DOE/ID-11029
September 2002

U.S. Department of Energy
Idaho Operations Office

Federal Geothermal Research Program Update Fiscal Year 2001

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DOE/ID-11023

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Fiscal Year 2001

August 2002

Prepared for the
U.S. Department of Energy
Idaho Operations Office

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

- Double the number of States with geothermal electric power facilities to eight by 2006
- Reduce the levelized cost of generating geothermal power to 3-5 cents per kWh by 2007
- Supply the electrical power or heat energy needs of 7 million homes and businesses in the United States by 2010 as well. Private-sector inputs to DOE's planning process are critical to a logical, balanced strategy for the Geothermal Program.

This Federal Geothermal Program Research Update reviews the specific objectives, status, and accomplishments of DOE's Geothermal Program for Federal Fiscal Year (FY) 2001. 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. The DOE/industry partnership guides the DOE research program towards more cost competitive power generation from geothermal resources. This partnership assesses the value of long-term research options as well. Private-Sector inputs to DOE's planning process are critical to a logical, balanced strategy for the Geothermal Program.

The three categories of work used to distinguish the research activities of the Geothermal Program during FY 2001 reflect the main components of real-world geothermal projects. These categories are described briefly here and form the main sections of the project descriptions in this Research Update. A fourth category, GeoPowering the West, fosters awareness of the availability and benefits of geothermal energy.

Geoscience

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. Geoscience 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. Improved geothermal tracer chemicals and tracer data interpretation techniques will optimize injection strategies and increase resource longevity. Capabilities for predicting scaling and corrosion have improved markedly with ongoing research in brine chemistry. Improved methods of numerically modeling reservoirs are increasing the understanding of fluid flow in geothermal systems.

Exploration and Drilling

Most of the U.S. hydrothermal systems with obvious surface manifestations have been explored. 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.

Drilling and completion of wells for exploration, production, and injection account for 20 to 40 percent of the cost of generating electricity from geothermal resources. Current geothermal drilling and completion technology derives 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. Ongoing research to avert lost circulation episodes in geothermal drilling is yielding positive results. Field-testing of prototype packer elements is underway to confine and regulate cementing operations for recovering from lost circulation. Flow meters capable of measuring flow rates into and out of a well are being field-tested. Advanced drill bits are under development. Slimhole drilling, which might reduce exploratory drilling costs by up to 50 percent, will facilitate reservoir confirmation. Cost-shared efforts to develop memory-based logging instruments and an acoustic telemetry system for downhole measurements are in progress.

Energy Systems Research and Technology (ESR&T)

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, favored 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 and improved performance of binary cycles will result from investigations in heat cycle research. High-temperature, scale-resistant, corrosion-resistant, and thermally-conductive liner materials are being developed for fluid transport systems, heat exchanger applications, and energy conversion processes. CO_2-resistant well cements able to withstand the aggressive chemistry of certain geothermal fluids are also under development. Biotechnology research focuses on solutions that characterize microbiological growth and changes with various processes and environments encountered in the geothermal settings, as well as methods to prevent and repair damage to equipment and facilities from microbiological attack.

CONTENTS

I. GEOSCIENCE PROJECTS

Numerical Analysis of Three Component Induction Logging in Geothermal Reservoirs

Contract/Grant #: DE-FG07-001D13955	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** **Name:** David Alumbaugh **Phone:** (608) 262-3835 **Fax:** (608) 263-2453 **E-mail:** alumbaugh@engr.wisc.edu

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

To understand the effect of the borehole on Geo-BILT data and test methods for removing the effect.
To test the sensitivity of the Geo-BILT tool to different fracture zone geometries.

Approach/Background:

In order to test a variety of realistic borehole and fracture zone scenarios, we have employed a 3D finite difference code developed at Sandia National Laboratories (Newman and Alumbaugh, 1995) as well as a 1D solution developed under another project at the University of Wisconsin (Lu and Alumbaugh, 2001) to simulate the response of the Geo-BILT induction logging tool to various scenarios. Both dipolar and finite sources have been simulated to determine how the source-dimensions employed in the EMI tool produce fields that differ from dipolar sources. The different borehole geometries include wellbore diameters of 10, 20 and 40 cm, invasions zone diameters of 80 and 120 cm, and different borehole and background conductivities. In addition one model includes a horizontal fracture that intersects the borehole. Three fracture geometries being analyzed include a thin infinite layer, a thin half-infinite layer truncated at the borehole, and a finite-width layer (16m) which is centered about the borehole. All conductors have a thickness of 1 meter and extend infinitely in the Y direction. In addition, models were run with both electrically isotropic and anisotropic fracture zones to determine how electrical anisotropy affects the results.

Status/Accomplishments:

The effects due to a borehole and invasion zone have been shown to increase as the diameter of the borehole/invasion zone increases, and as the borehole mud increases in conductivity when compared to the formation. Note, our modeling has indicated that a more resistive borehole mud does not produce significant effects when compared to a conductive mud. The most extreme case that was investigated consisted of a 0.1 m diameter borehole with a 0.8 m diameter invasion zone. The conductivity of the invasion zone for both models is 3.0 S/m, the borehole is 10.0 S/m, and the background is 1.0 S/m. The coaxial configuration results for the model with a borehole and invasion zone show a difference in the quadrature field of only ~13% at 2 m offset, when compared values for no borehole or invasion zone. The difference rapidly decreases with increasing offset such that at 5.0 m it is approximately only 2%. The coplanar configuration is much more susceptible as differences at 2 kHz decrease from 294% at 2.0 m offset to 160% at 5.0 m. At 20 kHz the problem is compounded by a zero crossing in the quadrature component of the field that changes position away from the transmitter depending on the borehole conductivity structure. When a fracture zone is present, the borehole is shown to cause a 'static shift' where by the response appears to maintain the same shape across the fracture but is shifted to either larger or smaller values overall. A frequency differencing method that employs data collected at two different frequencies has been demonstrated to significantly reduce these effects, but not totally eliminate them.

To determine the depth sensitivity, and vertical resolution of the Geo-BILT tool to conductive fracture zones that are thinner than the source-receiver separation, we ran a series of laterally half-infinite and infinite conductors positioned at varying lateral depths from the borehole. For the coaxial configurations, the simulations show the investigation depth is approximately twice the source-receiver separation. Conversely, the coplanar as well as the null-coupled coplanar response is sensitive to a depth of only 1 source-receiver offset. In addition, in most cases the depth-sensitivity was independent of frequency. The only exception to this was for the steeply dipping fracture at 60º, where the tool started detecting the fracture further above its intersection with the borehole at 4 kHz than at 40 kHz.

The vertical-resolution study indicates that at offsets larger than the fracture thickness, the response is "smeared out", and the amount of smearing is proportional to the offset employed. For example the 5m data show a magnetic field anomaly that is approximately 2.5 times the vertical 'width' of the 2m responses, and this holds for both coaxial and coplanar configurations. These results coupled with earlier work suggest that the best vertical resolution that will be obtainable is 1m, i.e., ½ the separation of the closest source-receiver pair.

One of the concerns of EMI was that the finite length of the source would cause the measured data to be somewhat smeared further decreasing the vertical resolution, and it would deviate substantially from data that would be produced by a point-dipole. Simulations that employed a 1m long solenoid source parallel to the borehole axis to mimic the vertically polarized source on the EMI tool showed that although the response deviates from that of a true dipole by 4% at 2m offset, at 5m offset the two solutions are virtually identical. When a 1m by 0.08m loop source with a magnetic moment perpendicular to the borehole axis was employed to simulate the horizontally polarized source that EMI employs, virtually no difference was observed between that solution and the dipole at distances of 2m and greater. However, when simulating logging runs with the tool through thin-conductive zones, some asymmetry was found to exist in the results that might be due to the finite nature of the source.

Sixteen simulations were performed for the infinite and half-infinite fracture geometries to determine what effect fracture-zone anisotropy has on the tool response. Dip angles of the fracture zone varied from 0^o to 60^o. For all simulations, the conductivity perpendicular to the plane of the fracture zone was twice that of the 0.1 S/m background, and the conductivity along the plane of the fracture-zone was 10 times that of the background. It was determined that fracture anisotropy decreases the response of the coaxial configuration, while increasing the co-planar response. Changes in isotropic conductivity of the fracture zone would increase or decrease the response of both configurations uniformly. This indicates that if anisotropy is present, it must be taken into account within the inversion scheme to produce a reliable interpretation.

Planned FY 2002 Milestones:

NA

Major Reports Published in FY 2001:

NA

Major Articles Published in FY 2001:

Stanley, D., and Alumbaugh, D. L., "Numerical Modeling of the Effects of Borehole Reflections on 3-Component EM Induction Logging," presented at the 2001 annual meeting of the Society of Exploration Geophysicists, September of 2001, San Antonio, TX.

Rock Physics Interpretation of P-wave Q and Velocity Structure, Geology, Fluids, and Fractures at the Southeast Portion of The Geysers Geothermal Reservoir

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization	**Principal Investigator(s)**
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Project Objective:

We examine how quantitative rock physics models, such as effective medium theories, can improve the interpretation of seismic parameters and material and fluid properties at The Geysers.

Approach/Background:

We use effective medium theories to estimate effects of fractures on velocities for The Geysers rocks. We compare theoretical velocity estimates to laboratory measurements from the literature and our seismic velocity values obtained from 1992 earthquake data. We approximate the reservoir as being homogeneous in mineral composition, with a constant density of fractures that close with increasing lithostatic pressure. Thus, we expect low velocities near the surface, increasing with depth up to the values observed in the lab on intact samples, 5.5–5.7 km/sec. We use a one-dimensional inversion of P-waves to obtain an “expected” P-wave velocity (Vp) and attenuation (Qp) relation as a function of depth for The Geysers rocks. We then use a threedimensional Vp and Qp inversion to find anomalous zones within the reservoir.

Status/Accomplishments:

We find portions with anomalously high Vp and Qp, high Vp and low Qp, and low Vp and low Qp. We interpret the regions with high Vp and Qp to be relatively less fractured, and the regions with low Vp and Qp to be significantly fractured. The high V and Q anomaly is centered on the zone of greatest pressure drop, and is mostly within the shallowest part of the felsite. The anomalous zones within the graywacke reservoir are on either side of the felsite, in areas of more moderate pressure depletion. More work is required to interpret the significance of these observations.

Planned FY 2002 Milestones:

Prepare a wider set of higher quality data for the same region.

Major Reports Published in FY 2001:

Patricia Berge, Lawrence Hutchings, Jeffrey Wagoner, and Paul Kasameyer; 2001, "Rock Physics Interpretation of P-wave Q and Velocity Structure, Geology, Fluids, and Fractures at the Southeast Portion of The Geysers Geothermal Reservoir."

Lawrence Hutchings, Patricia Berge, Paul Kasameyer, Jeffery Wagoner, Cynthia Hayek, Jennifer Swenson and Megan Flanagqan, 2001, "Relationship among Source Parameters of Small Earthquakes, Q and Velocity Structure, Geology, and Production and Injection at the Geysers Geothermal Reserevoir."

Major Articles Published in FY 2001:

None

Improved Geothermal Reservoir Management

Contract/Grant #: DE-AC07-99ID13727	**Contract/Grant Period: FY 2001**

Sponsoring Office Code: EE-12	**Performing Organization**
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Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** **Name:** K. K. Bloomfield **Phone:** (208) 526-5250 **Fax:** (208) 526-0969 **E-mail:** blookk@inel.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
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Project Objective:

Field Studies – Extend use of numerical modeling to planning and interpretation of tracer tests so that interpretation of tracer tests will provide a better understanding of reservoir properties.

Combined reservoir/plant management for enhanced sustainability – Demonstrate a means of optimizing geothermal energy use by combined reservoir/plant operations and economic analysis. This study compares baseline operations of an existing Basin and Range binary plant against optimized operations to demonstrate improved resource management.

Disseminate results of these studies to interested parties within the geothermal industry.

Approach/Background:

Effective management of a geothermal resource involves optimizing energy production and power generation through evaluation of multiple depletion scenarios. This project demonstrates several non-traditional uses of reservoir modeling designed to improve management of geothermal resources, either through obtaining estimates of reservoir parameters, or optimizing production and improving resource sustainability.

Reservoir simulation, power plant models and Monte Carlo simulation are used to demonstrate means of optimizing resource use while maximizing revenue. The example discussed below evaluates load following for a specific Basin and Range geothermal reservoir. Load following is the practice of increased power generation in times of demand. Generally the value of on-peak power is greater than that of off-peak generation. The purpose of this study was to determine the ability of geothermal operation currently producing 12MWe to load follow, with enhanced production of 8% for on-peak demand and curtailed production of 25% for off-peak demand. Our scenario will compare the revenues of load following and base load operation; the method is applicable to any reservoir in operation.

We use reservoir simulators to aid in the design of a tracer test. Fluid phase behavior data and coarse estimates of reservoir properties were developed as input, and models were run to provide information on mass of tracer required, sampling intervals, expected tracer breakthrough times, etc. Results of the tracer test are then history matched in the reservoir model to estimate reservoir parameters. The particular example given below is on a relatively mature field, but can be used early in the development of new resources.

Status/Accomplishments:

The load following investigation is an integrated study of reservoir, power plant and power generation market (Bloomfield and Mines). The study was to quantify the cost effectiveness of load following geothermal resources to increase revenue. At least $20,000 of increased revenue can be achieved per year, with 3% less fluid extracted from the resource. This investigation included the application of variable speed drive (VSD) applications for AC motor driven brine pumps. The VSD aided in optimizing brine flow for on and off peak power demand. The study used prices from the deregulated power market for load following operations. As the result obtained using 1999 market clearing prices from the California Independent System Operator the increased revenues were approximately 20K. The effects of ambient temperature and power output form the 12Mwe power plant was modeled to compare the energy produced under load following and base load operations.

A tracer test was conducted in January, 1999, to evaluate the movement of steam and liquid and the effects of injection at the Cove Fort geothermal resource (Bloomfield et al.). This is the first known application of simultaneous liquid phase and vapor phase tracers in geothermal reservoirs. Liquid (fluorescein) and vapor-phase (R-134a) tracers were both injected at a depth below the producing horizons. Numerical modeling, using accurate fluid properties but very crude approximations of reservoir properties, for example flow data from the field but not individual wells, was used to determine mass of tracer required and other test properties. R-134a was detected in all of the steam wells two weeks after injection. Numerical simulation predicted that the tracer would not appear until 2 months after injection. History match exercises were performed to update the reservoir description of the Cove Fort reservoir. Preliminary results indicate a significant degree of heterogeneity not captured in the original reservoir model.

Planned FY 2002 Milestones:

Study results of injection options for NW Geysers	(I)	Sep 02
Integrated reservoir management report on B&R reservoir model	C)	Jun 02

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

Bloomfield, K. K., J. N. Moore, M. C. Adams, T. L. Sperry (2001), "Tracer Test Design and Sensitivity Studies of the Cove Fort Geothermal Resource Tracer ," Geothermal Resources Council Transactions, 613–616.

Bloomfield, K. and G. Mines, 2000, "Cycling Geothermal Resources to Increase Revenues," Geothermal Resources Council Transactions, 105-108.

Integrated Plant/Field Operation

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
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Project Officer / Monitor Name: Joel Renner Phone: (208) 526-5250 Fax: (208) 526-0969 E-mail: rennerjl@inel.gov	**DOE Funding Allocation** $80K	**Cost Share Funding**

Project Objective:

The objective of this project is to produce a study that will provide and estimate of potential Operations and Maintenance (O&M) savings, increased revenues by applying adjustable speed drives on geothermal brine pump applications. An improved understanding of reservoir energy storage capabilities and the energy market could increase revenues of the geothermal operator. By cycling the resource during on and off peak energy demand, the resource can store energy by pressure and temperature build up that can be utilized during the on peak energy demand period.

Approach/Background:

The continued success of the domestic geothermal industry is contingent upon reducing operating and maintenance cost, maximizing revenues and sustaining the resource for geothermal power generation operations. In FY-00, INEEL investigators initiated a study to examine the use of variable speed motors in binary power plant applications as a means of maximizing the plant revenue stream during periods when the price for power generated was the highest. Of specific interest was the use of these motors with the brine production pumps. Investigators believe that this application could improve the management of house power or parasitic loads, lower the maintenance cost of brine pumps and motors, provide the flexibility to curtail power production during off peak energy demand, and optimize the power production from the maturing resources due to exploitation. Once the variable devices are successfully used applied to the brine production pump motors, it is anticipated they can have additional application, and compounded benefit throughout a binary plant.

Status/Accomplishments:

This investigation quantified the cost effectiveness of cycling some geothermal resources to increase revenues. The study concludes that from 450-hp brine pumps operating at 1780 rpm, at least $20,000 of increased revenue can be achieved per year, with 3% less fluid extracted from the resource. The study used values from the deregulated power market for load following operations. Currently, geothermal power producers off the cliff receive short range avoided cost for their power (their original contract), not the prices available from the California Power Exchange.

Planned FY 2002 Milestones:

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Manipulating Fractures with Chemical Treatment

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Project Objective:

Develop a capability using existing data, constitutive models, and geochemical modeling codes to predict the effect of chemical treatments on fracture growth and rock properties at simulated reservoir conditions.

Utilize this capability in a test calculation using relevant temperatures, and rock and fluid compositions to assess whether predicted changes in fracture growth would be meaningful.

Identify data gaps, and design and conduct appropriate experiments to provide a capability that is broader

Approach/Background:

The purpose of this project is to develop modeling and experimental methods to predict the effect of a given bore-hole chemical treatment on the fracture properties of a downhole rock. If it were possible to control fracture growth by chemical treatment during drilling, completion, and production, an important new tool would be available for improving geothermal energy production. Although experimental data exist that show that subcritical crack growth, critical stress intensity, and time dependent rock strength are strongly influenced by fluid chemistry and temperature, this information has not been used to develop a tool to manipulate fracturing downhole. We hypothesize, based on extant data, that fracture growth in the subsurface can be manipulated by the addition of appropriate chemicals at the surface.

Although the risk may be high, a predictive capability would provide a significant pay-off in the areas of drilling (improved ability to predict and prevent break-outs) and production (ability to exploit the natural stress field and/or enhance various fracturing methods). In the area of drilling, we note that chemical treatments have the potential to increase subcritical crack growth into velocity regimes that could measurably improve drilling rates. In the area of production, existing technology is limited by the inability to create fractures with a high connectivity to the natural fracture system and is usually inadequate to significantly improve permeability and heat production (Entingh, 1999). If this project is successful, a new hybrid technology is potentially possible in which directionally favorable fractures are first created using propellant technology, and then injected with porous or reactive proppants designed to slowly deliver fracture-enhancing chemicals to extend the propped fractures.

Status/Accomplishments:

It is clear from prior experimental work that fracture characteristics are influenced by fluid composition. Measurements of crack propagation velocities in minerals and rocks indicate that slow crack growth is strongly dependent on pH and temperature under laboratory conditions (Atkinson and Meredith, 1987). Laboratory hydrofracturing experiments at room temperature demonstrate that chemical additives affect the fracture number and style (Dunning and Huf, 1983). Laboratory deformation experiments indicate that rock is weaker under simulated reservoir conditions (Holl, et al., 1997). For example, the strength of typical granitic basement rocks is reduced (relative to dry rock) by ~30% when samples are tested in contact with water at 300 oC. However, because existing experimental data is so sparse, our preliminary analysis focuses only on quartz/fluid interactions.

