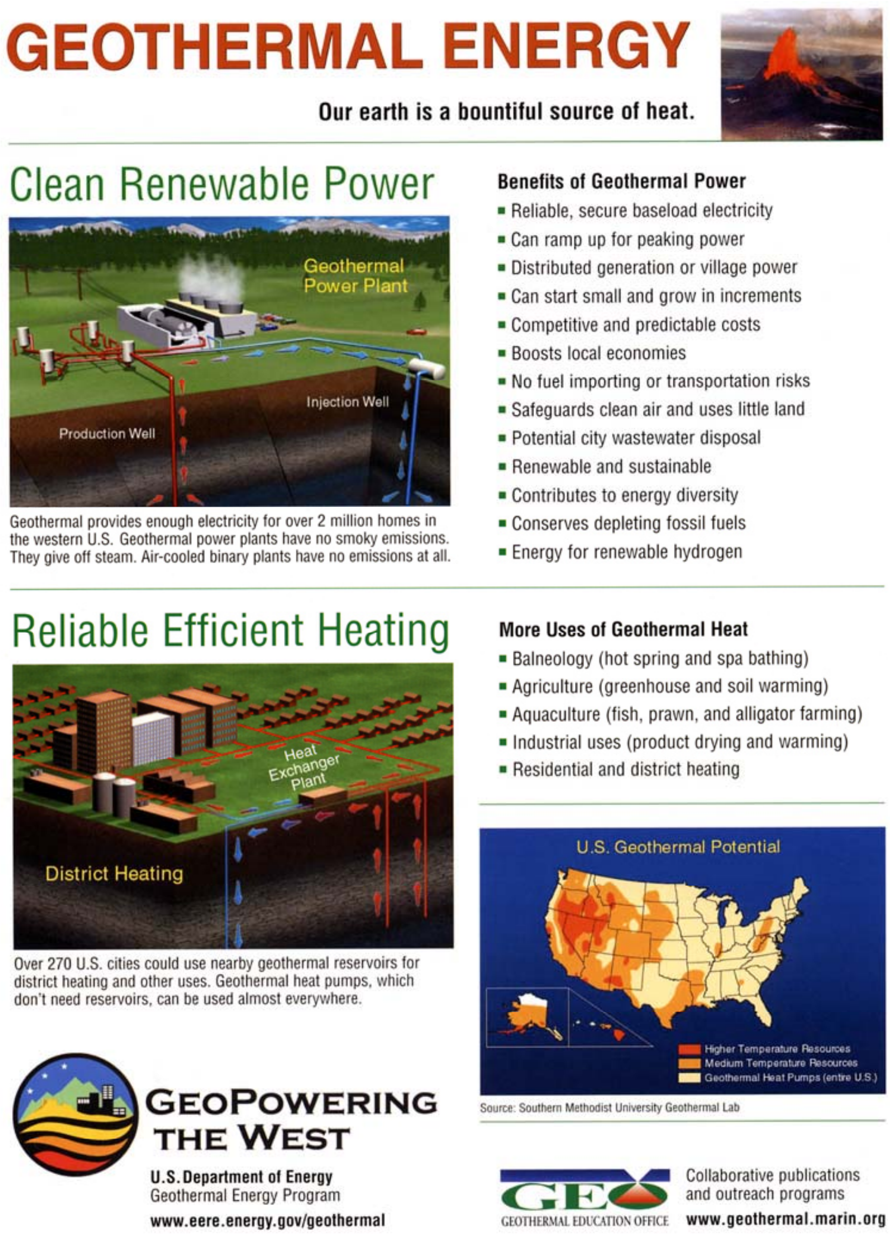
Project Objective: The purpose of this project is to support DOE's GeoPowering the West initiative to promote the use of geothermal energy throughout the Western U.S. GEO fosters geothermal energy deployment by assisting geothermal stakeholders to educate decision-makers in state and local governments and in the environmental and financial communities about the benefits and potential applications of geothermal energy.

Background/Approach: Most individual companies, regulatory agencies, organizations, consultants, educators and members of the media do not have the resources to create geothermal education and outreach materials independently – and the companies that do have the resources create project-, technology-, or company-specific materials. To fill this gap, GEO provides geothermal audio-visual, exhibit and print materials and performs outreach activities which significantly increase the preparedness of GEO and other key geothermal stakeholders in undertaking outreach and information dissemination activities.