Development of calculational capability – A kinetic model linking physical and chemical controls on subcritical crack growth of quartz was proposed by Dove (1995) on the assumption that dissolution and fracture growth are governed by similar reaction pathways. Dove (1994) has shown, by correlating a large amount of experimental data, that the kinetics of dissolution of quartz can be empirically related to its surface chemical composition, in particular, the proportion of surface sites that are protonated and deprotonated. An empiric relationship was developed to explain dissolution kinetics to 300 ºC for fluids with pH values ranging between 2 and 12, and sodium concentrations to 0.5 molar. Dove (1995) extended this constitutive relationship to fracture propagation in quartz, and showed for a very limited number of data sets, that a constitutive law related to the dissolution kinetic law could adequately explain the temperature and solution pH effects on subcritical fracture propagation. That is, higher pH values and temperatures increase the rate of subcritical fracture growth in quartz. The empiric constitutive relationship of Dove was able to reproduce the relationship between fracture propagation velocity and stress intensity factors for quartz in contact with deionized water for temperatures up to 80 ºC. Dove argues that the relationship should potentially be valid to 300 ºC if the reaction mechanisms of subcritical crack growth and dissolution are similar.

A test calculation using quartz as an example – As an example, we take a hypothetical geothermal rock with a composition similar to granite, and use the simulator to calculate the equilibrium pore fluid at 220 ºC. Although a calculated pore fluid is used as the starting point for this example, in practice the analyzed pore fluid and mineralogy would normally be used to assess the effect of a given chemical treatment. The simulator is then used to assess the changes in pore fluid composition that would occur based on addition of a well-bore chemical treatment at the surface.

At high temperatures, chemical equilibrium between solid and fluid would be expected to be rapid, hence the efficacy of a one-time treatment might be short lived due to reaction of the fluid with the rock. Hence, the kinetics of reaction will determine the effective treatment time. We used a geochemical reaction simulator with explicit accounting for dissolution kinetics to show the effect of three pH-affecting chemical 'treatments' on pore-fluid pH over a 10-day period following the treatment. For all three treatment scenarios we assume that ~2.7 kg of rock is in contact with 1 kg of pore fluid and that the reactant is added to the rock/fluid mixture over a 2.4 hour period. The rock/fluid ratio chosen accounts for a significant volume of fluid in the well bore in addition to that in the rock porosity, and that both fluids are in equilibrium with each other. Note that at this temperature, the neutral pH of water is about 5.6.

The addition of acid results in a rather short-lived (~2.5 dayas) low-pH excursion. Higher temperatures and/or larger rock/fluid ratios would be expected to decrease the time of this excursion further. Hence fracture properties affected solely by lowered pH might be expected to return to ambient conditions relatively rapidly. However, the solution composition is also changed in other ways; e.g., dissolved Si is lowered as a result of the treatment. The model predicts about a 30-fold decrease in subcritical crack growth at a constant stress intensity.

In contrast to acid treatment, the addition of base results in pH excursions that remain 10 days following treatment. Fluid compositions differ significantly from acid treatment, as well as differing for the two basic treatments. For example, the effect of NaOH treatment is to significantly increased dissolved Si, but the $Ca(OH)2$ treatment is predicted to only moderately raise dissolved Si. Hence, it may be possible to tailor a well-bore treatment to obtain a given pH regime, but moderate other fluid changes. The effect of the base addition is to increase the subcritical crack approximately 3-fold at constant stress intensity.

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Dunning, J.D., and Huf, W.L. (1983) The effects of aqueous chemical environments on crack and hydraulic fracture propagation and morphologies, J. Geophys. Res., 88, 6491-6499.

Entingh, D.J. (1999) A review of geothermal well stimulation experiments in the United States. Geothermal Resources Council Transactions. 23:17-20.

Holl, A., Althaus, E., Lemp, C., and O. Natau (1997) The petrophysical behavior of crustal rocks under the influence of fluids, Techtonophys. 275, 253-260.

Planned FY 2002 Milestones:

This project was funded at a reduced level to conduct preliminary investigations of the concept. The scoping study was successful. The next step is to extend the underlying data to higher temperatures (~150°C) with control of solution composition (not simply pH as was done in the literature) to make the predictive capability more robust. Direct observations of crack growth in the Hydrothermal Atomic Force Microscope at LLNL now appears to be the most appropriate experimental approach. Extension of the concept to other minerals (e.g., calcite and feldspars) will follow.

Major Reports Published in FY 2001:

B.P. Bonner and Viani, B.E., 2001. Model Predictions of Chemically Controlled Slow Crack Growth With Application to Mechanical Effects in Geothermal Environments. Geothermal Resources Council Transactions, Vol 25, August 26-29, 2001.

Major Articles Published in FY 2001:

None

A Thermoelastic Hydraulic Fracture Design Tool for Geothermal Reservoir Development

Contract/Grant #: **DE-FG07-99ID13855**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**
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Contracting Organization U.S. Department of Energy Idaho Operations Office 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** **Name:** Ahmad Ghassemi **Phone:** 701-777-3213 **Fax:** 701-777-4449 **E-mail:** ahmad_ghassemi@mail.und.nodak.edu

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Jay Nathwani **Phone:** 208-526-0239 **Fax:** 208-526-5964 **E-mail:** nathwaj@id.doe.gov	$180K	

Project Objective:

The objective of the project is to develop an advanced two-dimensional, thermo-mechanical model that captures the salient aspects of hydraulically driven fractures in a geothermal environment. This will be accomplished by developing fracture propagation algorithms that consider significant hydraulic and thermo-mechanical processes and their interaction with the in-situ stress state.

Approach/Background:

The project objectives will be met by developing fracture propagation algorithms that consider significant hydraulic and thermo-mechanical processes and their interaction with the in-situ stress state. The fracture model will be based on a complex variable and regular displacement discontinuity formulations. In the complex variable approach the displacement discontinuities are defined from the numerical solution of a complex hypersingular integral equation written for a given fracture configuration and loading. In addition to the fracture propagation studies, heat extraction solutions algorithms will also be developed that include the influence of fluid leak-off on power generation. The fracture and heat extraction models will be integrated in a user-friendly environment to create a tool for improving fracture design and investigating single or multiple fracture propagation in rock.

Status/Accomplishments:

(1) Quantitative analyses of the role of leak-off on power generation from a fracture in hot dry rock (HDR); (2) improvement of the 2D fracture propagation code to view propagation in real time; (3) development of the two-dimensional BEM for calculating thermal stresses induced by heat extraction from a fracture; (4) Boundary Element Method (BEM) solution of the 3D problem of heat extraction from a fracture in HDR + user interface; (5) a preliminary study of dual porosity porothermoelastic model for deformation of chemically-active rocks; (6) development of the building blocks for a 2D, fully-coupled porothermoelastic DD method for modeling fractures in geothermal environments; (7) investigation of the problem of injecting a viscous fluid in a joint; and (8) finalization of the fully-coupled porothermoelastic model for borehole failure & fracture. **Planned FY 2002 Milestones:**

(1) Improve the 3D BEM solution of heat extraction and calculate the thermal stresses; (2) improve the user interface for the 3D model; (3) extend and improve the 2D CVBEM model to allow coupled thermoelastic analysis; (4) improve the 2D CVBEM to enable analyses of faults and joints by introducing a Mohr-Coulomb joint model; (5) apply the fracture propagation and heat extraction numerical models to practical geothermal problems of interest.

Major Reports Published in FY 2001:

Five reports have been published: (1) NDRM-00-05: User Interface Development and Modeling Hydraulic Fracturing in a Geothermal Reservoir; (2) NDRM-01-06: Effect of Fluid Leakoff on Heat Extraction From a Fracture in Hot Dry Rock & User Interface Development for Fracture Propagation Software; (3) NDRM-01-07: Thermal Stresses Due to Extraction of Heat From a Fracture in Hot Dry Rock; and (4) NDRM-01-08: Two-Dimensional Thermoelastic Modeling of a Fracture & Solution of Thermoelasticity Problems by the Radial Basis Function Approximation and the Boundary Element Method; (5) NDRM-01-09: A Three-Dimensional Solution for Heat Extraction from a Fracture in Hot Dry Rock Using the Boundary Element Method.

Major Articles Published in FY 2001:

Ghassemi, A., Cheng, A. H.-D., and S. Tarasovs, 2001. A Three-dimensional solution for heat extraction from a fracture in HDR using the boundary element method. Submitted to the 27th Stanford Geothermal Workshop.

Cheng, A. H.-D & Ghassemi, A. 2001. Effect of fluid leakoff on heat extraction from a fracture in hot dry rock. *GRC 2001 Annual Meeting*, San Diego, CA.

Cheng, A. H.-D., Ghassemi, A., and Detournay, E. 2001. A two-dimensional solution for heat extraction from a fracture in hot dry rock. *Int. J. Numerical & Analytical Methods in Geomech*., 25, 1327-1338.

A Geochemical and Microanalytical Study of Silica Scale Deposition in Geothermal Brines

Contract/Grant #: **DE-FG07-00ID13954**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**
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Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
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Project Objective:

The precipitation of amorphous silica scale in pipes and wellbores can seriously degrade the efficiency of energy extraction during the processing of geothermal fluids. In the worst cases, corrupted equipment must be removed and replaced, often with difficulty and at great expense. Chemical inhibition of silica scale offers great potential as a cost-effective means of dealing with this problem, but geothermal brines with disparate compositions and ionic strengths may respond differently to a given inhibitor. Consequently, treatment regimens intended to prevent the development of silica scale must be tailored to a particular field site and even a particular well.

Our goal is to provide a general and comprehensive understanding of the chemical reactions that produce silica scale. The results from these investigations should enhance our ability to predict the conditions that promote flocculation of aqueous silica in particular brine chemistries. In addition, these studies may suggest new kinds of scale inhibitors for geothermal brines.

Approach/Background:

In collaboration with the Geothermal and Power Operations Division of Unocal, we have explored the chemical processes that occur during the coagulation of silica-enriched brines. To this end we have refined a novel method of separating populations of silica polymers on the basis of size using gel filtration chromatography, or GFC. When this method is combined with standard analytical techniques, it is possible to monitor the evolution of dissolved silica from silicic acid monomers to heavily networked gels in a robust and quantitative fashion.

Status/Accomplishments:

We have completed four and initiated another of the eight tasks outlined in our proposal. Specifically, we have assembled and tested the GFC apparatus (Task 1). Dr. Gary Icopini, the postdoctoral researcher supported by this grant, has tested and connected the components of this home-built system, which includes a fluid reservoir, variable speed diastolic pump, 70 cm chromatographic column, and fraction collector. He worked to optimize flow rates by experimenting with different methods of hydrating and packing the Sephadex soft gels, altering flow directions, testing multiple flow tube diameters, and varying pump speeds.

In addition, we have tested ultrafiltration (Task 2) and developed other techniques (Task 4) for sizing nanocolloids. In our previous efforts to size silica colloids using calibrated GFC, we observed that the first colloids to appear in solutions containing 500 to 1000 mg/kg silica at pH 7 for both low (0.005 M) and relatively high (0.24 M) ionic strengths measured 20 to 40 kD. We calculated that these weights correspond to sizes of 3 to 4 nm for these incipient colloids, and we confirmed these results by: 1) light scattering; 2) atomic force microscopy (AFM); and 3) transmission electron microscopy (TEM). The light scattering analysis was accomplished with a Microtrac Ultrafine Particle Analyzer utilizing a diode laser (780 nm), and the procedure indicated that the silica colloids have a mean particle diameter of 3.5 nm. For AFM characterization, colloids were deposited on an atomically smooth silicon wafer. Analyses of the particles in the vertical direction yielded diameters of 3.0±0.1 nm. Field emission TEM analysis of the low-density colloids revealed that the smallest particles were 3 nm in diameter, though some particles were clearly aggregates that measured up to 20 nm in size. The identification of these nanocolloids as SiO_2 was verified by energy dispersive spectroscopy. In summary, it is clear that accurate particle sizing of nanocolloids demands multiple methods of measurement. Our combined examination of the smallest silica colloids in geologically relevant solutions by light scattering, AFM, and TEM appears to confirm the sizing of silica colloids as ascertained by GFC as ~3 nm.

Long-term analysis of polymer evolution in siliceous brines (modeled after field sites exploited by Unocal) is in process (Task 3). Silica solutions with concentrations of 250, 750, and 1250 mg/L silica were prepared from pH 3 to pH 11 and with ionic strengths of 0.015 and 0.24. The disappearance of monomeric silica and the development of polymeric silica and silica gel is being monitored during these experiments. These studies are providing quantitative transformation kinetics for the reaction from dissolved silica to gel and they serve as a baseline for inhibition studies.

Inhibition studies involving sulfite were also initiated during this fiscal year (Task 7). In these experiments sodium sulfite (50mg/L sulfite) is added to solutions with the same solution compositions as our base line studies. These studies will provide a quantitative measure of the inhibiting qualities of sulfite as a function of pH and silica concentration.

Planned FY 2002 Milestones:

The major goals for the next year are as follows: 1) Analysis of transition metal complexation to colloidal silica. Silica solutions that have achieved steady state polymerization will be injected with metal chlorides to explore the effects particularly of trivalent Al and Fe on the formation of silica scale. Solutions will be analyzed by GFC, and elution fractions will be monitored for Si, Al, and Fe by ICP-AES. 2) Inhibition of silica polymerization by carboxylic acids. Silica solutions with concentrations of 250, 750, and 1250 mg/L ppm silica will be prepared as standard Unocal brines with EDTA, acetic acid, and citric acid. Polymer evolution will be assayed by wet chemical analysis and ICP-AES to ascertain the stages of polymerization that are interrupted by these inhibitors. 3) Titration of coagulated silica solutions. Solutions with concentrations of 2000 mg/L silica will be prepared and allowed to achieve steady state monomer/polymer concentrations. A suite of Groups I and II and transition metal cations will be added to these solutions in a range of concentrations to determine CCCs.

Major Articles Published in FY 2001:

Icopini* G.A., P.J. Heaney, N.P. Mellott, S.L. Brantley, and D.M. Yates, 2001, Sizing Silica Nanocolloids: A Comparison of Gel Filtration Chromatography with Diffraction and Imaging Methods, In Eleventh Annual V. M. Goldschmidt Conference, Abstract #3588, LPI Contribution No. 1088, Lunar and Planetary Institute, Houston (CD-ROM).

Fundamental of Steam-Water Flow in Porous Media

Contract/Grant #: **DE-FG07-99ID13763**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**
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Contracting Organization U.S. Department of Energy Idaho Operations Office 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** **Name:** Roland N. Horne **Phone:** (650)723-9595 **Fax:** (650)725-2099 **E-mail:** horne@stanford.edu

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
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Project Objective:

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.

Approach/Background:

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:

(a) Capillary Pressure and Relative Permeability Task

Various capillary pressure approaches were used to calculate steam-water relative permeabilities using the measured data of steam-water capillary pressure in both drainage and imbibition processes. The calculated results were compared to the experimental data of steam-water relative permeability measured in sandstone core samples. The steam-water relative permeability and capillary pressure were measured simultaneously. The differences between the Purcell model and the measured values were almost negligible for water phase relative permeability in both drainage and imbibition but not for the steam phase. The lack of significance of the effect of tortuosity on the wetting phase was revealed. A physical model was developed to explain the insignificance of the tortuosity. Steam phase relative permeabilities calculated by other models were very close to the experimental values for drainage but very different for imbibition as expected. The same calculation was made for nitrogen-water flow to confirm the observation in steam-water flow. The results showed that it would be possible and useful to calculate steam-water relative permeability using the capillary pressure method, especially for the drainage case.

The general conclusion based on this study was that the Purcell model can be used to calculate the water phase relative permeability and the Corey model can be used to calculate the steam phase relative permeability.

(b) Water Injection Task

Water injection has proven to be a successful engineering technique to maintain reservoir pressure in geothermal reservoirs and to sustain well productivity. However, many questions related to water injection into geothermal reservoirs still remain unclear. For example, how the in-situ water saturation changes with reservoir pressure and temperature, and the reservoir pressure influences well productivity. To answer these questions, we studied the effects of temperature and pressure on the in-situ water saturation in a core sample using an apparatus developed for the purpose. The in-situ water saturation decreases very sharply near the saturation pressure but not to the residual water saturation. When the mean pressure in the core sample decreases further, the in-situ water saturation decreases sharply again to the residual water saturation at a pressure much less than the saturation pressure. This demonstrated the significant effects of steam-water capillary pressure and physical adsorption on the in-situ water saturation.

Also investigated were the effects of pressure on the well productivity index. The well productivity increased with an increase of mean reservoir pressure within a certain range and then decreased. The well productivity reached the maximum value at a pressure close to the saturation pressure. The results of this study should be useful to evaluate projects such as the waste water injection scheme at The Geysers.

(c) Relative Permeability in Fractures Task

The mechanism of two-phase flow through fractures exerts an important influence on the behavior of geothermal reservoirs. Currently, two-phase flow through fractures is still poorly understood. In this study, nitrogen-water experiments were conducted in both smooth- and rough-walled fractures to determine the governing flow mechanisms. The experiments were done using a glass plate to allow visualization of flow. Digital video recording allowed instantaneous measurement of pressure, flow rate and saturation. Saturation was computed using image analysis techniques. The experiments showed that the gas and liquid phases flow through fractures in nonuniform separate channels.

The data from the experiments were analyzed using Darcy's law and using the concept of friction factor and equivalent Reynold's number for two-phase flow. For both smooth- and rough-walled fractures a clear relationship between relative permeability and saturation was seen. The calculated relative permeability curves follow Corey-type behavior. The sum of the relative permeabilities of the two phases is not equal to one, indicating phase interference. The equivalent homogenous single-phase approach did not give satisfactory representation of flow through fractures. The graphs of experimentally derived friction factor with the modified Reynold's number do not reveal a distinctive linear relationship.

Planned FY 2002 Milestones:

Application of the analytical decline curve analysis method in geothermal reservoirs.

Scaling of experimental data of spontaneous water imbibition.

Measurement of steam-water relative permeability through fractures.

Effect of initial water saturation on spontaneous water imbibition.

Development of apparatus and techniques to measure relative permeability in extremely low permeable geothermal rocks.

Major Reports Published in FY 2001:

Diomampo, G.P.: "Relative Permeability Through Fractures," June 2001.

O'Connor, P.A.: "Constant-Pressure Measurement of Steam-Water Relative Permeability Through Fractures," June 2001.

Major Articles Published in FY 2001:

Li, K., Nassori, H., and Horne, R.N.: “Experimental Study of Water Injection into Geothermal Reservoirs,” proceedings of the GRC 2001 annual meeting, August 26-29, 2001, San Diego, USA; GRC Trans. V. 25 (2001).

Li, K. and Horne, R.N.: “An Experimental Method of Measuring Steam-Water and Air-Water Capillary Pressures,” proceedings of the Petroleum Society’s Canadian International Petroleum Conference 2001, Calgary, Alberta, Canada, June 12 – 14, 2001.

Li, K. and Horne, R.N.: “Steam-Water Relative Permeability by the Capillary Pressure Method,” proceedings of the International Symposium of the Society of Core Analysts, Edinburgh, UK, September 17-19, 2001.

Li, K. and Horne, R.N.: “Differences between Steam-Water and Air-Water Capillary Pressures,” presented at the 26th Stanford Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA 94043, USA, January 29-31, 2001.

Li, K. and Horne, R.N.: “Gas Slippage in Two-Phase Flow and the Effect of Temperature,” SPE 68778, presented at the 2001 SPE Western Region Meeting, Bakersfield, CA, USA, March 26-30, 2001.

Li, K. and Horne, R.N.: “Wettability Determination of Geothermal Systems,” presented at the 27th Stanford Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA 94043, USA, January 28-30, 2002.

Li, K. and Horne, R.N.: “An Experimental and Theoretical Study of Steam-Water Capillary Pressure,” SPEREE (December 2001), p.477-482.

Li, K. and Horne, R.N.: “Characterization of Spontaneous Water Imbibition into Gas-Saturated Rocks,” SPEJ (December 2001), p.375-384.

Sullera, M.M., and Horne, R.N.: "Inferring Injection Returns form Chloride Monitoring Data", Geothermics, 30, (2001), 591-616.

Belen, R.P., Jr.. and Horne, R.N.: "Inferring In-Situ and Immobile Water Saturations from Field Measurements", Geothermal Resources Council Transactions 24 (2000).