Status/Accomplishments: Editing of Video, *Geothermal Energy: A Renewable Option*: GEO replaced selected graphics and footage, updated energy facts, and removed out-of date sections about energy regulatory issues.

CD of Introduction to Geothermal Energy "Slide Show": GEO has prepared the slide show in a new format for CD. Until now, a version with text captions for each slide was available only on the GEO website. The former CD version provided the PPT file for speakers only. Now the CD has a "selfteaching" version (i.e. one with text) for individual learners as well as the version for presenters. (The CDs will distributed in March of '04).

Handouts: During this period, GEO developed/printed a new one-page flyer about geothermal energy and reprinted existing materials as needed for distribution to GPW stakeholders.



Geothermal handout created for distribution at GPW events

Booths/Conferences: GEO has been "taking its show on the road." With this funding from the GPW program we have been able to take much greater advantage of DOE money spent in other grants developing our display. In FY 2003 GEO managed and staffed the Geothermal Energy booth at the following conferences and supplied materials to numerous others:

- *Harvesting Clean Energy*. February 9-12. Boise Idaho.
- *Nevada Legislature Renewable Energy Panel and Exhibit* , Nevada Renewable Energy and Energy Conservation Task Force April 7. Carson City, Nevada. Jim Combs and Dan Schochet volunteered at the booth.
- *Utility Energy Forum*. May 7-9. Tahoe City, CA. WAPA co-sponsored GEO booth.
- *Renewable Energy Summit*. June 23-25. San Francisco, CA, INEEL co-sponsored GEO's booth registration. Patrick Laney of INEEL volunteered at the booth.
- *National Conference of State Legislators*. July 23-25. Moscone Center, San Francisco, CA. Jack Pigott of Calpine volunteered at the booth.
- *Southwest Renewable Energy Fair*. August 8-10. Flagstaff, AZ,
- *GPW State Working Group Summit* and *Geothermal Direct Use Workshop*. September 11-12. Boise, ID

Curtis Framel, David Garman, Roger Hill, Southwest Renewable Energy Fair, Flagstaff, AZ, August 2003

Reports & Articles Published in FY 2003:

See Status/Accomplishments section above.

Presentations Made in FY 2003:

See status/Accomplishments section above.

Planned FY 2004 Milestones:

- *GRC/GPW Workshop*. October 21, 2003. Deschutes County Fairgrounds, Redmond, OR
- *Growing Renewable Energy in Central Oregon*. October 22. Deschutes County Fairgrounds, Redmond, OR
- *Joint Ventures: Partners in Stewardship* (meeting of primarily federal land managers). November 18-20, 2003. One of 80 Exhibitors. L.A. Convention Center, Los Angeles, CA
- *Geothermal Utility Workshop.* December 18, 2003. WAPA and CRS, convenors: Sacramento, CA
- *Harvesting Clean Energy/Northwest Food Manufacturers Association*. January 20-21, 2004. Portland, OR. John Geyer volunteered at the booth and answered questions about geothermal heat pumps. Empire Foods of Nevada provided display samples of onions/garlic dried with geothermal heat.
- *Geothermal Utility Workshop*. December 16, 2004, Pasadena, CA (Sent Materials for distribution)
- *GPW Hawaii Working Group*. January 12, 2004 (Sent Materials for distribution)
- *Exploring Utah Geothermal Opportunities*. January 20, 2004. (Sent Materials for distribution)
- *PowerGen Renewables*. March 1-3, 2004. Las Vegas. NV
- *Utility Energy Forum*. May 5-7, 2004. Collaboration with WAPA Tahoe City, CA
- *American Public Power Association*. Collaboration with WAPA. June 19-23, 2004. Seattle, WA
- *World Renewable Energy Congress*. August 28 – September 3, 2004. Denver, CO
- GPW State Working Group and other Meetings to be determined.
- Distribute CDs with edited version of slide show.

GEO booth set up for a GeoPowering The West event.