Wang, C., and Horne, R.N.: "Boiling Flow in a Horizontal Fracture", Geothermics, 29, 2000, 759-772.

Noble Gas Isotope Geochemistry in Geothermal Systems

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization Lawrence Berkley National Laboratory (LNBL) One Cyclotron Road Berkley, CA 94720	**Principal Investigator(s)** **Name:** B. Mack Kennedy **Phone:** (510) 486-6451 **Fax:** (510) 486-5496 **E-mail:** bmkennedy@lbl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

This project is aimed at critically assessing the value of isotope ratio measurements for characterizing geothermal reservoirs. Our objective is to develop a set of isotopic parameters, based on measurements of fluids, fluid inclusions, and rocks and minerals, that will help to identify past and present fluid sources in geothermal systems and to estimate their extent, heat content, and lifetime. Specific objectives include: (1) develop and apply noble gas compositions and concentrations as reliable natural tracers for monitoring the breakthrough of re-injected fluids; (2) identify past and present heat and fluid sources and develop a better understanding of the transition from magmatic to geothermal production fluid; (3) enhance reservoir simulation models by providing complementary information regarding fluid source, fluid mixing, and fluid flow paths; and (5) develop and expand geochemical exploration techniqes.

Approach/Background:

The isotopic compositions of elements in fluids provide a quantitative measure of material balance, therefore isotopes are extremely powerful in tracing fluid flow and history. We believe that systematic isotope studies will provide valuable information regarding fluid sources, migration pathways, fluid flow rates, and reservoir processes which could not be obtained with any other methods. The isotopic composition of a fluid moving through the crust will be modified in space and time in response to varying chemical and physical parameters and/or by mixing. During these processes, elements will either be conserved, thus preserving isotopic information related to initial conditions and sources or modified in a fashion that is diagnostic of fluid transit times, chemical reactions, and mixing along a flow path. Isotopic data also support hydrologic models by providing complementary information about the fluid flow regime. The temporal evolution of geothermal fluids can be investigated by comparing the compositions of fluid inclusions of different paragenetic histories with each other and with present day production fluids.

Status/Accomplishments:

(1) We have completed a time series study of noble gas compositions in production and re-injection fluids from the Dixie Valley, NV Geothermal Field. The objective was to demonstrate proof of concept for using noble gases as quantitative and sensitive tracers for monitoring re-injected fluids in the production stream. It was demonstrated that for typical steam fractions for geothermal production fluids (~25%), noble gas concentrations in the residual fluid are depleted by factors of 100-1000 and therefore are ~40-50 times more sensitive than more tradional natural injectate tracers (e.g. Cl). A similar, more applied project for using noble gases to identify and monitor co-production of re-injected fluids is currently underway at the Salton Sea Geothermal Field.

(2) Survey studies of noble gas isotopic compositions of the Ohaaki, New Zealand and Yangbajing, Tibet geothermal fields were conducted to identify heat sources and fluid flow paths through the reservoirs. The depth and chemical characteristics of the heat sources which drive the Ohaaki hydrothermal system are poorly understood. Our noble gas study confirmed the presence of two separate fluid upflow zones: the West and East Banks. Fluids associated with the East Bank upflow zone are enriched in B and F, have higher CO_2/3He ratios, higher CH_4-CO_2 13C fractionation temperatures, and lower 3He/4He and higher 40Ar/36Ar ratios than observed in the western upflow zone. Despite the low 3He/4He ratios associated with the eastern upflow zone, the other geochemical and isotopic signatures, particularly the high B and F contents that are unsupported by concentrations in the reservoir lithologies and the high CH_4-CO_2 fractionation temperatures, suggest the presence of a relatively young and shallow degassing intrusive beneath the eastern portion of the field. However, the high CO_2/3He ratios coupled with concentrations of non-volatile constituents suggests significant contributions from local sedimentary reservoir rocks. The low 3He/4He ratios may indicate aggressive leaching of sediments by acidic magmatic fluids that releases significant quantities of radiogenic 4He to the fluid system. The higher 3He/4he ratios associated with the western upflow zone are from an older more geochemically evolved system, where the fluids are presently in equilibrium with the reservoir rocks at local conditions.

The Yangbajing field is the first geothermal field to produce electricity in the Tibetan plateau. The field is located in a NE-SW elongated Cenozoic basin near the Yarlu-Zangbo suture zone. Production is from liquid-dominated, shallow, moderate-temperature (150–165°C) reservoirs. However, Na/K geothermometer temperatures and recent drilling in the NW sector of the field indicates the presence of a deeper, higher-temperature, (~300°C) reservoir beneath the shallow reservoir.

The 3He/4He ratios in fluids from the Yangbajing Field are low (0.26 Ra) relative to typical mantle values (8–9 Ra). Despite the discovery of the high-temperature deeper reservoir, a deep resistivity anomaly inferred to be a magma body, and long-held conceptual models for the Yangbajing Field calling on a magmatic heat source, the helium isotopic compositions suggests very little (if any) involvement of recently intruded magmas. In light of the helium isotopic data, the inferred significance of the resistivity anomaly should be re-considered. Perhaps it points to a deeper hidden geothermal reservoir, as opposed to the inferred magma body. Variations in helium abundance and isotopic composition that occur across the field are consistent with the mixing of a deep-high 3He/4He fluid (~0.26 Ra) with the shallower overlying reservoir (<0.09 Ra) currently being produced. Therefore, extensive exploitation of the deeper fluids could accelerate depletion of the shallow resource.

(3) We are participating in an IAEA sponsored project titled "State of the Art and Development Needs for Noble Gas Isotope Applications in Geothermal Reservoir Exploration and Monitoring" designed to facilitate transfer of noble gas and other isotopic technologies to member states of the IAEA. The project lead is Dr. Pang Zhonge-He, Scientific Secretary, IAEA, Vienna, Austria.

Planned FY 2002 Milestones:

Proof of concept for using noble gases as natural tracers for detecting and monitoring injectate has been completed and the technique is presently being applied at the Salton Sea Geothermal Field. To complete the project we are constructing a new sample preparation line for measuring high precision noble gas abundances with a quadrupole mass spectrometer. Once completed, this will significantly lower analytical cost, improve sample throughput, and enable transfer of the technology to industry.

The Ohaaki and Yangbajing projects are complete and papers detailing the results have been published or are in press. Future work will concentrate primarily on reassessment of geothermal potential in the western United States and on developing isotope techniques for identifying and assessing hidden geothermal systems. This marks the initiation of a longer term project in geothermal exploration.

Major Reports Published in FY 2001:

Ping, Z, Kennedy, B.M., Shuster, D., Ji, D., Ejun, X., and Shaoping, D. (2001), Implications of noble gas geochemistry in the Yangbajing geothermal field, Tibet. Proc. Int. Conf. Water-Rock Interaction 10th, Italy, v2 pp 947-950.

Major Articles Published in FY 2001:

Christenson, B.W., Mrocek, E.K., Kennedy, B.M., van Soest, T., Stewart, M.K., and Lyon, G. (2002), Ohaaki reservoir chemistry: Charateristics of an arc-type hydrothermal system in the Taupo Volcanic Zone, New Zealnd. J. Volc. Geothermal. Res. (in press).

Moore, J.N., Norman, D.I., and Kennedy, B.M. (2001), Fluid inclusion gas compositions from an active magmatic hydrothermal system: a case study of The Geysers geothermal field, USA. Chemical Geology, V173, p. 3-30.

Geysers Geochemical Baseline Study

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
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Contracting Organization Lawrence Berkley National Laboratory (LBNL) One Cyclotron Road Berkley, CA 94720	**Principal Investigator(s)** **Name:** M. J. Lippmann **Phone:** (510) 486-5035 **Fax:** (510) 486-5686 **E-mail:** mjlippmann@lbl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

The study of the behavior of a vapor-dominated reservoir when the volume of injected water is substantially increased is important to the allocation of injection water in order to optimize field management operations. In November 1997, the southeast Geysers first received water from Lake County for augmented injection in the strongly depleted reservoir. This resulted in an increase of steam (and electricity) production and changes in steam chemistry. In late 2002, a second pipeline will begin sending Santa Rosa wastewater to northern parts of The Geysers. Exploitation of some northern Geysers areas was stopped because of high gas content and corrosive steam coming from a deeper, higher-temperature reservoir. Other parts of the northern Geysers and some parts of the central Geysers are starting to produce similar fluids. Injection of liquid in those areas is expected to alleviate the gas and corrosion problems.

The project has two main tasks and objectives: (1) Non-condensable gas data are used to study changes observed in the "normal" steam reservoir of the Northern California Power Agency (NCPA) field of southeastern Geysers. The purpose is to identify reservoir processes resulting from large-scale production and increased liquid injection. (2) Geochemical data from wells completed in the "normal" and "high-temperature" reservoirs of the northern Geysers are compiled for a baseline study of the steam produced before the injection of water from the Santa Rosa Pipeline Project (SRPP) begins. The results of both tasks will allow the evaluation of the impact of liquid injection on the chemistry of the produced steam in different parts of The Geysers field.

Approach/Background:

In collaboration with NCPA and Calpine Corporation the geochemistry of the steam being produced at The Geysers are being studied in detail. Most of the FY-2001 effort was towards studying changes in non-condensable gases in the steam from the southeastern Geysers NCPA field. Variations of gas ratios in the produced steam were used to explain reservoir processes, especially those related to the increased amount of injected liquid from the Southeast Geysers Effluent Pipeline (SEGP) that brings lake water and treated sewage from Lake County to the southern part of the steam field.

Also during the fiscal year, data from Calpine's Aidlin area of northwestern Geysers was collected for a baseline study of that part of the field. Chemical and isotopic compositions data on the produced steam, as well as flow rates and enthalpies were beginning to be compiled. The data will be analyzed to better understand the properties of the high-temperature reservoir before the start of large-scale SRPP injection. The analysis of the information will be carried out mainly in FY-2002. Later on, the data from the study will be useful to follow changes that occur in The Geysers normal and high-temperature reservoirs as a result of SRPP injection.

Status/Accomplishments:

The study of the 1999-2000 steam composition confirmed that the NCPA steam field in the southeastern Geysers is near the edge of the reservoir and next to a condensation zone of high-gas steam to the east and south.

Gas geochemistry showed changes with time in the temperature and steam fractions of source areas of steam from individual wells. Steam produced from the center of the NCPA field originates under fairly uniform reservoir conditions due to the large-scale injection that began in 1997. On the other hand, the steam produced by wells located at the periphery of the field originates from progressively drier (i.e., liquid-poor) zones. It is expected that these wells may return to near original conditions if the amount or pattern of injection are changed.

By contouring the total non-condensable gas in the NCPA steam, it was shown that for most producing wells changes in the location and amount of injection is very effective in limiting gas concentration in the produced steam. By concentrating injection in the center of the field, the average amount of gas in the steam produced by the central and northern NCPA wells has been lowered. However, due to the position of the field at the margin of The Geysers reservoir, steam rich in gases from outside the drilled area continues to enter from the east and south.

Planned FY 2002 Milestones:

Initial report on the noble gases and their isotopic characteristics in the steam produced at the Aidlin field of northwestern Geysers (September 2002).

Major Reports Published in FY 2001:

Truesdell, A., Smith, B., Enedy, S. and Lippmann, M., 2001. "Recent geochemical tracing of injection-related reservoir processes in the NCPA Geysers field. Lawrence Berkley National Laboratory report LBNL-47874, May 2001.

Major Articles Published in FY 2001:

Truesdell, A., Smith, B., Enedy, S. and Lippmann, M., 2001. "Recent geochemical tracing of injection-related reservoir processes in the NCPA Geysers field. Transactions of the Geothermal Resources Council, Vol. 25, pp. 475-480.

Microearthquake Monitoring of an Injection to Determine Reservoir Properties

Contract/Grant #:	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**	
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Lawrence Berkley National Laboratory (LBNL) One Cyclotron Road Berkley, CA 94720	
Contracting Organization Lawrence Berkley National Laboratory (LBNL) One Cyclotron Road Berkley, CA 94720	**Principal Investigator(s)** **Name:** E. L. Majer **Phone:** (510) 486-6709 **Fax:** (510) 486-5686 **E-mail:** elmajer@lbl.gov	
Project Officer / Monitor **Name:** **Phone:** **Fax:** **E-mail:**	**DOE Funding Allocation** $55K	**Cost Share Funding** $75K – Unocal Geothermal

Project Objective:

To collect and analyze a high-quality data set of microearthquake (MEQ) data prior, during and after a stepped up injection at Tiwi, a mature geothermal field on which there is a large amount of information available. Although there has been considerable effort placed on MEQ monitoring of The Geysers and Coso fields, they are a limited set of potential geothermal areas. The detailed data and results obtained from the proposed survey are meant to provide a valuable case study to compare the response of Tiwi to that of The Geysers, and other geothermal areas. In addition, it will provide information to validate MEQ surveys in general.

Approach/Background:

This project began in 2001. During a four-month period (approximately March through June of 2001) 12 portable digital (200 samples/sec.) MEQ instruments with three component sensors were placed in the Tiwi field operated by Unocal Geothermal. The purpose was to provide a high resolution array to monitor seismic activity before, during and after the level of injection has been stepped up. The instruments were borrowed from the Incorporated Institute of Seismology (IRIS) by LBNL and sent to Tiwi for Unocal to operate (no foreign travel was required by LBNL personnel). LBNL and IRIS trained Unocal personnel prior to the deployment of the array. The instruments continuously recorded data for four months and were maintained by Unocal personnel. Unocal bore all costs of field deployment (shipping, maintaining the instruments, etc.). The data and instruments were returned to LBNL and IRIS , respectively where the MEQ data will be analyzed. Unocal will supply relevant reservoir injection information, as well as other field data. LBNL personnel working closely with Unocal personnel will sort and hand pick the MEQ data, concentrating on the injection area. The MEQ events will be processd by LBNL with the results jointly interpreted by Unocal and LBNL personnel.

Status/Accomplishments:

The data were collected from March through June of 200, augmenting the lower resolution analog array in place buy Unocal. The data were sent to LBNL and the instruments returned to IRIS. Several meeting were held with Unocal personnel from the TIWI and Santa Rosa , CA offices to discuss initial results and a path forward. The data volume is twice the size originally planned (initial plans were for two months of recording, but the injection period shifted and was extended). Unocal also provided the injection data and volumes to correlate the MEQ activity with . At LBNL the process of finding and picking the MEQ events began in July of 2001. Because the data were recorded continuously all of the data (over 300 Gigabytes) had to be preprocessed to time align the data from the different individual recorders. After this all of the data had to be displayed and visually inspected for events. The data alignment and culling of the events was 50 percent completed by the end of FY01. Results to date indicate that over 300 MEQ events will be available for processing. The hand picking of the P and S-waves on the three componet recordings will be used for detailed locations and source mechanism studies

Planned FY 2002 Milestones:

Milestones Reports on:

MEQ locations and attributes (size, type, etc.) as a function of time	(I)	March 1, 2002
Correlation of MEQ data with production/injection parameters and known geologic structures	(II)	April 1, 2002

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Phases Behavior of Fluorocarbons for Geothermal Tracers

Contract/Grant #:	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830
Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** **Name:** Blake Maxfield **Phone:** (208) 526-2636 **Fax:** (208) 526-8541 **E-mail:** bmaxfiel@inel.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Jay Nathwani **Phone:** (208) 526-0239 **Fax:** (208) 526-5964 **E-mail:** nathwaj@id.doe.gov	$170K	

Project Objective:

The purpose of this work is to provide thermodynamic property data of candidate geothermal tracer compounds so that their interactions in a geothermal environment can be predicted and modeled. Included in the required data are thermal stability, solubility and phase equilibria of the candidate tracers with geothermal fluids at elevated temperatures and pressures. The ultimate goal is to use the tracers to provide understanding of the subsurface geothermal field and flows.

Approach/Background:

Following initial screening by EGI of Utah, two groups of candidate tracers were identified for further evaluation. One group included freons that were partially fluorinated methane and ethane gases. The other group included fully fluorinated liquids of which perfluoromethylcyclohexane was typical. Most of the physical data for the individual tracer candidates was available but the interactions in the geothermal environment needed to be evaluated in order to successfully plan, execute and interpret a tracer field test.

Data demonstrating stability of fluorocarbons in air at temperatures up to 400°C was available in the literature. However, their stability in high temperature water was not known. As temperatures approach the critical point of water, 383°C, water becomes very aggressive as a chemical oxidant. The thermal stability of the tracer candidates under geothermal conditions is being evaluated.

The tracer is being evaluated to see if it has an affinity for the solid matrix. Even mild interaction that would only delay the candidate tracer by a relatively small amount, could be enough to remove it from the list of viable tracer candidates.

Finally the candidate tracers are being evaluated to determine how they will partition in the liquid and gaseous phases of the geothermal fluids.

Status/Accomplishments:

Stability data of the various tracer candidates have been obtained and show less than 1% degradation of the fluorocarbon tracer candidates after 100 hours at 300°C.

Halide stress corrosion of the test equipment and vessels was evaluated based on the degradation of the fluorocarbon to form fluoride ions. While this is not a concern in the field where the chloride concentration is a much larger concern for halide stress corrosion cracking compared to the small amount of fluoride ion produced, however, in the laboratory this fluoride stress corrosion cracking is a major concern that was addressed and is being monitored.

Initial solubility data of three of the tracer candidates was obtained.

Data collected on several of the tracer candidates on a solid matrix of sand at ambient conditions show that they are conservative under these conditions. Some preliminary results with heat treated sand show a dramatic increase in the retention time of the tracer in the sand at ambient conditions. Currently a processs is underway to determine if the increase in retention time of the heat treated sand is a function of heating or a secondary function. Secondary functions such as static electricity may be introduced since the extra dry sand may have built up a static electrical charge during sample preparation.

Planned FY 2002 Milestones:

Completion of the tracer/ solid matrix evaluation is expected in the next few weeks.

The phase partitioning equalibria of the tracer candidates in the geothermal liquids and gases will be determined.

From this data, equation of state parameters will be extracted that can be used to model the geothermal system in order to successfully plan, execute and interpret a field tracer test.

Major Reports Published in FY 2001:

An interum report was presented in August 2001 to the DOE Geothermal Energy Program, Geoscience Peer Review in San Diego, California.

Major Articles Published in FY 2001:

None

Technology for Increasing Geothermal Energy Productivity
Computer Models to Characterize the Chemistry of Geothermal Reservoirs and Energy Extraction Processes

Contract/Grant #: DE-FG07-99ID13745	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	University of California, San Diego Department of Chemistry & Biochemistry, M/C 0340 9500 Gilman Drive La Jolla, CA 92093
Contracting Organization Idaho Operations Office 850 Energy Drive, MS 1225 Idaho Falls, ID 83401-1563	**Principal Investigator(s)** **Name:** PI: Nancy Moller and CoPI: John H. Weare **Phone:** 858-534-6374 and 858-534-3286 **Fax:** 858-534-7244 **E-mail:** nweare@ucsd.edu and jweare@ucsd.edu

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Jay Nathwani **Phone:** 208-526-0239 **Fax:** 208-526-5964 **E-mail:** nathwaj@id.doe.gov	$1,997,133 * over 5-year grant period. *This allocation reduced by $125,000 in 10/1/00-9/30/02.	$17,229 (UCSD) Equipment match removed due to DOE budget cut.

Project Objective(s):

- Reduce the costs of geothermal energy production by developing computer models that accurately predict the chemistry of energy extraction processes for wide ranges of temperature, pressure and composition.
- Develop advanced modeling methods that decrease the reliance on experimental data in model construction.
- Develop advanced modeling technologies that facilitate the expansion of geothermal energy production by accurately describing the high temperature, pressure hydrothermal environments found in deep crustal resources.
- Develop user interfaces to make model codes easy-to-use and accessible on our web site (geotherm.ucsd.edu).
- Train experts in geothermal chemistry.

Approach/Background:

Many of the problems encountered by the geothermal industry that decrease productivity reflect complicated chemical interactions between solids, gases and liquids. Chemical models can provide useful information about geothermal reservoir performance and energy extraction processes for wide ranges of composition, temperature and pressure (XTP). They also can summarize and extend the applicability of large amounts of data. Our modeling approach describes the thermodynamics of mixed brine-rock-gas systems via their free energies and allows construction of solubility, phase equilibria and heat property models as a function of XTP. Below about 300°C and near 1 atm, where the main variation of the liquid phase free energy is due to solute concentration changes, we use free energy equations to construct models of complex liquid/solid equilibria to high concentration and temperature. Gas phases are easily included. To treat higher temperature reservoirs, we develop phenomenologies that can treat the large changes in density and high solute mole fractions occurring above the critical point of water. In the supercritical region, the density of a system changes dramatically and continuously as a function of pressure. Reservior simulation studies predict that geothermal reservoir fluids evolve to near critical conditions. We utilize special scaling EOS to predict vapor-liquid equilibria near the critical region. To reduce the amount of experimental data required in model construction, we develop more theoretical modeling approaches (e.g., molecular simulation). To facillitate the transfer of our technology we develop extensive user interfaces so that our models can be bundled into easy-to-use applications packages (TEQUIL, GEOFLUIDS, GEOHEAT) for distribution via the Internet.

Status/Accomplishments:

We have made considerable progress building a comprehensive suite of models for application to geothermal operations for wide XTP ranges. These models can provide important tools for assessment of resource potential and performance (e.g., flashing, scaling, injectate behavior), predicting downhole and reservoir chemistry and testing problem abatement strategies. During the 2001 project period, we made many advancements in our modeling packages and methodology. TEQUIL: the compositional and acid/base description of brines to 250°C was considerably expanded. The addition of HSO_4^-, OH^-, SiO_2(quartz) and $H_3SiO_4^-$ species and many new solid phases improves solubility and pH predictions (allowing pH modification and brine geothermometer applications). GEOFLUIDS: New EOS models were added allowing the prediction of multiple phase processes, such as flashing and miscibility, and high TP behavior associated with deep hydrothermal reservoir fluids. Scaling EOS were developed to predict vapor-liquid equilibria in the near critical region. GEOHEAT: Enthalpy prediction in NaCl-brines to 300°C was improved. This enthalpy model, when coupled with our EOS for the CO_2-CH_4-H_2O system, allows brine steam ratio prediction. MOLECULAR SIMULATIONS: Significant advancements in our molecular simulation studies yielded important thermodynamic "data" and fundamental information about vapor-liquid equilibria in aqueous fluids.

Planned FY 2002 Milestones:

- New acid/base and carbonate (H_2SO_4-HCl-H_2CO_3) models in Na, K, Ca brines for the TEQUIL package.
- Continue modeling rock/water interactions in Na-K-Ca-Mg-carbonate system to high temperature.
- Continue developing model of aluminum speciation in brines.
- Continue adding new salt species to the GEOFLUIDS NaCl-CH_4-CO_2-H_2O EOS.
- Continue molecular simulation to generate needed thermodynamic information for model development.
- Improve enthalpy prediction in GEOHEAT of gas-H_2O models for heat extraction and steam ratio calculations.
- Incorporate user interfaces in new model codes and implement updates of TEQUIL, GEOFLUIDS, **GEOHEAT models on our web site.**

Major Presentations in FY 2001:

Invited Presentation: "Thermodynamic Models of Natural Fluids: Theory and Practice." 221st. Meeting ACS, April 1-5, 2001, San Diego CA.

Presentation: "Monte Carlo Gibbs Ensemble Simulation of Phase Equilibria of the RWK2 Water." 221st. Meeting ACS, April 1-5, 2001, San Diego CA.

Invited Presentation: "Technology for Increasing Geothermal Energy Productivity," DOE Geothermal Subcontractors' Meeting, May 8-10, Albuquerque NM.

Invited Presentation: "From Molecular Models to Equations of State." 11th Annual Goldschmidt 2001 Conference, May 20-24, 2001, Hot Springs, VA.

Invited Keynote Presentation: "First Principles Dynamical Simulations of Hydrothermal Solution Behavior." 11th. Annual Goldschmidt 2001 Conference, May 20-24, 2001, Hot Springs, VA.

Invited Presentation: "Parallel Implementation of Large-Scale A*b Initio* Molecular Dynamic Algorithms: Scaling Issues." 1st Computational Chemistry Conference, U. Kentucky, Lexington, KY, Oct. 17, 2001.

Major Articles/Reports Published in FY 2001:

Report: DOE Peer Review, August 23-24, San Diego, CA.

Paper: "Equation of state for the NaCl-H_2O-CH_4 system and the NaCl-H_2O-CO_2-CH_4 system: phase equilibria and volumetric properties above 573K," submitted for publication in *Geochim. Cosmochim. Acta.*

Western U.S. Geothermal Systems

Contract/Grant #: DE-FG07-00ID13891 Task 2	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Allan Jelacic Phone: (202) 586-6054 Fax: (202) 586-8285 E-mail: allan.jelacic@hq.doe.gov	Energy & Geoscience Institute 423 Wakara Way, Suite 300 Salt Lake City, UT 84108	
Contracting Organization U.S. Department of Energy Idaho Operations Office 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** Name: Gregory D. Nash Phone: (801) 585-3889 Fax: (801) 585-3540 E-mail: gnash@egi.utah.edu	
Project Officer / Monitor Name: Jay Nathwani Phone: 208-526-0239 Fax: 208-526-5964 E-mail: nathwaj@id.doe.gov	**DOE Funding Allocation** $323K	**Cost Share Funding**

Project Objectives:

- To test new remote sensing data types in novel applications for geothermal exploration including the use of hyperspectral data to map soil-mineralogy and geobotanical anomalies that may indicate buried permeable structures and potentially lead to the discovery of hidden geothermal systems.
- To test and apply precision gravimetry for steam field hydrologic monitoring and characterization.
- To enhance technology transfer through the Internet and web-based GIS.

Approach/Background:

This project explores the use of geomatics technologies, including remote sensing and geographic information systems, to solve specific problems in geothermal exploration and technology transfer. This includes a primary focus on the testing and use of new remote sensing data types and data processing techniques that facilitate the interpretation of features on the surface of the Earth that can indicate hidden faults and areas of permeability, and that may lead to the discovery of hidden hydrothermal convection systems. Precision gravimetry is also being applied and tested as a tool to monitor and characterize geothermal systems. This is particularly useful for steam fields were reinjection programs have been initiated to monitor the progress.

Additionally, technology transfer has traditionally been accomplished via publication in journals and presentation and publication in conference proceedings. While this is not to be neglected, the audience it reaches is typically small. Publication on the web has improved accessibility to research results through hyperlinked digital documents. Therefore, this project also includes an effort to improve technology transfer through the use of the Internet including the use of Internet based GIS that allows access to documents and data through a logical spatial interface.

This project directly addresses *DOE Program Objectives* related to "Economic Competitiveness – Reducing Geothermal Power Development Costs", as these new techniques can provide important geologic information leading to greater success in drilling to find and develop vitally needed new geothermal resources. This research also specifically addresses the "Geoscience and Supporting Technologies, University Research – Active Faulting Areas" area of the DOE Geothermal Strategy.

Status/Accomplishments:

1. A successful project at Cove Fort-Sulphurdale, Utah, was completed for hyperspectral geobotanical anomaly mapping as related to hydrothermal convection. This project was undertaken to determine if geobotanical anomalies had occurred in response to reservoir pressure decreases that were related to steam production. Geobotanical anomalies were detected using hyperspectral data acquired with a field spectrometer. The anomalies were generally spatially correlative with known faults and may have indicated some unmapped structures that have also been interpreted from other geophysical data. This technique will be useful for mapping faults and zones of permeability in areas where geothermally produced gasses, such as H_2S and Co_2, reach the Earth's surface affecting the soil and vegetation. A final report has been completed for this project.
2. Success has also been achieved in using hyperspectral data to map hydrothermal convection system soil-mineralogy anomalies at Dixie Valley, Nevada. In this study both unsupervised and supervised spectral unmixing techniques were used to derive spectral end-members representing minerals mixed within pixels. The end-members were then used to produce relative abundance maps. The relative abundance maps revealed a prominent calcium carbonate anomaly that was associated with buried permeable structures. There may also be elevated kaolinte associated with this anomaly. Further work needs to be done to establish if this anomaly statistically valid. It is currently thought that the soil-mineralogy anomalies are related to past fumarole activity and/or hydrothermal alteration of the rock associated with the buried fault. Active fumaroles formed in this area shortly after the image was captured. This activity was precipitated by decreases in reservoir pressures resulting from production.
3. Good progress was also made for a fault kinematics study at Karaha-Telaga Bodas, Indonesia in support of the Andesitic Hosted System task. This included mapping faults/lineaments at multiples scales, generating fault statistics with a GIS database, and extrapolating fault geometries from drill core and EMI log interpretations.
4. April 2001 and September 2001 field campaigns at The Geysers resulted in a network of 160 stations, which provide dense (1 km spacing) coverage over the production field, and decreasing station density outside the field. This work has revealed an overall decrease in gravity of up to -0.7 mGal since 1979. Spatial trends in the gravity data correlate well with the known production history of the field. The known mass loss predict a gravity decrease of ~-0.65±0.13 mGal; given the uncertainties in the predicted gravity signal, the observed and predicted signals are in agreement. The gravity change predicts a dry-out bulk porosity of ~2%, which is in agreement with values used for modeling of the reservoir.
5. The Internet technology transfer objective has been met. A web site was developed for this purpose and enhanced with an ESRI Internet Map Server. Users can access publications, resulting from Western U.S. Geothermal Systems, via project information pages or using spatial queries of study areas in a GIS environment. A section specifically detaining work from this task is also in place giving interested parties access to publications with additional comments and specific instructions on how to replicate results where needed.

Planned FY 2002 Milestones:

- Dixie Valley, Nevada. Work done in FY 2001 revealed that the ATREM atmospheric correction method, the best known technology for this purpose at the beginning of this project, fell short in some expectations. Hyperspectral data processed with this technique appeared to have some remaining haze and some spurious absorptions that can interfere with specific mineral identification. A new method (ACORN) was acquired at the end of FY 2001. An initial test indicates that this method solves many of the mentioned problems. Although ATREM processed data proved very useful in the Dixie Valley soil mineralogy anomaly mapping effort in FY 2001, the data will be reprocessed using ACORN, the results of which will be reanalyzed to determine if additional mineral end-member can be identified, quantified, and mapped. At least one paper detailing this study and the results will be completed. It will be submitted to the 2002 Stanford Workshop on Geothermal Reservoir Engineering. It is also anticipated that an additional paper, integrating the results of this study and those of the Western U.S. Geothermal Systems task regarding Dixie Valley, will be completed and submitted to *Geothermics* or another peer reviewed journal for publication in FY 2002. Additionally, the experiments being done to spatially enhance AVIRIS data for structure mapping in Dixie Valley will be completed using ACORN processed data. It is believed that AVIRIS and other types of hyperspectral data will be superior for structure mapping, and that spatial enhancement will add an element of additional functionality in this respect.

- Dixie Valley, Nevada. Advanced Spaceborne Thermal Emission and Reflectance Spectrometer (ASTER), acquired from NASA in the fourth quarter FY 2001, for the Dixie Valley area, will be processed and analyzed to (1) determine if its spectral resolution in the short-wave infrared (SWIR), which is higher than Landsat Thematic Mapper (TM) but lower than AVIRIS, is adequate for mineralogy and soil anomaly detection and mapping. The Dixie Valley data set was chosen for these experiments as good ground truth, acquired from related Dixie Valley studies, is in-hand. This study will also spatially extend the boundaries of the study to include areas outside of the above hyperspectral study. The results of this project could aid in the expansion of development of the producing steam field.
- Salton Sea, California. Landsat 7 TM data, covering the Salton Sea area in California, were acquired during FY 2001. These data underwent preliminary preprocessing and interpretation during the fourth quarter of FY 2001. Further analysis for (1) more detailed structure mapping and (2) general hydrothermal alteration mapping, to aid in structure detection, will be done in FY 2002. This will be done in an integrated effort complimenting other work being done under this contract by EGI related to the characterization of the geothermal system in this area. The results of this work will be integrated into publications as directed by Western U.S. Geothermal Systems task PI Jeffery Hulen.
- Karaha-Telaga Bodas, Indonesia. Work will be continued regarding Fault Kinematics in the Karaha-Telaga Bodas, Indonesia, Geothermal Field. This is in support of other work being done under the Andesitic Systems task related to the characterization of the geothermal system in this area. The results from this work will be integrated into publications as directed by Andesitic Systems CoPI, Joseph Moore.
- The GIS/Web-based Geothermal Information System will be enhanced and data, results, and published documents will be added throughout the year. Users will be able to browse and manipulate data generated from this study. This includes browser based GIS layer control, feature identify, hyperlinked ancillary data, query capability, and linked documents. This will allow non-GIS users from industry, government, and the general public to access, visualize, and use the data produced from these studies. The results of this effort will be documented in a paper to be presented at the GRC conference 2002. The GIS effort will also allow the integration of the data and results of several EGI DOE studies to better facilitate hydrothermal convection system characterization, specifically the integration of the mineralogical studies of Dixie Valley, Nevada and geologic studies of Salton Sea, California and Karaha-Telaga Bodas, Indonesia.
- The effort to acquire hyperspectral data over priority areas will continue with NASA and private sources. EGI will cooperation and collaborate with Lawrence Livermore National Laboratories in this effort.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

Allis, R.G., Gettings, P., P., Isherwood, W.F., Chapman, D.S., 2001, Reservoir monitoring at The Geysers with Repeated high-Precision Gravity and GPS, Geothermal Resources Council Transactions Vol. 25, p. 631-634.

Gettings, P., Allis, R.G., Harris, R.N., Chapman, D.S., 2001, High-Precision Gravity and GPS Monitoring of The Geysers Geothermal System, EOS Trans. Am. Geophys. Union, v82 (abstract)

Nemcok, M, J. McCulloch, G. Nash, and J. Moore, 2001, Fault Kinematics in the Karaha-Telaga Bodas, Indonesia, Geothermal Field: An Interpretation Tool for Remote Sensing Data, Geothermal Resources Council Transactions, Vol. 25, p. 411 – 415.

Nash, G. D. and M. W. Hernandez, 2001, Cost-Effective Vegetation Anomaly Mapping for Geothermal Exploration, Proceedings: Twenty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 28-30, 2001, SGP-TR-168.

Studies of Geothermal Reservoir Dynamics

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization Lawrence Berkley National Laboratory (LBNL) One Cyclotron Road Berkley, CA 94720	**Principal Investigator(s)** **Name:** Karsten Pruess **Phone:** (510) 486-6732 **Fax:** (510) 486-5686 **E-mail:** bmkennedy@lbl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	$180K	$175K

Project Objective:

This project will apply and enhance mathematical modeling techniques (numerical simulation) for the study of geothermal reservoir behavior. Issues to be addressed include (1) design and analysis of phase-partitioning tracer tests in boiling geothermal systems, and (2) mineral dissolution and precipitation effects in geothermal reservoirs during the natural evolution and during production and injection operations.

Approach/Background:

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 solute concentrations. Industry needs more accurate and comprehensive numerical simulation capabilities that can incorporate geochemical information, in order to develop more reliable reservoir models, and to optimize field development and management, especially fluid injection for enhanced energy recovery.

Status/Accomplishments:

Capabilities for numerical modeling of phase-partitioning tracers were developed, including noble gases, other non-condensible gases, isotopes such as tritium, and a variety of halogenated hydrocarbons and other man-made volatile organic chemicals (VOCs). The new simulation capabilities were applied to modeling tracer tests at The Geysers vapor-dominated reservoir, where increased fluid injection has prompted a strong interest in tracer testing as a means for determining fluid flow paths and reservoir processes, such as boiling of injectate. Using “generic” reservoir parameters borrowed from previous modeling work at The Geysers, we have simulated tracer tests for undepleted (i.e., large water saturation) as well as strongly-depleted (i.e., small water saturation) reservoir conditions. Simulated tracer breakthrough curves (BTCs) agree well with field observations by Beall et al. (1994, 1998), supporting the interpretations proposed by Beall et al., and suggesting that injected fluid is subject to rather complete and virtually instantaneous vaporization in strongly-depleted reservoir zones, while vaporization in undepleted conditions is only partial and slow. For depleted conditions, BTCs show long tails which are due to diffusive exchange of tracer between fractures and matrix. These features of the BTCs may offer a means for estimating average fracture spacing, a parameter that is of vital interest in quantifying heat transfer to the injected fluid.

With internal LBNL funding and support from DOE’s offices of Basic Energy Sciences (BES) and Civilian Radioactive Waste Management (OCRWM), we have developed capabilities for numerical simulation of reactive chemical transport in very general hydrothermal mineral systems. Our modeling capabilities for chemical interactions between rocks and fluids under non-isothermal and two-phase conditions have been implemented as an extension of the TOUGH2 code, known as TOUGHREACT (Xu and Pruess, 2001a; Xu et al., 2001a). These capabilities have recently been applied to a number of geothermal problems, including mineral alteration in fractured caprock, mineral recovery from geothermal brines, and problems arising in geothermal reservoir management (Xu and Pruess, 2001b; Pham et al., 2001; Xu and Pruess, 2001b).

TOUGHREACT was applied to study mineral alteration in fractured caprock of a magmatic hydrothermal system, which was patterned after conditions observed in the Long Valley Caldera (LVC). The flow system models fluid leakage from a high-temperature geothermal system through fractures in the caprock. It includes fracture-matrix interaction, mixing with waters from shallow cold aquifers, and eventual discharge at the land surface. Rather detailed and comprehensive specifications were used for water chemistry and rock mineralogy, based on data from drillholes in the LVC. Issues addressed in the modeling work include fracture-matrix interaction, participation of gas phase in chemical reactions (CO_2), kinetic effects in rock-fluid interactions, and temperature effects on thermophysical and chemical processes and properties. The model predicts formation of three different mineral zones, an upper (shallow) zone with smectite-kaolinite that also includes unaltered glass, quartz, and K-feldspar; an intermediate zone with mixed illite-smectite; and a lower illite zone where kaolinite and smectite are absent, with calcite and chlorite present. These predicted mineral assemblages agree well with field observations at Long Valley. A full report on this work has been published (Xu and Pruess, 2001b).

In collaboration with GeothermEx, Inc., TOUGHREACT was applied to a number of reactive chemical transport problems that arise in geothermal production and injection operations. The purpose of these studies was to examine the utility of TOUGHREACT for practical reservoir problems. Issues addressed include mineral recovery from hypersaline brines in the Salton Sea field, California, effects of injecting silica-supersaturated brines or fluids of low-pH, and long-term trends in production of non-condensible gases. A first report on this work concluded that TOUGHREACT was capable of modeling all of the processes studied, and showed promise as a practical tool for reducing costs and environmental impact of geothermal power generation (Pham et al., 2001). A more detailed discussion of the modeling of zinc recovery at the Salton Sea geothermal field was presented by Xu et al. (2001b).

Planned FY 2002 Milestones:

An enhanced fluid property module for TOUGH2 with capabilities for fractionating and non-fractionating volatile tracers and a comprehensive description of thermophysical properties of all noble gases will be developed. A major effort will be devoted to completing a beta-testing version of TOUGHREACT, including code, documentation, and sample problems. We will also investigate the possibility of seeing "blind" systems in the Cascades by combining reservoir engineering, geophysical, and geochemical observations.

Develop a TOUGH2 fluid property module for (saline) water with noble gases, and report on identifying reservoir processes from noble gas concentrations.	May 02
Report on mineral dissolution and precipitation effects in geothermal reservoirs during the natural evolution and during production and injection operations.	July 02

Report on geophysical visibility of hidden geothermal features. Sep 02

Major Reports Published in FY 2001:

Pham, M., C. Klein, S. Sanyal, T. Xu and K. Pruess. Reducing Cost and Environmental Impact of Geothermal Power through Modeling of Chemical Processes in the Reservoir, *Proceedings, Twenty-Sixth Workshop on Geothermal Reservoir Engineering,* pp. 216 - 223, Stanford University, Stanford, California, January 29-31, 2001.