Geopowering the West (NREL)

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.:

Performing Organization: National Renewable Energy Laboratory

Principal Investigator: R. G. Nix
Phone: (303) 384-7566
E-Mail: Gerald_nix@nrel.gov

Collaborating Researcher: Barbara Farhar

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@hq.doe.gov

DOE Funding Allocation: $300K

Cost Share Funding: None

Project Objective: The goal is to act as a catalyst to significantly enhance the use of geothermal energy and the installation of geothermal plants by the private sector. Specific objectives of GPW are to double, from 4 to 8, the number of states with geothermal electric power facilities by 2006, to supply geothermal energy to at least 7 million homes by 2010 and to supply at least 10 percent of the electricity needs of the American West by the year 2020 with geothermal energy.

Background/Approach: GeoPowering the West (GPW) is a major task that fosters awareness of the availability and benefits, and promotes the development and use of geothermal energy throughout the western United States where geothermal resources are most readily accessible. The effort begins with education, awareness and outreach activities aimed at a variety of stakeholders such as businesses, government organizations, Native American groups, and the general public. For the outreach, this project addresses the collaboration of a cooperative team of geothermal organizations and experts put together to provide a broad-based approach to applying various forms of geothermal technical assistance and to provide education materials, information dissemination and technology transfer requests from individuals, government, private businesses and industry.

The approach is to:

- Develop reports and presentations to promote geothermal energy
- Create grass-root state working groups to promote awareness and application of geothermal energy
- Target specific groups such as Native Americans that have geothermal resources for potential uses
- Act as an enabler to multiply the success of the overall effort to promote use of geothermal energy
- Actively seek opportunities for funding of projects using money from other sources

- Define and seek to remove barriers to application of geothermal energy

NREL defined, organized and implemented 2 workshops of geothermal industry, and federal and state officials on access and permitting of geothermal plants on public lands. The results were a significant factor in the President's National Energy Plan. In addition, NREL supported local actions and working meetings in Nevada, Idaho and New Mexico.

Status/Accomplishments: NREL targeted the development and sustainability of working groups in the primary states of Nevada, Alaska and Hawaii. Secondary states included Colorado and Wyoming.

Activities in Nevada included program definition and supporting presentation of geothermal topics at the DOE Industrial Technologies Mining Industries of the Future meeting in Elko, NV Aug 26-28, including use of the geothermal booth at the associated trade show.

Activities in Alaska included cataloging of the geothermal opportunities and active outreach to the community. This culminated in an invitation to Assistant Secretary Garmin, from Governor Murkowski to visit potential geothermal sites at Dutch Harbor on Unalaska and at Akutan.

NREL supported the initial geothermal meeting in Hawaii, with the meeting held in Jan 2004. NREL supported meetings and outreach activities in CO, especially with the Delta-Montrose Electric Association for a meeting emphasizing geothermal heat pumps. NREL supported a visit and outreach to the Wind River Indian Reservation in WY.

NREL completed the production of the report ***Near-Term Opportunities for Geothermal Development on Public Lands in the Western United States*** on CD-ROM and attended the press conference of Assistant Secretary Rebecca Watson, U.S. Department of the Interior, to release the report to the public. NREL distributed the report to several hundred requestors; participated in media interviews on the report; and assisted the Bureau of Land Management and the GeoPowering the West program in promulgating the report and its findings.

NREL represented GPW in the first round of procurements under the Farm Aid Bill, by participating in the USDA Informational Meeting in Oklahoma City, April 7-9. NREL reviewed the geothermal proposals and has participated in the efforts to better focus the effort for 2004.

NREL targeted Native Americans and has developed an excellent relationship with the Council for Energy Resource Tribes (CERT). NREL develop a brochure outline for a geothermal brochure for Native American Tribes (to be distributed at the CERT Regional Workshops). NREL has supported the DOE Program to promote applications of renewable energy by the Tribes, including various presentations and review of proposals.

Reports & Articles Published in FY 2003:

Nix, Gerald and Barbara C. Farhar. 2002. "Geothermal Energy: Government Initiatives in Partnership with Industry." Presentation at the International Energy Conference and Exposition, Reno, Nevada, November 13-15.

Farhar, Barbara C. 2002. "Geothermal Access to the Public Lands." Presentation at the International Energy Conference and Exposition, Reno, Nevada, November 13-15.

Farhar, Barbara C. 2002. "Geothermal Access to Federal and Tribal Lands." *GRC Transactions 26:* 611-615.

Farhar, Barbara C. and Donna M. Heimiller. 2003. *Opportunities for Near-Term Geothermal Development on Public Lands in the Western United States.* CD-ROM with report, maps, and GIS data. Golden, CO: U.S. Department of Energy, National Renewable Energy Laboratory. Report No. DOE/GO-102003-1707. April. Http://www.nrel.gov/docs/fy03osti/33105.pdf.

Farhar, Barbara C. and Paul Dunlevy. 2003. "Native American Issues in Geothermal Energy." Paper prepared for the 2003 Annual Meeting of the Geothermal Resources Council, Morelia, Mexico. October 12-15, 2003. Also prepared the PowerPoint presentation for this paper.

Farhar, Barbara C. 2004. "Evaluation of Geothermal Public Power Utility Workshops, December 16 and 18, 2003, Pasadena and Sacramento, California." (Draft). Golden, CO: National Renewable Energy Laboratory, January 15. 22 pp.

Presentations Made in FY 2003:

Attended and presented at the National Geothermal Collaborative Meeting, Denver, CO, May 12-13, 2003.

Attended and presented at a meeting of NREL staff with U.S. Forest Service staff on assessing renewable resources on Forest lands, Washington, DC, May 15-16. Held follow-up meetings with DOE and BLM staff.

Attended and presented at the GeoPowering the West State Summit and Direct-Use Workshop, Boise, Idaho, September 8-11, 2003.

Provided technical assistance for planned WAPA-led survey of municipal utilities on geothermal energy.

Developed technical session on "Revitalization of Rural Communities through Geothermal Energy" for the World Renewable Energy Congress (WREC) VIII, Denver, Colorado, Aug.-Sept. 2004.

Organized 5 geothermal sessions at the 2003 GRC, including acting as chair of 2 sessions. Supplied and manned the geothermal booth at the GRC meeting in Morelia, MX.

Attended and was rapporteur at the Council of Energy Resource Tribes (CERT) Sustainability Conference, Albuquerque, New Mexico, April 14-16, 2003. Served as rapparteur and prepared notes on the meetings for CERT's reporting requirements.

Provided technical assistance on tribal issues including preparation and presentation of a map showing tribal lands and geothermal resources.

Made a web-cast to all DOE Regional offices in May, describing geothermal energy.

Planned FY 2004 Milestones:

Support WAPA at Utility Workshops	Dec 03
Support the Hawaii Geothermal Meeting	Jan 04
Re-constitute and energize the Nevada Working Group	Mar 04
Hold a workshop in Alaska, with formation of a working group	May 04
Hold a workshop in Colorado, with formation of a working group	Aug 04
Define an action plan to enhance use of geothermal energy in Hawaii	Sept 04

Geopowering the West (INEEL)

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DOE Contract DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory (INEEL)
Renewable Energy & Power Technologies Department
2525 North Fremont Drive, P.O. Box 1625
Idaho Falls, ID 83415-3830

Principal Investigator: Robert M. Neilson, Jr.
Phone: (208) 526-8274
E-Mail: rmn@inel.gov

Collaborating Researchers: Patrick T. Laney, ptl@inel.gov

DOE HQ Program Manager: Susan L. Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $250K

Cost Share Funding: None

Project Objective: The objective of this project is to support the accomplishment of GeoPowering the West goals through the development and dissemination of information, educational materials, and technology transfer. These goals are:

1. Double, from 4 to 8, the number of states with geothermal electric power facilities by 2006,
2. Supply geothermal energy to at least 7 million homes by 2010, and
3. Supply at least 10 percent of the electricity needs of the American West with geothermal energy by the year 2020.

Background/Approach: The GeoPowering the West (GPW) task promotes the development and use of geothermal energy throughout the western United States by fostering awareness of its uses, availability, and benefits. The task focus is on the western United States since this is where domestic geothermal resources are most readily accessible. GPW is an outreach effort that targets a wide range of stakeholders with an interest in geothermal energy, including federal, state, and local government organizations, Native American nations, industry and business, educational entities, environmental groups, and the general public. Under DOE-HQ direction, a team consisting of geothermal organizations and experts has developed a collaborative, integrated approach to performing geothermal energy outreach to achieve GPW goals.