Xu, T., K. Pruess, M. Pham, C. Klein and S. Sanyal. Reactive Chemical Transport Simulation to Study Geothermal Production with Mineral Recovery and Silica Scaling, presented at 2001 Annual Meeting, Geothermal Resources Council, San Diego, CA, August 2001b.

Major Articles Published in FY 2001:

Xu, T. and K. Pruess. Modeling Multiphase Non-isothermal Fluid Flow and Reactive Geochemical Transport in Variably Saturated Fractured Rocks: 1. Methodology, *American Journal of Science*, Vol. 301, pp. 16-33, 2001a.

Xu, T. and K. Pruess. On Fluid Flow and Mineral Alteration in Fractured Caprock of Magmatic Hydrothermal Systems, *J. Geophys. Res.,* Vol. 106, No. B2, pp. 2121 - 2138, 2001b.

Xu, T., E. Sonnenthal, N. Spycher, K. Pruess, G. Brimhall, and J. Apps. Modeling Multiphase Non-isothermal Fluid Flow and Reactive Geochemical Transport in Variably Saturated Fractured Rocks: 2. Applications to Supergene Copper Enrichment and Hydrothermal Flows, *American Journal of Science*, Vol. 301, pp. 34-59, 2001a.

Pruess, K. Numerical Simulation of Multiphase Tracer Tests in Fractured Geothermal Reservoirs, submitted to *Geothermics,* August 2001.

Pruess, K. Multiphase Flow in Fractured Rocks - Some Lessons Learned from Mathematical Models, in B. Faybishenko, P.A. Witherspoon, S.M. Benson (ed.), *Dynamics of Fluids in Fractured Rock,* Geophysical Monograph 122, pp. 225 - 234, American Geophysical Union, Washington, DC, 2000.

Characterization of Fracture Patterns in the Geysers Geothermal Reservoir by Shear-Wave Splitting

Contract/Grant #: DE-FG07-00ID13956	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
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Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** Name: J. A. Rial Phone: (919) 966-4553 Fax: (919) 966-4519 E-mail: jar@email.unc.edu	
Project Officer / Monitor Name: Joel Renner Phone: (208) 526-9824 Fax: (208) 526-0969 E-mail: rennerjl@inel.gov	**DOE Funding Allocation** $467K	**Cost Share Funding**

Project Objective:

On the basis of shear wave splitting data recorded and processed from The Geysers and Coso geothermal fields this project aims at developing a computer-based methodology to produce 3D maps of the crack distribution in fractured reservoirs. The raw data for the project consists of seismographic recordings of microearthquakes (MEQ) detected by arrays of sensors for several years in both reservoirs. With the experience acquired with the processing and interpretation of these data we are developing a novel computer-based technology for the exploration of geothermal and other fractured reservoirs. The final product will consist on three software packages written in Matlab-compatible language:

(1) Data analyzing package.

(2) Forward modeling package

(3) Inversion package.

Approach/Background:

A shear-wave propagating through rocks with stress-aligned cracks will split into two waves, a fast one polarized parallel to the predominant crack direction, and a slow one, polarized perpendicular to it. In fact, the polarization direction F of the fast split shear wave parallels the strike of the predominant cracks regardless of its initial polarization at the source, while the time delay DT between the fast and the slow waves is proportional to 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 intensity of fracturing in the subsurface, which, if developed as a computer application, could become a highly desirable technical and industrial resource to explore fracture-controlled geothermal and hydrocarbon reservoirs. For the last few years we have studied and processed shear-wave splitting data in two seismically active, fracture-controlled environments, The

Geysers and Coso geothermal fields in California, using 14- and 16-station seismic arrays of 3-component, mostly down-hole instruments running at 420 samples/sec (Lou and Rial, 1994; 1997; Rial and Lou, 1996; Lou et al., 1997; Erten and Rial, 1998, 1999; Erten et al., 2001). From the analyses and processing of over 60,000 local microearthquakes 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:

All phases of the proposed research are on schedule. Mapping of fast shear-wave polarizations and delay times in The Geysers and Coso has been completed and the results described in the previous peer revirew report (San Diego, August 2001) and preliminary results published (see below).

The data analyzing package (1) is now completed. The program consists in Matlab-based fully interactive GUIs (Graphic user interfaces) that allow the display, windowing, spectral analysis and polarization analyses of three-component seismograms. The code allows the operator to plot the ground particle motion in 2D and 3D diagrams, rotate the components to determine the polarization F, time delay DT and automatically store them for later use in the modeling and inversion procedures. This code has been successfully tested and used in the analyses and processing of The Geysers and Coso shear-wave splitting database.

The forward modeling package (2) is near completion. This package has two important uses: a) it allows the operator to map polarization F and delay DT on the area of interest, which helps determine data consistency, data anomalies and general azimuthal distribution of the data prior to interpretation. b) The operator can interactively construct synthetic seismograms that reproduce the polarizations of the P, fast S1 and slow S2 split waves traveling through a standard Horizontal Transverse Isotropic (HTI) model that fully simulates the anisotropy induced by a crack system. The operator can change the dip of the crack system and the crack density, as well as specify whether cracks are empty or fluid-saturated. 3D graphs depicting the predicted synthetic polarizations are obtained for the P, S1 and S2 waves, as well as synthetic seismograms from which the predicted values of F and DT are compared with actual ones in a station-by-station basis. The purpose of this pacakge is to produce a first trial-and-error inversion of the data to use as fundamental constraints in the next step. The synthetic seismogram compuattions have been successfully tested against published results of F and DT for transversely isotropic (TI) models.

This project has so far fully supported two graduate students and partially supported a post-doctoral associate.

Planned FY 2002 Milestones:

A) Completion of the forward modeling package (2). This includes the incorporation of an automatic code to detect and store the differences between synthetic and observed seismograms.

B) Completion of two research papers that describe the results obtained in The Geysers and Coso regarding crack distribution. A research paper with a comprehensive study of the space-time variation of F and DT at Coso and its implications to monitoring local tectonics and production has been submitted to the Journal of Volcanology and Geothermal research (see below).

C) Development of the inversion package (3). The inversion package consists of two main parts: a) Station-by-station inversion of the DT data to determine crack dip. The results reflect local structure because accurate measurements of DT are limited to rays arriving at the station within the 35 degree vertical angle that constitutes the shear-wave window. At any given station F and DT vary with azimuth in a predictable manner. The objective of this first inversion approach is therefore to use the observed azimuthal variations of F and DT to refine the crack direction determined before and determine the crack dip, in the neighborhood of each array station. b) Inversion of the crack density. DT measurements corrected for crack dip will then be used to invert for crack density using groups of near stations and, if possible, the entire array. Because of the shear window limitation we anticipate that the density of ray crossings will be optimal only for some groups of nearby stations. The technique is however to be implemented for any distribution of sensors.

Using F and DT for tomographic inversion of cracked reservoirs is a novel approach. With the high quality of data available we are in a unique position to produce a first-time result that will not only provide a close look at the 3D crack distribution in The Geysers and Coso, but may stimulate new research into seismic imaging of anisotropic/fractured media.

Major Reports Published in FY 2001:

Erten, D., M. Elkibbi and J.A. Rial (2001): Shear wave splitting and fracture patterns at The Geysers (California) geothermal field., Geothermal Res. Eng. Proceedings, 26th Workshop, p139-147.

Erten, M. Elkibbi and J.A. Rial (2001) Shear wave Splitting and Fracture patterns at The Geysers, Spring Meeting, EOS AGU,.Boston.

Vlahovic, G., Elkibbi, M., and J. A. Rial (2002). Temporal Variations of Fracture Directions and Fracture Densities in the Coso Geothermal Field from Analyses of Shear-wave Splitting, Geothermal Reservoir Engineering Proceedings, Twenty-seventh Workshop, Stanford Uni-versity. SGP-TR-171 (In press).

Major Articles Published in FY 2001:

Finished in 2001, to be published in 2002: Vlahovic, G., Elkibbi, M., and J. A. Rial (2002). Shear Wave Splitting and Reservoir Crack Characterization: Coso Geothermal Field. Submitted to Journal of Volcanology and Geothermal Research

The Development of Tools for Managing Injection in Geothermal Reservoirs

Contract/Grant #: DE-FG07-00ID13891, Task 6	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization	**Principal Investigator(s)**
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Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Jay Nathwani **Phone:** (208) 526-0239 **Fax:** (208) 526-5964 **E-mail:** nathwaj@id.doe.gov	$216K	

Project Objective:

The primary objective of this project is to develop thermally stable tracers for the geothermal industry. In addition to thermal stability, these tracers must be environmentally benign, very detectable by conventional analytical techniques, reasonably affordable, and resistant to adsorption on reservoir rock. A secondary objective is to develop a simple and affordable online (wellhead) tracer detector based upon either fluorescence or absorption detection.

Approach/Background:

The reinjection of produced fluids into geothermal reservoirs via dedicated injection wells is used primarily as a means of maintaining reservoir pressures. If the injection wells are located too close to the production wells, however, there exists a risk of premature thermal breakthrough. Thermally stable tracers are needed within the geothermal industry in order to optimize well placement. Likewise, since a distinct tracer is required for each injector that is tagged, many tracers are needed.

During the past few years, the EGI Tracer Development Laboratory has conducted research directed at developing fluorescent geothermal tracers. A family of compounds known as polyaromatic sulfonates were tested in the laboratory and found to be suitable for use in high-temperature, liquid-dominated geothermal systems (Rose et al, 2001). The compounds were successfully tested in tracer tests in geothermal reservoirs in Dixie Valley, Nevada; Steamboat Hills, Nevada; Ohaaki, NewZealand; Awibengkok, Indonesia; Soultz-sous-Forets, France; and Bulalo, Philippines.

Geothermal reservoir operators have long desired a simple, rugged, and affordable detector that can measure and record tracer returns at the wellhead, obviating the need to take samples and send them to a laboratory for analysis. With the recent advances in lasers, fiber optics, long pathlength flow cells, and charge-coupled-device (CCD) spectrometers, the technology will soon be available for the online analysis of chemical tracers. We have therefore initiated a project to develop a simple affordable detector that can be used to analyze tracers by both absorption and fluorescence at the wellhead.

A recent development in the area of nanotechnology research was the discovery that semiconductor particles can be made strongly fluorescent if they are fabricated with diameters in the range of a few nanometers. What makes this class of compounds especially interesting for geothermal tracing work is that by fine tuning their diameters, mixtures of compounds can be made to emit light at a variety of wavelengths upon absorbing light at a common wavelength. Thus, by simply controlling the fabrication process, a family of distinct tracers could be fabricated with similar chemical and physical properties.

Status/Accomplishments:

Deliverables proposed this year included:

1. Two additional fully characterized (laboratory- and field-tested) high temperature fluorescent tracers;
2. Five viable nonfluorescent dyes for use in medium-temperature geothermal systems;
3. The initial design, fabrication, and testing of a fluorescence/absorbance detector for field-based tracer detection;
4. The evaluation of solubilized nanoparticles (quantum dots) for use as fluorescent tracers.

Deliverable 1 was successfully completed. The candidate tracers 1-naphthalene sulfonate and 2,6-naphthalene disulfonate were tested in the laboratory and found to be among the most thermally stable tracers tested to date and to be suitable for use in reservoirs exceeding 330°C. They were also successfully tested in the field at the Dixie Valley geothermal reservoir.

Deliverable 2 was partially completed. Two nonfluorescent dyes (Acid Orange 10 and Acid Yellow 23) were studied in the laboratory (see second and third quarterly reports) under conditions that simulate a geothermal environment and found to be quite thermally unstable. We have proceeded to identify a family of non-azo dyes (sulfonated anthraquinones) that promise much greater thermal stability. Preliminary tests have confirmed our predictions and have shown that the dye anthraquinone-2,6-disulfonate possesses excellent thermal stability and a strong absorbance cross-section.

Deliverable 3 was partially completed. An absorbance detector for field-based tracer detection was designed and fabricated based upon the emerging technologies of laser light sourcing, CCD spectrometry, fiber optics and long pathlength flow cells. Preliminary tests indicate that instrument exceeded expectations.

Deliverable 4 was successfully completed. See section 4.0 of the quarterly report ending June 30, 2001.

Planned FY 2002 Milestones:

1. The laboratory characterization of one additional tracer for use in high temperature geothermal reservoirs
2. The evaluation of that high temperature tracer in a field test at a geothermal reservoir and publication of the results of that tracer test in the proceedings of a geothermal conference
3. Development of a method for the simultaneous HPLC analysis of seven naphthalene sulfonate tracers and publication of that method in the proceedings of a geothermal conference
4. The decay kinetics characterization of a nonfluorescent dye for use in medium-temperature geothermal systems
5. The initial design, fabrication, and testing of a fluorescence detector for field-based tracer detection

Major Reports Published in FY 2001:

Rose, P.E., Johnson, S.D., and Kilbourn, P.M. (2001) Tracer testing at Dixie Valley, Nevada, using 2-naphthalene sulfonate and 2,7-naphthalene disulfonate: *Proc. Twenty-Sixth Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-168, pp. 60-65.

Major Articles Published in FY 2001:

Rose, P.E., Benoit, W.R., and Kilbourn, P.M., 2001, The application of the polyaromatic sulfonates as tracers in geothermal reservoirs: *Geothermics*, 30(6), pp. 617-640.

Kleimeyer, J.A., Rose, P.E., and Harris, J.M., 2001, Determination of ultratrace-level fluorescent tracer concentrations in environmental samples using a combination of HPLC separation and laser-excited fluorescence multiwavelength emission detection: application to testing of geothermal well brines: *Applied Spectroscopy*, 55(6), 690-700.

Tracer Test Interpretation Methods for Reservoir Properties

Contract/Grant #: **DE-AC07-99ID13727**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**	
DOE HQ Program Manager: Alan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830	
Contracting Organization U.S. Department of Energy Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** **Name:** G. Mike Shook **Phone:** (208) 526-6945 **Fax:** (208) 526-0875 **E-mail:** ook@inel.gov	
Project Officer / Monitor **Name:** Jay Nathwani **Phone:** (208) 526-0239 **Fax:** (208) 526-5964 **E-mail:** nathwaj@id.doe.gov	**DOE Funding Allocation** $150K	**Cost Share Funding**

Project Objective:

The purpose of this project is to develop tools used to interpret tracer tests and obtain estimates of reservoir and operational parameters for optimizing resource management. The specific parameters that are estimated include reservoir volume and injectate sweep efficiency, thermal velocities arising from injection, and thermal sweep efficiency. The interpretation methods will ultimately be available to industry users in the form of spreadsheet type interpretation tools.

Approach/Background:

Tracer testing in geothermal fields has become somewhat a standard reservoir management tool in recent years, with over 30 tracer tests having been conducted domestically. Tracer tests provide a relatively inexpensive means of interrogating a subsurface formation (e.g., a geothermal reservoir) and determining various properties, such as fluid velocities (effective permeability field), injection sweep efficiency, reservoir pore volume, and the nature of the reservoir boundaries (open or closed, etc.). Injection operations are designed to extract heat from the reservoir rock and transport that energy to extraction wells. Intuitively one knows that the injection will ultimately lead to extraction of cooler fluid, since the injectate is typically much cooler than the fluid in-situ. Therefore, the need also exists to predict thermal velocities (and thus the timing of cooling in extraction wells) from tracer tests.

The approach taken in developing tracer test interpretation methods is to identify relationships between fluid and thermal velocities from analysis of the mass and energy conservation equations. The mean residence time of a tracer provides information regarding the swept reservoir volume; the shape of the tracer recovery curve yields information on the distribution of streamlines within the reservoir. A variable transformation allows the tracer data to be used as a proxy for thermal velocities within the reservoir. These analyses are readily performed in a spreadsheet program (e.g. Excel).

Status/Accomplishments:

For single phase conditions, temperature velocities, v_T, arising from injection of cooler fluids into a geothermal reservoir can be expressed in terms of fluid velocity, v_w, as:

$$v_T = v_w\left(\frac{\varphi\rho_w C_{pw}}{\varphi\rho_w C_{pw} + (1-\varphi)\rho_r C_{pr}}\right) = v_w\left(\frac{1}{1+D_T}\right) \quad \textbf{(1)}$$

Thus, if fluid velocity can be measured, temperature velocities (and therefore timing to the onset of cooling of extracted fluid) is readily estimated. In heterogeneous porous media, fluid velocities are variable, but can be estimated by transforming tracer effluent data. The transformation provides information on the distribution of streamlines within the reservoir, and is written as:

$$T_p(t) = \frac{\int_0^t q(\tau)C(\tau)\ d\tau}{\int_0^\infty q(t)C(t)dt}$$

where T_p is tracer data transformed into a temperature prediction, q is the volumetric flow rate of a given production well, and C is the tracer concentration. The predicted time to the onset of cooling is retarded relative to real time by the reservoir thermal inertia:

$$t^* = t(1 + D_T) = t\left(1 + \frac{(1-\varphi)\rho_r C_{pr}}{\varphi\rho_w C_{pw}}\right)$$

This method was shown to be effective in predicting thermal velocities (and thermal breakthrough in wells) in heterogeneous porous media. Evaluation of thermal velocities in two phase or superheated systems demonstrated that two temperature waves (velocities) exist: an interfacial temperature that is dictated by the extraction pressure followed by the injection temperature. The injection wave velocity can be estimated using the equations given above; the interfacial temperature velocity, v_{Ti}, is a function of the amount of excess heat available in the reservoir, and is given as:

$$v_{Ti} = v_w \frac{\varphi\rho_{wI} L_v}{\varphi\rho_{wI} L_v + (1-\varphi)\rho_R C_{pR}(T_I - T_i)}$$

The only difficulty in applying this equation is that the fluid velocity in two-phase conditions varies both spatially and temporally, and is thus appreciably more difficult to estimate. Work is planned in out years to address this problem.

This method for estimating thermal velocities in single phase liquid systems was also extended to fractured media in FY 01. In a limiting case of fractured media, the fluid travels only through the fracture volume, but heat travels through both the fracture and rock matrix; therefore, an additional retardation term needs to be included to account for the rock matrix. A simple trial function was tested in FY01 as given below:

$$v_T = v_w\left(\frac{1}{1 + D_{T1} + D_{T2}}\right)$$

where

$$D_{T1} = \left[\frac{(1-\varphi)\rho_r C_{pr}}{\varphi\rho_w C_{pw}}\right]_{fr} \quad ; \quad D_{T2} = \left(\frac{V(t)_{ma}\overline{\rho C}_p}{(V_b\varphi)_{fr}\rho_w C_{pw}}\right)$$

D_{T1} is the same as given in Equation 1 above, and is for the fracture domain, and D_{T2} is the thermal inertia associated with heat conduction in the rock matrix. The volume of rock affected, V(t) can be estimated from the "thermal penetration distance" as:

$$V(t) = \int_0^L Wz(x,t)dx = \frac{8}{3} W v_w \sqrt{\kappa} \left(t^{3/2} + \left(\frac{\rho_w C_{pw} b}{K_r} - 1 \right) \left(t - \frac{L}{v_w} \right)^{3/2} \right)$$

Preliminary testing of this function indicated its utility at relatively little cooling (e.g., before effluent cooled more than 40% from its initial temperature).

Planned FY 2002 Milestones:

None are planned. This project is temporarily suspended until FY03.

Major Reports Published in FY 2001:

Shook, G.M., "Thermal Velocities Arising from Injection in 2-Phase and Superheated Reservoirs," **Trans**., 26th Stanford Workshop on Geothermal Reservoir Engineering.

Shook, G.M., "Prediction of Thermal Velocities from Tracer Tests in Fractured Media," Trans., Geothermal Resources Council, V. 25.