In FY 2001, an implementation plan was developed for the GeoPowering the West task under which the DOE Program's lead laboratories play a critical role in developing and implementing outreach activities, especially for the states to which they have been assigned. In FY 2001, the principal states supported were Nevada, Idaho, and New Mexico, which were assigned to NREL, INEEL, and Sandia respectively. In FY 2002, Roger Hill, Sandia National Laboratory, was appointed National Technical Director for the GPW task and Gordon Bloomquist, WSU, was added to the core team as State Working Group Coordinator. The states supported were expanded to include (with assigned national laboratory lead) Alaska (NREL), Arizona (Sandia), California (WAPA), Hawaii (NREL), Oregon (INEEL), and Washington (INEEL). In addition to identification of state lead assignment, the national laboratories have assumed responsibility for specific areas supporting the GPW task. In this regard, the INEEL has the primary responsibility for resource assessment within GPW with a focus on developing state geothermal resource maps.

In FY 2001, the INEEL organized the Idaho Geothermal Energy Stakeholders Workshop, which was held on May 31, 2001 in Boise, Idaho and hosted by U.S. Senator Larry Craig. The following day, the Idaho Geothermal Energy Working Group, initially consisting of approximately of about thirty stakeholders from Idaho, was formed. During FY 2002 the INEEL, working closely with the Idaho Department of Water Resources-Energy Division, initiated efforts to further the Idaho Geothermal Energy Working Group. These efforts focused on the development of a strategic plan for the development of geothermal resources within the state and a group structure and operating guide. The draft strategic plan was completed in April 2002.

Status/Accomplishments: The primary information activity in FY 2003 was the development of geothermal resource maps for the thirteen western states (AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, UT, WA, and WY) and a western states regional map. These maps are designed for general public information purposes and include information on the locations of geothermal wells and springs, geothermal power production, and direct use applications (such as resorts and spas, greenhouses, aquiculture, etc.). The maps also indicate broad areas where there is potential for geothermal applications. These maps have been used extensively in printed form at state working group meetings and have been posted on the internet in several formats (to provide flexibility for the user) at http://geothermal.is.doe.gov/maps-software.shtml.

A primary INEEL focus has been working closely with working groups in assigned states. As mentioned previously, these include Idaho, Utah, Oregon, and Washington.

The INEEL helped to organize and supported three meetings and other activities of the Idaho Geothermal Energy Working Group (IGEWG) in FY 2003.

At its October 10, 2002 meeting, the working group formally accepted the Idaho Geothermal Energy Development Strategic Plan. Subcommittees were formed to accomplish the eight strategic objectives identified in this plan and subcommittee chairpersons identified.

The INEEL participated in and helped to plan the Idaho Geothermal Trade Mission to Nevada, which was held on November 18-19, 2002 in Reno, NV and included visits to the Brady geothermal power plant and to Gilroy foods, as well as a session where the twenty-one Idaho participants were able to discuss geothermal energy development with their Nevada counterparts. The trade mission was very successful with a large amount of information provided to Idaho policy makers who were impressed with the geothermal operations visited and the potential opportunities for geothermal development in Idaho. The information provided during this trade mission is useful for the development of policies and legislation promoting the utilization of geothermal energy in the state. Idaho Senator Joe Stegner, who is the author of the Idaho Renewable Energy Act of 2003 (which was not enacted), was one of the trade mission participants.

The second working group meeting was held on July 23, 2003 in Burley, Idaho. During this meeting, the geothermal trade mission to Nevada was discussed and subcommittee chairs described their activities since the last working group meeting. Two proposed geothermal electric power projects were discussed. Doug Glaspey, U.S. Geothermal, described plans for his company's geothermal electric development at Raft River, ID. U.S. Geothermal is planning to develop a 15 MWe plant, which may be expanded to 30 MWe in a subsequent development phase. Carl Austin, Idatherm, described his plans for development of a prospect in eastern Idaho at Willow Springs, which may ultimately produce as much as 100 MWe of geothermal electric power. Both of these projects are projected to come on line in mid-2005 and as such will directly contribute to the GPW goal of doubling the number of states with geothermal electric power by 2006.

The third Idaho Geothermal Energy working group meeting was help on September 11, 2003 in Boise, Idaho. In addition to subcommittee reports, this meeting also had a presentation by Dr. Christian Petrich, University of Idaho, on development of the Boise Front geothermal aquifer model. This work, funded by DOE and supported by the INEEL is working to develop an improved understanding of the aquifer, which could be used to support further develop of geothermal direct use applications in the Boise area.

The INEEL helped to develop a geothermal working group in Utah in FY 2003. Working closely with the Utah Geological Survey and the Utah State Energy Office, the INEEL helped to form the Utah Geothermal Working Group. A meeting to discuss the formation of this working group was held in Salt Lake City on November 8, 2002. The first formal meeting of the Utah Geothermal Working Group occurred in Salt Lake City on March 4, 2003 and was attended by thirty-three people representing a variety of interests. Bob Blackett, Utah Geological Survey, agreed to serve as the lead for the Utah Geothermal Working Group. A subsequent working group meeting was held on September 5, 2003. A draft structure and operations guide for the working group has been prepared and was submitted to the working group at their September meeting.

Together with Gordon Bloomquist, WSU, the INEEL helped to plan a working group meeting for Oregon, that was held in Portland, OR on July 16, 2003. This meeting, attended by approximately thirty people, included an overview and update of the progress since the first combined WA-OR working group meeting in June 2002. Mike Grainey, Director of the Oregon Department of Energy, agreed to take the lead for an action to develop a strategic plan for the Oregon working group.

The INEEL planned, organized, and executed a one-day regional geothermal direct use workshop "Making Your Direct Use Applications Happen" in Boise, ID on September 10, 2003. This workshop, attended by seventy-one people provided detailed information on how to apply geothermal energy for agriculture, aquiculture, industrial processing, and district heating applications. This workshop is considered a template for future direct use workshops in other states.

The INEEL participated in a number of conferences to promote geothermal energy. These included the International Energy Conference and Exposition in Reno, NV on November 13-15, 2002, Harvesting Clean Energy Conference in Boise, ID on February 10-11, 2003, and the Renewable Energy Investors Conference, in San Francisco, CA on June 24-25, 2003.

The INEEL also participated in the GPW Strategy Meeting held in Washington, DC on December 12, 2002, the Wind River Reservation renewable energy site survey on July 2, 2003, and the GPW State Summit held in Boise, ID on September 9, 2003.

Reports & Articles Published in FY 2003:

K. Kit Bloomfield, Joseph N. Moore, and Robert M. Neilson, Jr., "Geothermal Energy Reduces Greenhouse Gases," Geothermal Resources Council Bulletin, 32(2), 77-79, March/April 2003.

The following maps were prepared and made available in printed form and on the INEEL Geothermal Website

Laney, Patrick and Julie Brizzee, Alaska Geothermal Resources INEEL/MIS-2002-1623
Laney, Patrick and Julie Brizzee, Arizona Geothermal Resources INEEL/MIS-2002-1616
Laney, Patrick and Julie Brizzee, California Geothermal Resources INEEL/MISC-03-01044
Laney, Patrick and Julie Brizzee, Colorado Geothermal Resources INEEL/MIS-2002-1614
Laney, Patrick and Julie Brizzee, Hawaii Geothermal Resources INEEL/MISC-03-01045
Laney, Patrick and Julie Brizzee, Idaho Geothermal Resources INEEL/MIS-2002-1618 Rev 1
Laney, Patrick and Julie Brizzee, Montana Geothermal Resources INEEL/MIS-2002-1619
Laney, Patrick and Julie Brizzee, Nevada Geothermal Resources INEEL/MIS-2002-1620
Laney, Patrick and Julie Brizzee, New Mexico Geothermal Resources INEEL/MISC-1001-395 Rev 1
Laney, Patrick and Julie Brizzee, Oregon Geothermal Resources INEEL/MIS-2002-1621
Laney, Patrick and Julie Brizzee, Utah Geothermal Resources INEEL/MIS-2002-1617
Laney, Patrick and Julie Brizzee, Washington Geothermal Resources INEEL/MIS-2002-1622
Laney, Patrick and Julie Brizzee, Wyoming Geothermal Resources INEEL/MIS-2002-1615
Laney, Patrick and Julie Brizzee, Western United States Geothermal Resources INEEL/MISC-03-01046

Presentations Made in FY 2003:

Robert M. Neilson, Jr., "Green Renewable Energy-Complimentary Resources for Energy Production and Reliability" presented at the International Energy Conference & Exposition, Reno, NV, November 14, 2002.
Patrick T. Laney, "Oregon Geothermal Resources Map" presented at the Oregon Working Group meeting, Portland, OR, July 16, 2003.
Robert M. Neilson, Jr., "Mapping Geothermal Resources" presented at the 2003 GPW State Summit, Boise, ID, September 9, 2003.
Robert M. Neilson, Jr., "Making Geothermal Direct Uses Happen" presented at the Geothermal Direct Use Workshop, Boise, ID, September 10, 2003.
Joel L. Renner, "Geothermal Energy Applications" presented at the Geothermal Direct Use Workshop, Boise, ID, September 10, 2003.