Major Articles Published in FY 2001:

Shook, G.M., "Prediction of Thermal Breakthrough in Heterogeneous Media from Tracer Tests," *Geothermics* Vol. 30, pp. 573-589.

Numerical Model Improvement and Support

Contract/Grant #: DE-AC07-99ID13727	**Contract/Grant Period: FY 2001**

Sponsoring Office Code: EE-12	**Performing Organization**
DOE HQ Program Manager: Alan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830
Contracting Organization	**Principal Investigator(s)**
U.S. Department of Energy Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Name:** G. Mike Shook **Phone:** (208) 526-6945 **Fax:** (208) 526-9822 **E-mail:** ook@inel.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Jay Nathwani **Phone:** (208) 526-0239 **Fax:** (208) 526-5964 **E-mail:** nathwaj@id.doe.gov	$50K	

Project Objective:

The objective of this project was to validate and verify the most current version of the TETRAD reservoir numerical simulator, used by a majority of domestic and international geothermal modelers. The version of TETRAD that was evaluated was 13.3. A second objective was to evaluate the need for code enhancements.

Approach/Background:

The review of geothermal reservoir simulators began at the 1978 Stanford Geothermal Workshop, and resulted in the development of a geothermal problem set. The fundamental reason for the review was determine the role of numerical simulators in major investment decisions of geothermal projects. Because of the complexity of multi-phase fluid and energy (heat) flow in geothermal systems, the geothermal industry was concerned about the validity of simulation studies. As a result of the geothermal industry's recommendation that reservoir simulators be benchmarked, a problem set was created. The problem sets were hypothetical reservoir problems designed to test the simulator. The approach of this project was to solve the problem sets with the current version of TETRAD and verify and validate the results. Results of the study were made available to domestic TETRAD users.

Because of the widespread use of TETRAD by the geothermal industry, the INEEL has also been in contact with the various operators to discuss code enhancements desired. These include pre- and post-processing, coupling of reservoir models to geophysical models, and support for short courses.

Status/Accomplishments:

The simulation study on the problems sets first presented at the 1980 Stanford workshop were completed and compared to the solutions obtained with earlier versions of TETRAD. An internal report of the study was prepared. Discussions were held with various domestic geothermal operators to evaluate numerical model upgrades and support needs. These discussions have been instrumental in developing internal priorities.

Planned FY 2002 Milestones:

Major Reports Published in FY 2001:

Internal report of sample problems and data sets.

Major Articles Published in FY 2001:

None

Improved Geothermal Reservoir Management

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Alan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830	
Contracting Organization U.S. Department of Energy Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** **Name:** G. Mike Shook **Phone:** (208) 526-6945 **Fax:** (208) 526-9822 **E-mail:** ook@inel.gov	
Project Officer / Monitor **Name:** Joel Renner **Phone:** (208) 526-9824 **Fax:** (208)-526-0969 **E-mail:** rennerjl@inel.gov	**DOE Funding Allocation** $175K	**Cost Share Funding**

Project Objective:

Tracer tests are conducted regularly in geothermal fields to trace flow pathways. A properly designed and interpreted tracer test can provide quantitative information regarding reservoir volume contacted, and can be used to predict thermal velocities in the subsurface (and therefore thermal breakthrough time). This project demonstrates a method for interpreting tracer test results and obtain estimates of reservoir volume and predict temperature velocities.

Approach/Background:

Reinjection of spent geothermal fluid is a standard field practice that helps maintain reservoir pressure and improve energy extraction. Benefits of reinjection are obvious; however, a poorly-designed injection program can lead to premature cooling of produced fluids and adversely affect power generation. Tracer testing has become a standard operational tool in the past decade. By injecting a tracer with injection fluid, the fluid pathways can be traced and reservoir volume estimated. Analysis of the governing equations further demonstrates that temperature velocies can be predicted from tracer return data. Predicting temperature velocities allows for the estimation of the onset of cooling at extraction wells that arises from injection of cooler fluids. These predictions of thermal breakthrough are typically made well in advance of such cooling, so field operations can be changed to mitigate the effects.

This project has demonstrated a method to quantitatively estimate reservoir flow volume and temperature velocities in heterogeneous, permeable media from tracer test analysis. These methods are being extended to fractured media and two-phase conditions in the current FY.

Status/Accomplishments:

A method for predicting thermal velocities (and thus, time to the onset of cooling of produced fluids) has been derived from mass and energy conservation equations. The derivation shows that temperature velocities are retarded relative to fluid velocities by a constant related to the thermal inertia of the reservoir rock. Various cases were studied that demonstrate the validity of the analytical solution.

Work was begun in FY00 to extend this analysis to fractured media, and to two-phase and superheated conditions. That work is continued in FY01.

Planned FY 2002 Milestones:

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Modeling Production/Injection Strategies in Fracture-Dominated Geothermal Reservoirs

Contract/Grant #: DE-FC07-98ID13621	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Alan Jelacic Phone: (202) 586-6054 Fax: (202) 586-8285 E-mail: allan.jelacic@hq.doe.gov	Mechanical & Nuclear Engineering Department Kansas State University Manhattan, KS 66506
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U.S. Department of Energy Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	Name: Dr. Daniel Swenson Phone: (785) 532-2320 Fax: (785) 532-7057 E-mail: swenson@ksu.edu

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Fax: (208) 526-5964	3/00-3/01 $161K	$7,208
E-mail: creedrj@inel.gov		

Project Objective:

The objective of this project is to improve modeling of flow in fracture-dominated reservoirs. Realistic models of fractured reservoirs are needed because long-term, economic operation of geothermal reservoirs requires that re-injection be used to recharge fluid and recover additional thermal energy. However, flow on fractures can cause short-circuits and prematurely cool the produced fluid. In addition, there is increasing recognition that fractures will often be encountered at commercial reservoir scales and that these fractures will significantly affect flow. Realistic fracture models can help both in designing re-injection strategies and in operation of fractured reservoirs.

In a larger sense, this project complements investments being made in reservoir diagnostic technologies. Significant effort is being applied to improved tracer data, borehole imaging, tomographic imaging (such as Electrical Resistance Tomography), and micro-seismic data analysis. All of these technologies are beginning to make it possible to map major features in a reservoir. When these technologies come to fruition, it will be possible to create a model that incorporates the major features of a reservoir before the reservoir is brought into production. At the same time, future computer power will make it possible to perform complex calculations in a much more routine manner than is now possible. Our goal is to make future reservoir modeling have the same engineering usefulness that structural analysis has today.

Approach/Background:

This research developed a 3D finite element model (Geocrack3D) that explicitly represents the fractures and treats the flow in fractures directly. It uses a high level geometric representation of the reservoir, rather than the traditional mesh-focused representation. That is, the user interactively defines geometric features (the boundaries, wellbores, and fractures) of the reservoir. Geocrack3D automatically stores a valid geometric model that is then independent of the details of how the problem will be meshed and a solution obtained. This was accomplished using a topological representation of geometry and object oriented programming.

The project included numerical model development at Kansas State University, tracer and reservoir analyses at the Energy & Geoscience Institute at the University of Utah, and oversight and industrial collaboration with Oxbow Power Services.

Status/Accomplishments:

The project was completed in September, 2001. The major technical accomplishments include:

1. Use of a Geometric Model to Represent a Reservoir: A geometric model is a high-level, geometry-based representation of an object and was a key component in the development of Geocrack3D.
2. Implementation of Coupled Hydro-Thermal-Structure Finite Element Program: Object-oriented software methods were use to design a finite element program framework to implement solution of the coupled hydro-thermal-structure problem, while allowing extension and application to other problems.
3. Interactive Cross-Platform User Interface: The user interface provides functionality to create the model and to define all the other information needed for an analysis (material properties, boundary conditions, etc.). The interface was implemented in Java, interfacing to a C++ model, to allow cross-platform capability.
4. Meshing of 2D Surfaces and 3D Volumes: Automatic meshing of 2D surfaces and 2D volumes was needed to implement the finite element solution. To accomplish this, we extended 2D and 3D meshing software developed at Cornell University.
5. Matrix Solver: The current implementation uses a banded matrix solver (with bandwidth minimization) to solve the systems of coupled equations. The solver is applicable to symmetric matrices and matrices that have a symmetric structure, but unsymmetric values in the coefficients.
6. Logarithmic Well Element: The solution for flow in the vicinity of a well has a logarithmic pressure distribution. We implemented a new finite element that uses logarithmic shape functions, thus ensuring that the correct analytic solution is obtained near a well.
7. Implementation of Upwinding: When two fractures intersect, the fluid flowing in one fracture can be hot and flow in the other fracture cold. To allow reasonable elements to be used in the 3D mesh, we implemented upwinding in Geocrack3D using the SUPG method described in Mizukami and Hughes, 1985.

A simple application of the program was made to the Dixie Valley reservoir to demonstrate capability. Geocrack2D and Geocrack3D were also used to model the Australian Hot Dry Rock reservoir (Henschke, 2001) and the Soultz-sous-Forets reservoir (Coumou, 2001; Coumou, Harris, and vd Berg, 2001). Geocrack3D is currently being applied to the Hijiori reservoir in Japan.

Collaboration with industry included booths at the 1998, 1999, 2000, and 2001 GRC meetings. International collaboration included presenting three papers at the World Geothermal Congress 2000. In collaboration with Tohoku University, Japan, Professor Takatoshi Ito spent most of August, 2000, at Kansas State University, working with us on Geocrack2D and Geocrack3D. He used Geocrack2D to simulate the effect of changes in temperature on permeability of rock. In addition, the work on Geocrack3D was partially supported as part of the Murphy Project funded by NEDO, Japan. The goal of the Murphy project was to extract more detailed fracture information from the micro-seismic data and use it to create more detailed models of the reservoir.

In addition to the direct focus of the work, this research has resulted in a spin-off application of the technology to develop a pre- and post-processor for the TOUGH2, TETRAD, and STAR programs. This software will be released commercially in 2002.

Planned FY 2002 Milestones:

This research is complete and available on the web at www.mne.ksu.edu/~geocrack. Development is anticipated to continue as part of a proposal submitted headed by the Energy & Geoscience Institute at the University of Utah as part of Enhanced Geothermal Systems research.

Major Reports Published in FY 2001:

Final project report was completed and mailed to sponsors and industry. A user's manual was written and is available on the web.

Major Articles Published in FY 2001:

Liu, Tan and Swenson, Daniel, “An Effective Logarithmic Finite Element for Flow Near a Well,”, Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 29-31, 2001.

Swenson, Daniel, Robert DuTeau, Rovert, and Okabe, Takashi, "Fracture Deformation Effects in Deep-Seated Rock Masses," invited paper and presentation at Int’l Workshop on Potential Thermal Extraction from Deep-Seated Rock Masses, October 25-26, 2001, Tohoku University, Japan.

Development of Multi-Frequency, Multi-Component Electromagnetic Logging Tool for Geothermal Applications

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Lawrence Livermore National Laboratory (LLNL) & EMI Electromagnetic Instruments, Inc. 1301 S. 46th Street, Bldg 300 Richmond, CA 94804
Contracting Organization Lawrence Livermore National Laboratory 7000 East Avenue, P.O. Box 808 L-203 Livermore, CA 94551	**Principal Investigator(s)** **Name:** Mike Wilt (EMI) and Paul W. Kasameyer (LLNL) **Phone:** (510) 232-7997 and (925) 422-6487 **Fax:** (510) 232-7998 and (925) 422-3925 **E-mail:** mike@emiinc.com and kasameyer1@llnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

Electromagnetic Instruments, Inc., LLNL, other DOE labs and universities, are collaborating in a project jointly funded by the California Energy Commission and DOE. We are designing, testing and demonstrating an innovative, high temperature, multi-component, multi-frequency and multi-spacing electromagnetic logging tool for geothermal applications. The tool is designed to allow the detection of anisotropy or anomalous resistivities several meters from the borehole. In addition we are developing software to aid interpretation of data from the tool. The system is called the Geothermal Borehole Induction Tool (GEO-BILT). It will be available for DOE or industry sponsored surveys in geothermal fields.

One DOE strategy for reducing the cost of geothermal production is to improve technologies for well-siting and fracture detection. If it were possible to detect permeable zones near (but not intersected by) a borehole, then operators would know what direction to aim kick-out drilling or where to hydrofracture in order to increase the productivity of geothermal wells. Furthermore, detection of reservoir anisotropy near the wellbore could also provide insights for wellfield operations. There are currently no logging tools that can operate in a geothermal well in order to determine anisotropy or the direction to features at distances of several meters from the borehole.

Approach/Background:

Our approach has four elements, design, manufacture and calibration, field tests and development of interpretation software. These four elements are chosen to produce a functioning demonstrated logging tool concept that can be that can be commercialized by EMI.

Design: Our approach is to design a new and innovative logging tool that is improved by the experience EMI has had building EM logging tools for the Japanese. The main innovation in GEO-BILT is the inclusion of three transmitter orientations along with multiple spacing three component receivers. This design will allow the collection of nine component "vector" data sets needed for the delineation of off-axis structures and anisotropy. In addition, its design would make it more reliable, easier to use, than its predecessor, the MAIL tool.

Manufacture and Calibration: EMI is responsible for the manufacture, calibration and "in-house" testing of the tool components. This effort includes detailed measurements of signals generated by the sources, and environmental tests at high pressure and temperature.

Field trials: LLNL and EMI planned to collaborate on two types of field trials. First, we planned to field existing EM logging tools in a geothermal field in order to gain experience with operational issues and to collect background data to compare the data collection rate and resolution of the new tool with older systems. Second, the GEO-BILT Tool would be tested in three different ways. Initial "shakedown" tests were planned at the Richmond Field Station, adjacent to EMI, where there are boreholes through a well-studied salt and fresh-water section. These tests allowed easy repair and modification to the tool if problems were detected. A second set of tests were planned at a water-flood site in the central valley. Once again, the electrical structure at this site is well known and the performance of the tool can be tested in a realistic setting without the risk of high temperatures and getting the tool stuck in the hole. Finally, the tool would be demonstrated at a geothermal site to be chosen.

Field data Interpretation software: To meet the interpretation needs posed by this complex tool, DOE is supporting LLNL, LBNL, University of Utah, and the University of Wisconsin to develop and enhance software for modeling EM response within complex structures. Much of this work is discussed in other presentations. David Alumbaugh, of the University of Wisconsin, is developing 3-D modeling codes capable of handling arbitrarily complex media. Ki Ha Lee of LBNL is developing software for modeling discrete sheets within a layered space. Al Tripp, of University of Utah, and Hugo Bertete-Aguirre of LLNL are developing codes for examining specific issues such as bore-hole irregularity and excentricity, in the presence of complicated media.

Status/Accomplishments:

We have designed, manufactured and deployed the GEO-BILT system in a non-geothermal environment. The system works efficiently, so that logging can be done rapidly, and results repeat in repeat runs. The vertical coils replicate data from industry-standard well-logging systems, and the horizontal sensors and receivers provide new information,which we are learning how to interpret. Interpretation codes have been developed that indicate the effectiveness of the tool, and a "baseline" dataset with older tools has been collected at Dixie Valley Geothermal Field. Those data will be used to illustrate that added value from the multi-component, multi-received GEO-BILT Tool.

We have only begun to look at data from the field deployments. However it is clear that they indicate the tool works and that it provides information about complex resistivity structures. The GEO-BILT tool is undergoing some final pressure and temperature testing which will be important when we run in a geothermal area.

Planned FY 2002 Milestones:

We plan to deploy the GeoBilt Tool at Dixie Valley, December 2002.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

Kirkendall, B.A., Mallan, R., Wilt, M.J., Osato, K, 2001, Subsurface electrical measurements at Dixie Valley, Nevada, using single-well and surface-to-well induction logging, PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 29-31, 2001

Bertete-Aguirre, H., Al Tripp, E. Cherkaev, The Borehole Environment in Triaxial Induction Logging. PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 29-31, 2001

Field Studies of Geothermal Reservoirs Rio Grande Rift, New Mexico

Contract/Grant #: DE-FG07-98ID13653	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization	**Principal Investigator(s)**
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Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

Prior to this study, the structural settings on regional and local scales for intermediate-temperature geothermal systems in the Rio Grande rift were not well understood. Also, the behaviors of the systems through time were not characterized except for the systems associated with the Valles Caldera area in Jemez Mountains of northern New Mexico. This project defines the main geologic and hydrogeologic characteristics of higher temperature geothermal systems in the rift not associated with a Neogene silicic volcanic center. Field case studies developed by this project will assist efforts to successfully explore and wisely develop "blind" Basin and Range or rift-related and fracture-dominated geothermal systems.

Approach/Background:

Geothermal studies in the Rio Grande rift include the Jemez Pueblo geothermal resource in northern New Mexico and the first detailed and integrated hydrostratigraphic, structural, and alteration studies of three geothermal areas in southern New Mexico. The goal in all four studies areas is to bring the geothermal history and reservoir stratigraphic and structural controls into focus so that development of the resources is facilitated for best uses. The three southern New Mexico areas, Rincon, San Diego (Tonuco) Mountain, and Hillsboro are associated with siliceous sinter deposits of various Pleistocene to Holocene ages and are believed to be intermediate-to-high temperature systems at depth. The Jemez Pueblo low-temperature system is part of the outflow plume of the Valles high-temperature geothermal system.

This project details several concepts that are new to Rio Grande rift geothermal systems. Higher temperature Rio Grande rift systems are bedrock-hosted and occur in structurally-high terrane in normal fault footwalls or horst blocks and are associated with regional rift and local normal fault accommodation or transfer zones. The systems also show a strong pre-rift basement structural setting that is especially well characterized by Laramide (Late Cretaceous -early Tertiary) zones of convergent compressional deformation. Quaternary to late Miocene horst blocks formed by structural inversion and penetrative uplift of up to several km's through mid and early Miocene rift basin interiors show the strongest fracture permeability potential and alteration. These sites have erosionally- and tectonically-stripped aquitards that expose fractured bedrock to form "geohydrologic windows" at relatively low elevations for discharge of geothermal waters associated with deeply-penetrating regional bedrock and "thermally-sweeping" ground water flow systems.

This study documents the temporal and spatial evolution and development of geohydrologic windows for rift geothermal systems with respect to architectural elements of the rift and complementary normal faults and stratigraphy to include older deeply-penetrating pre-rift structures for fracture permeability and reservoir hosts. The systems hydrothermal histories are detailed and compared to Neogene timelines of regional and local geologic development and climate. Finally, a dipole-dipole resistivity survey to determine the lateral and vertical extent of a known shallow geothermal resource at Jemez Pueblo will have use in assessing near-term geothermal direct-use potential for the Pueblo.

Recognition of geohydrologic windows through the use regional subcrop map compilations, coupled to regional drainage and elevation provide a first-order geologic model to predict resource occurrence on regional and intermediate scales. Older Laramide Orogeny northwest-trending convergent zones of compressional deformation where they underlie Neogene geohydrologic windows provide the best local sites for intermediate-to-high temperature geothermal systems in the rift and southern Basin and Range.

Status/Accomplishments:

Geologic mapping and alteration petrography is complete for the Rincon, Hillsboro, and San Diego Mountain areas. Available temperature gradient and heat flow data for the Rincon, Hillsboro, and San Diego Mountain geothermal areas and been compiled and evaluated. These data, when used in conjunction with structural and alteration data, show that local transfer zones along major normal faults are very important in localizing the shallow out flow. The three southern New Mexico areas have received the attention of current industry geothermal exploration and leasing for small-scale binary electrical power generation.

A dipole-dipole resistivity survey of about 4 km^2 of Jemez Pueblo is complete and analysis of the data with existing geologic data and other geophysical survey data show several promising drill targets for production wells. The Jemez Pueblo system will probably be used for a geothermal direct-use by the Jemez Pueblo in the near future.

Planned FY 2002 Milestones:

Project Completed.

Major Reports Published in FY 2001:

None.

Major Articles Published in FY 2001:

None.