Planned FY 2004 Milestones:

Develop a prototype, on-line, interactive geothermal resource map database	Sep 04
Conduct up to three, half-day regional "direct use mini-workshops" in Idaho	Sep 04

Geopowering the West (SNL)

Reporting Period: FY 2003 (October 1, 2002 to September 30, 2003)

DOE Grant/Contract No.: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
Geothermal Research Department
MS 1033, P.O. Box 5800
Albuquerque, NM 87185-1033

Principal Investigator: Roger Hill
Phone: (505) 844-6111
E-Mail: rrhill@sandia.gov

Collaborating Researchers: Jim Witcher, jwitcher@nmsu.ed

DOE HQ Program Manager: Susan Norwood
Phone: (202) 586-4779
E-mail: Susan.Norwood@ee.doe.gov

DOE Funding Allocation: $375K

Cost Share Funding: N/A

Project Objective: The DOE initiative "GeoPowering the West" is designed to promote the use of geothermal energy, both direct use and electrical generation, throughout the Western United States. The focus is on general education and outreach, institutional barriers, and technical assistance for development of projects.

The objectives are to (1) support the DOE Geothermal Technologies Program efforts in overcoming barriers and to result in continued growth of the industry to meet the nation's energy needs, and (2) achieve the deployment goals of the Geothermal Program.

Background/Approach: In general, the GPW will proceed along multiple thrusts:

1. Education and Outreach--where the objective is to build awareness,
2. Federal Participation--where land ownership issues are brought forward for resolution,
3. Technology Advancement and Deployment--where resources of the Geothermal program can be used for projects identified through GPW,
4. Exploration and Confirmation--where likewise resource information developed through the Geothermal program can be applied,
5. Policy Incentives--GPW will work with stakeholders promoting appropriate policies, and
6. Institutional Improvements--GPW will improve communications between stakeholders and governmental bodies, including Native Americans.

The first step in this process is to create state networks that lead to the development of State Working Groups in assigned states to identify stakeholders and champions.

Status/Accomplishments: In FY2002, Roger Hill served as Technical Director of the GeoPowering the West program. In that role, supported DOE HQ and the DOE Regional offices in planning and execution of the GPW program activities. Participated in many outreach functions including those listed below. Worked with the Albuquerque DOE office and WAPA to advance renewables procurement through a RFI for renewable energy. Made states aware of geothermal resources (technology as well as institutional) while supporting those engaged in policy areas. Worked with governmental stakeholders as well as Tribes.

Planned various events and moderated discussions at the annual State GPW Summit. Participated in regulatory activities that led to improved policies for geothermal in Arizona (geothermal now identified as a qualified renewable) and New Mexico (10 % RPS brought into effect). Brought the firm of Beckley Singleton into the GPW team with progress made in Utah and Idaho. Expanded the integrating (geologic) role of NMSU in New Mexico, Arizona and the national team.

In all cases, designed activities for sustainable and on-going geothermal development within the State Working Groups by involvement of the local geothermal stakeholders.

Led site investigations with two tribes, the Walker River Paiute and the Wind River Shoshone.

Reports & Articles Published in FY 2003:

Paper for the annual GRC conference: GeoPowering the West: Addressing Barriers to New Geothermal Development, SAND 2003-3183P.

Presentations Made in FY 2003: Presented at many conferences and workshops including:

Idaho Geothermal Trade Mission to Nevada
Public Renewables Partnership/California Energy Commission Renewables/Transmission Meeting
Arizona GeoPowering the West meeting
Jemez Pueblo Project Review
Berkley Geothermal Program Review
Building a Renewable Portfolio Conference
National Tribal Sustainability Conference
GeoPowering the West: State of Oregon Geothermal collaborative
Southwest Renewable Energy Conference
New Mexico Geothermal Working Group
GeoPowering the West: State Working Group Summit Meeting

Planned FY 2004 Milestones:

Initiate Hawaii SWG	Jan 04
Initiate California SWG	Apr 04
Document activities with short year end report	Sep 04

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