II. EXPLORATION AND DRILLING PROJECTS

Exploration

Electromagnetic Methods for Geothermal Exploration

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization	Principal Investigator(s)
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Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

The objective of the proposed research is to develop efficient numerical inversion codes in 2-D and 3-D for mapping high-permeability zones using single-borehole electromagnetic (EM) data. These codes are simple to use and will not require major computational resources, while retaining a reasonable resolution. The work is in conjunction with the rapid development in instrument used for borehole EM surveys in geothermal fields.

Approach/Background:

A simple 2-D inversion code for analyzing data obtained in single borehole configuration was developed and field-tested for routine on-site use. The numerical method adopted is the integral equation method based on the modified extended Born approximation (MEBA). The extended Born, or localized nonlinear approximation (Habashy et al., 1996) of integral equation solution has been applied to inverting single-hole EM data using a cylindrically symmetric model. The MEBA is less accurate than a full solution but superior to the conventional Born approximation. The resulting inversion algorithm is simple enough to be implemented on PCs operated in the field. The efficiency and robustness of a regularized inversion scheme is very much dependent on the proper use of Lagrange multiplier (λ), which is often provided manually to achieve a desired convergence. When the parameter λ is selected as too small, the minimization process tends to reduce the data misfit. This will result in an unstable solution. When λ is chosen too large, the minimization will result in a smooth solution in which the role of measured data is not important in the inversion process. Thus the critical question in solving inversion problems is the selection of the optimal regularization parameter λ. Occam's inversion (Constable et al., 1987) is an excellent method for obtaining a stable inverse solution, but it is extremely slow because many forward simulations are needed to get an optimum regularization parameter. We have implemented an automatic Lagrange multiplier selection scheme in which only three forward modeling results are required at each iteration, thereby greatly improving the utility of the code in handling field data.

References:

Habashy, T.M., Groom, R.M., and Spies, B.R., 1993, Beyond the Born and Rytov approximations: a nonlinear approach to electromagnetic scattering, *J. Geophys. Res.*, 98, 1795-1775.

Constable, S.C., Parker, R.L., and Constable, C.G., 1987, Occam's inversion: A practical algorithm for generating smooth model from EM sounding data, *Geophysics*, 52, 289-300.

Status/Accomplishments:

Electromagnetic Instruments Inc. (EMI) conducted a field test of the newly built Geo-BILT tool (Figure 1) at Lost Hills oil field in southern California operated by Chevron USA in May 2001. As part of the final evaluation of 2-D inversion code, we obtained the data and conducted inversion using only the vertical magnetic fields at 2 m and 5 m separations due to vertical magnetic dipole sources and the result is shown in Figure 2. We assumed a cylindrical symmetry in this test. The same data will be used for future development of the 3-D approximate inversion scheme.

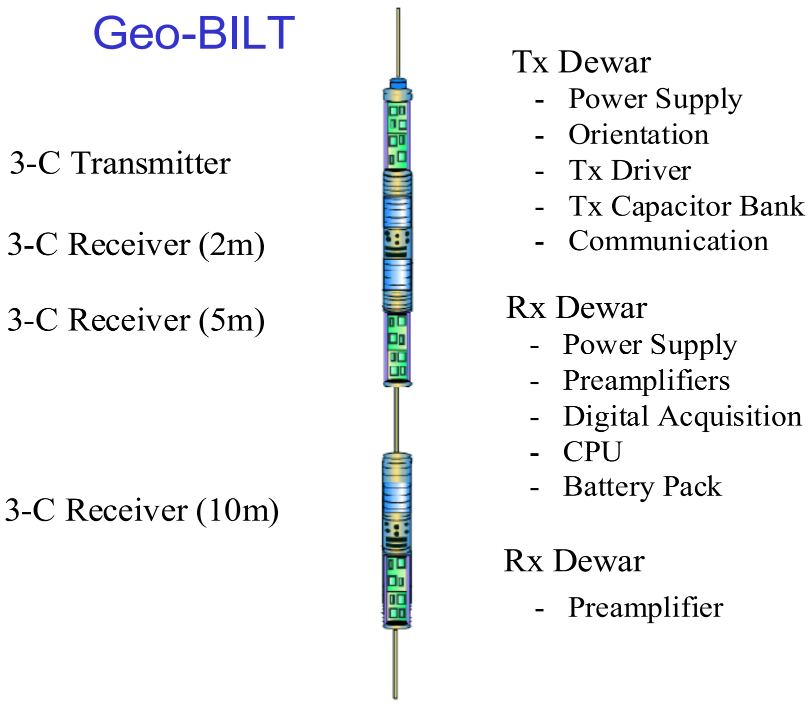

Figure 1. Layout of Geo-BILT

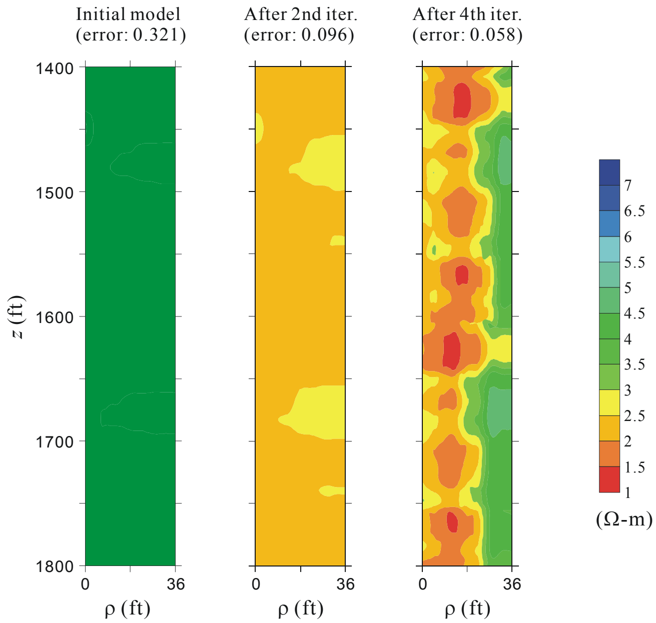

Figure 2. Resistivity obtained from Chevron data

Planned FY 2002 Milestones:

The modified extended Born approximation (MEBA) algorithm will be further modified to investigate 3-D electrical structures in the vicinity of borehole. In principle, the modification has been implemented and tested in dealing with general 3-D EM inversion problems with limited success. Our research plan includes following tasks:

- Further improve modification of the MEBA algorithm in terms of the continuity of current instead of the continuity of electric field
- Take full advantage of the high-temperature Geo-BILT tool, equipped with three-component sources and three-component magnetic sensors at multiple offsets. This unique capability offers full 3-D EM data in a single borehole environment
- Minimize computational requirement so that the inversion can be accomplished on a PC platform

Major Reports Published in FY 2001:

Lee, K.H., Kim, H.J., Tseng, H.-W. and Wilt, M., Electromagnetic Methods for Geothermal Exploration, Annual Meeting of the Geothermal Resources Council (GRC), August 26-29, 2001, San Diego.

Major Articles Published in FY 2001:

Seol, S.J., Suh, J.H., Song, Y., Kim, H.J., and Lee, K.H., 2001, On the potential of fracture imaging using high frequency single-hole EM data, accepted for publication in *Geophysics*.

3-D Seismic Methods for Geothermal Reservoir Exploration and Assessment

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization Lawrence Berkley National Laboratory (LBNL) One Cyclotron Road Berkley, CA 94720	**Principal Investigator(s)** **Name:** E. L. Majer **Phone:** (510) 486-6709 **Fax:** (510) 486-5686 **E-mail:** elmajer@lbl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

The goal of this work is to evaluate the most promising methods and approaches that may be used for improved geothermal exploration and reservoir assessment. It is not a comprehensive review of all seismic methods used to date in geothermal environments. This work was motivated by a need to assess current and developing seismic technology that if applied in geothermal cases may greatly improve the chances for locating new geothermal resources and/or improve assessment of current ones.

Approach/Background:

In the contract period a literature search was conducted and a report written to evaluate the potential of using mainly active seismic methods to image the 3-D properties of currently known and potential geothermal systems. The study concentrated on four different areas: Data acquisition, modeling, improved theory and processing/interpretation.

A wide variety of seismic methods covering the spectrum from DC to kilohertz have been employed at one time or the other in geothermal environments. The reasons have varied from exploration for a heat source to attempting to find individual fractures producing hot fluids. For the purposes of this review we assumed that the overall objective of seismic imaging is for siting wells for successful location of permeable pathways (often fracture permeability) that are controlling flow and transport in naturally fractured reservoirs. The application could be for exploration of new resources or for in-fill/step-out drilling in existing fields. In most geothermal environments the challenge has been to separate the "background" natural complexity and heterogeneity of the matrix from the fracture/fault heterogeneity controlling the fluid flow. Ideally one not only wants to find the fractures, but the fractures that are controlling the flow of the fluids. Evaluated in this work is current state-of-the-art surface (seismic reflection) and borehole seismic methods (Vertical Seismic Profiling (VSP), Crosswell and Single Well) to locate and quantify geothermal reservoir characteristics. The focus is on active methods; the assumption being that accuracy is needed for successful well siting. Passive methods are useful for exploration and detailed monitoring for in-fill drilling, but in general the passive methods lack the precision and accuracy for well siting in new or step out areas. In addition, MEQ activity is usually associated with production, after the field has been taken to a mature state, thus in most cases it is assumed that there is not enough MEQ activity in unproduced areas to accurately find the permeable pathways. The premise of this review is that there may new developments in theory and modeling, as well as in data acquisition and processing, which could make it possible to image the subsurface in much more detail than 15 years ago. New understanding of the effect of fractures on seismic wave propagation are now being applied to image fractures in gas and oil environments. It now may be appropriate to apply these methods, with modifications, to geothermal applications. It is assumed that to implement the appropriate methods an industry coupled program tightly linked to actual field cases, iterating between development and application will be pursued.

Status/Accomplishments:

The main conclusions of the review were to address three main areas:

1. Sensitivity analysis of the different methods in typical geothermal areas
   This activity would include taking a suite of geothermal geologic condition and modeling the effect of various different factors to determine which seismic methods would be the most appropriate. This would be using both discrete and equivalent media approaches. Modeled would be the elastic 3-D response at a variety of frequencies and geometries of data acquisition using P-wave, S-wave single component and multi-component recording. Capability now exits to perform these calculations with many of theoretical responses predicted. The result of this activity would be various designs of possible field acquisition geometries and costs as a function of information gained.

2. Data acquisition
   A variety of methods (surface and borehole) now exist to apply. In most instances surface reflection would be the choice where no boreholes are available. The most likely applications in exploration and early drilling are:
   A. Surface studies
      1) Reflection seismic. AVO, AVA, vs. frequency content with P&S wave, 2-D and 3-D
      2) Tomographic (surface to surface)

   B. VSP
      1) Multicompact sources to 3-components receivers in complex media for same contribution as 1(a).
      2) The borehole to borehole and single well would be included in later phases of development and in-fill drilling, i.e.
         a. P&S wave sources for tomography
         b. Guided wave
         c. Continuity logging
         d. Reflection imaging using AVA, AVO, vs. frequency

   C. Single well studies using both P&S wave for imaging fracture to properties
      1) CDP imaging
      2) Refraction tomography
      3) Guided wave.

3. Processing, interpretation and integration
   The final goal of the seismic work is not to provide images of the subsurface, that is an intermediate goal. The objective is to integrate the work such that an accurate estimation of the flow and transport properties can be derived in order to site wells and optimize production This will require an integrated effort of a variety of seismic methods over a variety of scales. A wide range of different analysis approaches are available, but the focus should be on methods that discriminate between matrix heterogeneity and fracture heterogeneity. As was observed in the oil and gas industry, one can now apply single component and multi-component measurements to determine anisotropy and infer fracture directions. What is needed is further quantification of the subsurface properties, for example while fracture direction is useful, one wants to know the fracture fillings, (gas or water) connectivity, and density.

Planned FY 2002 Milestones:

Implement modeling and processing on existing data sets to apply state-of-the-art thery and methods

Major Reports Published in FY 2001:

3-D Seismic Methods For Geothermal Reservoir Exploration and Assessment , E.L Majer Lawrence Berkley National Laboratory Report, 34 pages, 2001

Major Articles Published in FY 2001:

None

Improving Exploration Models of Andesite-Hosted Geothermal Systems

Contract/Grant #: DE-FG07-00ID13891 Task 2	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Energy & Geoscience Institute 423 Wakara Way, Suite 300 Salt Lake City, UT 84108
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U.S. Department of Energy Idaho Operations Office 850 Energy Drive Idaho Falls, ID 83401	**Name:** Joseph N. Moore **Phone:** (801) 585-6931 **Fax:** (801) 585-3540 **E-mail:** jmoore@egi.utah.edu

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

This project has three major objectives. The primary objective is to reduce the cost of exploration and development by minimizing the number of wells needed and by improving drilling targets. Second, it will lead to improved exploration strategies within the high Cascades, which holds great potential for geothermal development in the U.S. but is still largely untapped and poorly understood. Finally, this information will allow the U.S. industry to remain leaders in geothermal exploration and development. The U.S. geothermal industry has concluded that the best strategy for reducing risk is through a better understanding of the fundamental nature and geology of geothermal resources.

Approach/Background:

Conceptual models provide the framework for essentially all geothermal exploration and development. These models are used to locate and prioritize geothermal systems, site drill holes and predict the characteristics of the reservoir before extensive drilling has occurred. Most of the world's producing geothermal systems are associated with andesite volcanoes. Similar geothermal systems are likely within the Cascades of the western U.S., but this province is still largely untapped and poorly understood.

U. S. geothermal companies specifically requested the investigations being conducted under this five-year program. Our study of Karaha-Telaga Bodas (Indonesia) is a joint effort between the Karaha Bodas Co. LLC (an affiliate of Caithness Energy LLC) while work on Bulalo (Philippines) is a cooperative program with Philippine Geothermal Inc. (a subsidiary of Unocal).

The basic premise behind this investigation is that there are common geologic factors that favor the formation and growth of geothermal systems in specific geologic environments. The geologic factors that are most important will become evident through a comparison of detailed studies of individual systems. Downhole temperature, pressure, production and geochemical data are allowing us to characterize the present-day structures of the geothermal reservoirs. Mineralogic and fluid inclusion studies are providing information on their evolutions. Modeling of the geophysical data is yielding insight into their geometries and heat sources. Satellite images of surface structural trends and alteration zones, thin sections of core and cuttings samples, fracture logging of core holes and electric image logs are being used to characterize permeabilities at different scales. Information on the age of the systems and major hydrothermal events is being obtained from $^{40}Ar/^{39}Ar$ and ^{14}C dating.

The results of these investigations are being critically examined in light of concepts generated from studies of other geothermal systems. In this regard, recently completed investigations of Tiwi, Philippines (Moore et al., 2000a) and The Geysers, U.S. (Moore et al., 2000b, 2001a) are particularly relevant.

Moore, J.N., Powell, T.S., Heizler, M.T. and Norman, D.I. (2000a), "Mineralization and hydrothermal history of the Tiwi geothermal system, Philippines," *Economic Geology*, 95, 1001-1023.

Moore, J.N., Adams, M.C. and Anderson, A. J. (2000b), "The fluid-inclusion and mineralogic record of the transition from liquid- to vapor-dominated conditions in The Geysers geothermal system, California," *Economic Geology*, 95, 1719-1737.

Moore, J.N., Norman, D.I. and Kennedy, B.M. (2001), "Fluid inclusion gas compositions from an active magmatic-hydrothermal system: A case study of The Geysers geothermal field, U.S.A.," *Chemical Geology*, 173, 3-30.

Status/Accomplishments:

Prior to our investigations of Karaha-Telaga Bodas, little was known about this potentially significant resource or about the evolution of vapor-dominated geothermal systems in volcanic terrains. Karaha-Telaga Bodas is associated with Galunggung Volcano in western Java, Indonesia. Exploration of the geothermal system by the Karaha-Bodas Co. LLC was initiated in the mid 1990s. They have provided more than 4 km of core, cuttings from production wells drilled to depths of 3 km, MT and gravity data, the results of downhole pressure, temperature, and gamma-ray surveys, electric image logs, analyses of fluid samples, well-test data, and existing petrographic and geologic information. This is the most comprehensive data set currently available from any andesite-hosted system. Analyses of these data and samples are already providing important new insight into the behavior of volcanic-hosted systems.

A conceptual model of the Karaha-Telaga Bodas geothermal system based on the downhole temperature and pressure measurements was developed. These data indicate that the resource is partially vapor-dominated and that these conditions extend laterally for more than 10 km and vertically to depths below sea level. A liquid-dominated resource with measured temperatures of at least 350°C and low salinities (1-2 weight percent TDS) lies beneath the vapor-dominated regime.

Mineral parageneses, fluid inclusion systematics and ^{14}C dating indicate that the vapor-dominated regime developed very recently. The ^{14}C dating indicates that lakebeds encountered at a depth of 988.8 m were deposited 5910 +/- 76 years BP. These lakebeds predate a period of significant volcano building, high-temperature hydrothermal alteration (>300°C) related to an extensive liquid-dominated system and the development of the modern vapor-dominated regime. This liquid system probably formed in response to the intrusion of quartz diorite that underlies much of the geothermal system. Modeling of the gravity data suggests that the intrusion reached depths of less than 3 km near the Telaga Bodas thermal area.

The transition from a high-temperature liquid-dominated system to vapor-dominated conditions is represented by the widespread deposition of chalcedony and quartz. Fluid inclusions in quartz indicate that the, chalcedony was deposited at temperatures in excess of 250°C. At these temperatures, extreme supersaturation of silica with respect to quartz is required. Continued boiling and escape of the steam resulted in a progressive increase in the salinities of the residual fluids. Fluids with salinities up to 24 weight percent $NaCl-CaCl_2$ equivalent were trapped in the quartz crystals. Catastrophic depressurization and boiling is required to produce chalcedony at temperatures >250°C. Depressurization of the liquid-dominated system could have been triggered by the massive slope failure that produced the crater on Galunggung Volcano. The crater is thought to have formed ~4200 years ago (Katili and Sudradjat, 1984).

As the liquid levels and pressures within the reservoir declined, steam condensate percolated downward. Interactions between the condensate and wall rocks produced advanced argillic alteration assemblages and veins dominated by the successive appearance of anhydrite, pyrite, calcite and fluorite. Fluid inclusions trapped in anhydrite and calcite suggest that temperatures increased again after deposition of the quartz due to renewed magmatic heating. Boiling off of the descending condensate resulted in a progressive increase in its salinity with depth and eventually the deposition of chemical precipitates consisting of NaCl, KCl, $FeCl_x$ and Ti-Si-Fe. The presence of these precipitates demonstrates that the rocks had dried out prior to drilling. Hypersaline fluids trapped in anhydrite at 300°C may record conditions shortly before complete dry out occurred.

The waters encountered in the reservoir rocks underlying the vapor-dominated region could not represent residual liquids remaining after deposition of the chalcedony and quartz. These fluids would have had salinities much greater than the 1-2 weight percent of the produced waters. The low salinity waters most likely represent mixtures of meteoric recharge and descending condensate.

Planned FY 2002 Milestones:

Papers will be prepared on the following topics:

1. The fluid inclusion and mineral evidence for catastrophic boiling at Karaha-Telaga Bodas;
2. The origin of the hydrothermal fluids at Karaha-Telaga Bodas based on fluid inclusion gas analyses; and
3. The mineralogic effects of downward percolating acid-sulfate waters.

Major Articles Published in FY 2001:

Moore, J.N., Allis, R.G. and McCulloch, J.E. (2001), "The origin and development of vapor-dominated geothermal systems," invited presentation, *11th Annual V.M. Goldschmidt Conference*, May 20-24, 2001, Hot Springs, Virginia.

Moore, J.N., Norman, D.I. and Kennedy, B.M. (2001), "Fluid inclusion gas compositions from an active magmatic-hydrothermal system: A case study of The Geysers geothermal field, U.S.A.," *Chemical Geology*, 173, 3-30.

Nemcok, M., McCulloch, J. and Moore, J. (2001), "Stress control of a fractured reservoir: analysis of electrical images and core from the Karaha-Telaga Bodas geothermal system, Indonesia," *Geothermal Resources Council Transactions*, 25, 417-421.

Nemcok, M., McCulloch, J., Nash, G. and Moore, J. (2001), "Fault kinematics in the Karaha-Telaga Bodas, Indonesia, geothermal field: an interpretation tool for remote sensing data," *Geothermal Resources Council Transactions*, 25, 411-416.

Nemcok, M., Moore, J.N., Allis, R. and McCulloch, J. (2001), "Fracture development within a stratovolcano: the Karaha-Telaga Bodas geothermal field, Java volcanic arc," invited presentation, *Symposium on Mechanics of Jointing in the Crust*, Aug. 1-4, 2001, England.

Norman, D.I., Blamey, N. and Moore, J.N. (2001), "Overabundance of gaseous species and the source of organic compounds in geothermal fluids," *Twenty-sixth Workshop on Geothermal Reservoir Engineering*, Stanford University.

Powell, T., Moore, J., DeRocher, T. and McCulloch, J. (2001), "Reservoir geochemistry of the Karaha - Telaga Bodas prospect, Indonesia," *Geothermal Resources Council Transactions*, **25**, 363-367.

Tripp, A., Cherkaev, E. and Moore, J. (2001), "Representation and inductive response of fractal resistivity distributions," *Twenty-sixth Workshop on Geothermal Reservoir Engineering*, Stanford University.

Gas Analysis Of Geothermal Fluid Inclusions: A New Technology For Exploration

Contract/Grant #: **DE-FG07-00ID13953**	**Contract/Grant Period:** **1 July 2000 - 30 June 2002**

Sponsoring Office Code: **EE-12**	**Performing Organization**	
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	New Mexico Institute of Mining and Technology 801 Leroy Place Socorro, NM 87801-8324	
Contracting Organization U.S. Department of Energy Idaho Operations Office 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s)** **Name:** David Norman **Phone:** 505-835-5404 **Fax:** 505-835-6436 **E-mail:** dnorman@nmt.edu	
Project Officer / Monitor **Name:** Jay Nathwani **Phone:** 208-526-0239 **Fax:** 208-526-5964 **E-mail:** nathwaj@id.doe.gov	**DOE Funding Allocation** $180K	**Cost Share Funding** $9K

Project Objective:

Increase our knowledge of gaseous species in geothermal systems by fluid inclusion analysis in order to facilitate the use of gas analysis in geothermal exploration. Specifically

1. Update the New Mexico Tech fluid inclusion gas analysis facility.
2. Validate magmatic N_2-Ar-He-CO_2 ratios.
3. Analyze the volatiles in fluid inclusions studied by Joe Moore.
4. Develop a technology base for the analysis of fluid inclusion organic compounds.
5. Develop simple diagrams, nomograms and mathematic equations for interpretation of fluid inclusion gas analyses.

Approach/Background:

Objective 1:

- Increase number of species measured per crush by development of dual quadrupole system.
- Increase accuracy for H_2, He, and organic species measurement by purchase of a new quadrupole mass spectrometer.
- Increase sensitivity and precision for all species by purchase of diaphragm-backed pump.
- Increase sample throughput by sample changing inlet/crushing system and UPS.

Objective 2: Analyze volcanic gases by the analysis of magmatic gas and magmatic glass inclusions. Choose the best analytical method for accurate analyses.

Objective 3: Perform analyses of all fluid inclusion material worked on by Joe Moore. In addition, gain additional information about the geothermal systems he is studying by analysis of opaque minerals.

Objective 4: Perfect analytical methods of fluid inclusion organic compound analysis. Determine if environmentally sensitive species like benzene occur in geothermal fluids at significant levels. Determine which are the major species.

Perform literature search concerning source rock and type of species evolved from them. Develop methodology, and perform boiling model calculations for the major organic species in order to understand how fluid boiling will fractionate organic species. Test hypothetical models of fluid source and processes against analytical data, geology, and the data and interpretations supplied by Moore.

Objective 5: Experiment with data plots that show relationships between gas geochemistry, fluid processes, and fluid source. Test the plots with geothermal gas analyses, and with the mineralogy, paragenesis, and fluid inclusion microthermometry analyses supplied by Moore. The test for a successful diagram is one that provides new insights into geothermal processes or fluid source.

Status/Accomplishments:

1. The new gas analytical system is completed, calibrated, tested, and the data reduction programs written and working.
2. Completed analysis of sample backlog submitted by Susan Lutz and Joe Moore
3. Completed analysis of 72 of 93 new samples submitted to us by Joe Moore, resulting in about 400 fluid inclusion analyses.
4. Completed work on geothermal organic compounds, and how to interpret analyses for source and process.
5. Have initiated analysis of volcanic gases in fluid inclusions in order to validate magmatic gas ratios, and developed the analytical methods.
6. Have developed 5 new discrimination diagrams for interpreting geothermal gas analyses.

Planned FY 2002 Milestones:

1. Complete the last analyses for Joe Moore.
2. Complete analysis of volcanic gas inclusions.
3. Finish Giggenbach paper
4. Write final report

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

Blamey, N.J.F., and Norman, D.I., 2001, Fluid inclusion evidence for a supercritical magmatic fluid, modified by wall-rock interaction and mixing with meteoric waters: Proceedings 26th Workshop on geothermal reservoir engineering, Stanford Univ., Palo Alto. pp. 243-251.

Norman, D.I., and Blamey, N.J.F., 2001, Overabundance of gaseous species and the source of organic compounds in geothermal fluids: Proceedings 26th Workshop on geothermal reservoir engineering, Stanford Univ., Palo Alto. pp. 235-242.

Moore, J.N., Norman, D.I., and Kennedy, B.M., 2001, Fluid inclusion gas compositions from an active magmatic hydrothermal system: A case of The Geysers geothermal field, USA: Chemical Geology, v. 173, p. 3-30.

Adams, M.C., Moore, J.N., Bjornstad, S., and Norman, D.I., 2001, Geological History of the Coso Geothermal System: Proceedings World Geological Congress, Toyko,

Norman, D.I., and Blamey, 2001, Quantitative Analysis of Fluid Inclusion Volatiles with a Two Mass Spectrometer System: Proceedings ECROFI, Portugal.

Blamey, N.J.F., and Norman, D.I., in press, New Interpretations of Geothermal Fluid Inclusion Volatiles: Ar/He and N_2/Ar ratios - A Better Indicator of Magmatic Volatiles, and Equilibrium Gas Geothermometry: (submitted to 27th Workshop on geothermal reservoir engineering, Stanford Univ., Palo Alto)

Norman, D.I., and Blamey, N.J.F., in press, Interpreting geothermal processes and fluid sources from fluid inclusion organic compounds and CO2/N2 ratios: (submitted to 27th Workshop on geothermal reservoir engineering, Stanford Univ., Palo Alto)

Lutz, S.J., Moore, J.N., Blamey, N.J.F., and Norman, D.I., in press, Fluid-Inclusion Gas Chemistry of the Dixie Valley (NV) Geothermal System: (submitted to 27th Workshop on geothermal reservoir engineering, Stanford Univ., Palo Alto)

Hyperspectral Geobotanical Remote Sensing for Geothermal Resource Exploration

Contract/Grant #:	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	UC Santa Cruz 1156 High Street Santa Cruz, CA 95064
Contracting Organization University of California	**Principal Investigator(s)** **Name:** William L. Pickles **Phone:** (925) 422-7812 **Fax:** (925) 423-7914 **E-mail:** pickles1@llnl.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Paul Kasameyer **Phone:** (925) 422-6487 **Fax:** (925) 422-3925 **E-mail:** kasameyer1@llnl.gov	$82K	**$50K**

Project Objective:

To develop new hyperspectral remote sensing imagery methods for geothermal resource exploration. We are developing geobotanical hyperspectral remote sensing tools for finding subtle signatures, of geothermal resources. Examples of some of the signatures are: hidden faults, elevated soil temperatures at plant root depth, geothermal waters in springs and rivers, altered minerals, plant species mix alteration, plant health, and CO_2 emissions.

Approach/Background:

For the last three years, we have been developing geobotanical remote sensing tools for finding subtle signatures of geothermal resources. Our group is a collaboration between LLNL and UC Santa Cruz (UCSC). It is a multidisciplinary group with Dr. William L. Pickles, an LLNL physicist, Professor Donald C. Potts, a UCSC professor of Biology, and Professor Eli A. Silver, Professor of Geology. There are five graduate students at UCSC in our group. Ms Brigette A. Martini, a Ph. D. graduate student at UCSC, has taken the lead in developing the geobotanical remote sensing techniques at Mammoth Mountain CA and in the Long Valley caldera as part of her Ph. D thesis. The methods we are developing use hyperspectral airborne visible and near infrared imagery with 3 to 5 meter spatial resolution.

The hyperspectral geobotanical remote sensing techniques that we are developing use advanced commercial airborne imaging spectrometer systems available in the USA and worldwide. The system that we normally contract for in overhead imaging missions produces visible and near IR reflected light images with spatial resolution of 1 to 5 meters in 128 wavelength bands. Please see http://www.hyvista.com/ The average spatial resolution of about 3 meters allows us to detect and discriminate individual species of plants as well as the complexities of the geological and man made objects in the images. We then can interpret the observed plant species distributions and their relative health along with a detailed understanding of the local geology, and the local human activities. We are able to distinguish terrestrial and aquatic plant species, all types of geological formations and soil types, and many different types of human activities. We can then look for biological impacts of geothermal water and soil temperature at plant root depth, CO2 releases, altered minerals, plant species mix modifications around geothermal springs and distinctive algae growth in geothermal springs in large complicated areas. These techniques do not require before and after imagery because they use the spatial patterns of plant species and health variations, and plant life cycle modifications, present in the one image to detect and discriminate geothermal surface signatures.

Status/Accomplishments:

This program was completed at the end of FY 01.

Recently work that was started by the LLNL Geothermal Program three years ago to develop visible and near IR hyperspectral imaging for mapping subtle geobotanical surface expressions of geothermal systems has shown great promise. The results of this research has given us encouragement that we can explore for hidden surface expressions to extend known geothermal areas and to discover new ones. An overview of the newly emerging field of hyperspectral geobotanical remote sensing and the collaborative team at LLNL and University of California Santa Cruz developing these techniques can be viewed at http://emerald.ucsc.edu/~hyperwww/ and http://emerald.ucsc.edu/~hyperwww/proj.html

The promising new results that include the discovery of hidden faults at Mammoth Mountain can be viewed at http://emerald.ucsc.edu/~hyperwww/mammoth.html and are summarized below.

On September 7, 1999, seven LLNL-funded lines of hyperspectral data were flown of the caldera with the HyMap instrument (Integrated Spectronics, Ltd.), satisfying our initial objective to acquire higher spatial resolution imagery than previously available.

The Long Valley dataset samples reflectance is from 400 to 2500 nm, in 126 separate but contiguous bands. Each pixel is from 3-5 m in dimension and the signal-to-noise is reportedly greater than 1000:1. The atmospherically corrected images were processed spectrally using an algorithm called the Minimum Noise Fraction (MNF), and spatially using the Purest Pixel Index (PPI) algorithm contained within the software program ENVI. The goal in this processing is to isolate spectrally pure endmembers of earth materials for use in an array of supervised classifications and unmixing algorithms.

The presence of alunite in particular, indicates a high acid-sulfate temperature and low pH, in agreement with the hypothesis that a high temperature hydrothermal reservoir exists beneath Mammoth Mt.

The northeast-trending fault that we see spectroscopically on the southwestern flank, is consistent with faults mapped just to the northeast of Mammoth Mt. in the Discovery Fault Zone. In addition, regional northeast-trending structures can be found to the south in the Deep Springs Fault Zone, to the northeast in the Excelsior Mountains, and to the north in the Bodie Hills. Local minimum compressive stress in the western caldera is orientated NW-SE and the 1989 dike intrusion beneath Mammoth was orientated approximately N20E and lay beneath the southwestern flank. We interpret these NE-trending faults as part of a rotational fault system slipping left-laterally in a larger NW-trending system of right shear. This kinematic pattern results in local extension along the NE-trending faults and easier egress of both magma and geothermal fluids in the Long Valley caldera and in other geothermal systems associated with the Eastern California Shear zone.

The effect of volcanic phenomena on caldera ecosystems is also studied. Biological-geological interactions can be identified and mapped such as a spectral-based tree-kill map. Massive magmatic CO2-induced tree kills were initiated in 1989 after the dike intrusion event mentioned previously. Since 1989, over 50 hectares of trees have died surrounding the volcano.

The Horseshoe Lake Tree-kill is the site of highest flux on the mountain with approximately 100 tons/day fluxing diffusively out of the ground (http://quake.wr.usgs.gov/VOLCANOES/LongValley/CO2.html). Spectral signatures of healthy robust trees, dead trees, and physiologically stressed trees were extracted from the imagery and used in several mapping schemes. The kill itself was mapped, including transitional zones of sub-morbid populations. Maps showed the comparison of the kill boundaries as mapped by traditional field methods and via hyperspectral data analysis. Such maps are available for other kill regions on the volcano.

The examples show that hyperspectral data can provide geological and biological information about a system quickly, synoptically and without a host of other ground-based monitoring programs. This makes it an attractive tool for studying other calderas and other geothermal areas. The signatures developed would be combined with basic maps as well as seismic, GPS, and geochemical monitoring programs.

The expense of hyperspectral data will likely decrease once such instruments are spaceborne. The computational requirements of these techniques are easily met with the WIN NT 4.0 or WIN 2000 workstations and laptops currently available from vendors such as Dell or Gateway.

These new techniques developed by Brigette A. Martini as part of her Ph. D. thesis have shown that the need for intensive fieldwork on the ground is eliminated.

Planned FY 2002 Milestones:

We are starting a follow on program that will determine, the most interesting areas in the Basin and Range and in the Cascades, and the most appropriate remotesensing methods for these areas to provide detailed accurate surface geobotanical signatures for geothermal resource mapping.

Major Reports Published in FY 2001:

William L. Pickles, Hyperspectral Geobotanical Remote Sensing for Geothermal Resource Exploration, U.S. Department of Energy Geothermal Energy Program Geoscience Peer Review, August 2001

Major Articles Published in FY 2001:

Pickles, W.L., P. W. Kasameyer, B. A. Martini, D. C. Potts, E. A. Silver, Geobotanical Remote Sensing for Geothermal Exploration, Geothermal Resources Council Transactions, Volume 25, page 307, August 26, 2001

Martini, B.A., Silver, E.A., Potts, D.C., Pickles, and W.L. (2000). Insights into the Hydrothermal, Magmatic, and Structural Systems of a Restless Caldera, Long Valley Caldera, CA, USA, Proceedings of the Fourteenth International Conference on Applied Geologic Remote Sensing. p. 28-35

B. A. Martini, E. A. Silver, W. L. Pickles, (2000) “Hyperspectral Remote Sensing for Research and Monitoring in Active Volcanic Regions”, American Geophysical Union (AGU), San Francisco, paper V22F-05, December, 2000

Brigette A. Martini, Eli A. Silver, Donald C. Potts, (2001), Hyperspectral Remote Sensing in Long Valley Caldera: Issues of Scale, Resolution, and Signal to Noise, Summaries of the Tenth JPL Airborne EarthScience Workshop, NASA JPL, Pasadena CA, February 27-March 2, 2001

Brigette A. Martini, Eli A. Silver, New Prospectives on Old Problems, Hyperspectral Imaging an Active Volcanic Environment, Long Valley Caldera CA, USA, Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, IGARSS 2001, Sydney Australia, August 2001

Resistivity Measurement and Interpretation for Geothermal Applications

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Lawrence Livermore National Laboratory (LLNL) 7000 East Avenue, P.O. Box 808 L-203 Livermore, CA 94551
Contracting Organization Lawrence Livermore National Laboratory (LLNL) 7000 East Avenue, P.O. Box 808 L-203 Livermore, CA 94551	**Principal Investigator(s)** **Name:** Jeff Roberts and Brian Bonner **Phone:** (925) 422-7108 **Fax:** (925) 423-1057 **E-mail:** roberts17@llnl.gov and bonner1@llnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Paul Kasameyer **Phone:** (925) 422-6487 **Fax:** (925) 422-3925 **E-mail:** kasameyer1@llnl.gov	$205K	

Project Objective:

The objective of this project is to make laboratory electrical measurements of fractured and intact volcanic geothermal host rocks at a variety of reservoir conditions including temperature, confining and pore pressure, and fluid saturants. These physical properties measurements and data will be applied by combining the new laboratory results with results from a very well constrained field test funded by the Yucca Mountain Project (YMP). The objective of combining the laboratory and field results is to develop the means of inverting field electrical measurements for quantitative saturation and fracture detection.

Approach/Background:

We conduct laboratory studies of intact and fractured geothermal rocks and model materials at reservoir conditions to determine how electrical anomalies can be used to locate and track zones of high fluid permeability. Direct measurements of the temperature dependence of resistivity for liquid saturation of appropriate lithologies are necessary to relate laboratory measurements to the field and to invert field electrical data for quantitative determinations of saturation. The development of models of changing saturation and the interaction of fluids in the fractures and the matrix is necessary to develop fracture detection techniques based on electrical geophysical surveys.

Analysis of field measurements of fluid infiltration and thermally driven water transport in a large block of tuff at Fran Ridge Nevada will determine if fractures can be detected with electrical methods under conditions where the ground truth is known. Laboratory resistivity measurements will be used in the interpretation and then extrapolated to reservoir temperatures to determine if the resistivity contrast between fractured regions and matrix persist at reservoir conditions.

Status/Accomplishments:

The primary results for FY2001 can be summarized in three main points.

1. Laboratory electrical measurements were performed on intact and fractured rocks at temperatures up to 185°C at a variety of saturations. Both intact and fractured rocks were studied and the resistivity contrast between intact and fractured rocks was determined.

2. Based on the laboratory data, a resistivity model including temperature and saturation dependence was developed.

3. The field electrical resistance tomography data of the large block test were inverted for quantitative determinations of saturation and agreed well with other saturation determinations, and regions of rapidly changing saturation were located based on the inversion results. These locations were correlated with fluid movement on active fractures.

Conclusions. Laboratory measurements of electrical resistivity were performed on representative geothermal reservoir rocks. Measurements on intact rocks as functions of saturation and temperatures up to 145°C were used to calculate saturation changes in a 3 X 3 X 4.5 m heated rock mass. The resulting constitutive model permits the prediction of electrical resistivity at temperatures up to 200°C, assuming no change in conduction mechanism. Measurements on rocks with synthetic propped fractures reinforce the idea that electrical measurements provide a means for fracture detection. The resistivity contrast after boiling appears to be relatively insensitive to fracture aperture but may increase with accessible fracture surface area.

The time-lapse field ERT measurements at the Large Block Test (LBT) were used in combination with a laboratory-derived model to image dynamic saturation changes. The results were confirmed by comparing with saturations determined by independent geophysical tests such as neutron logging. Fractures can be detected by locating the regions of highest resistivity contrast. The time dependence of the resistivity contrast is useful for monitoring fluid migration from fractures into the matrix. A rewetting episode attributable to mechanical displacement of a fracture was observed during the LBT. These results are applicable to fracture detection in other rock types and other field areas.

Planned FY 2002 Milestones:

Additional laboratory measurements of resistivity of fractured rocks at reservoir conditions are necessary to complete this project. Rocks to be examined include core from reservoirs containing natural and mineralized fractures. A critical aspect of this work will be the time dependent electrical properties. Models of fracture flow and fracture matrix interaction matrix saturation as a function of pore pressure are planned for the coming year. These studies will focus on fracture permeability and mineral evolution and the effect these properties have on matrix re-wetting. Electrical properties are an ideal exploration and analysis tool because of their sensitivity to saturation and temperature changes.

FY 2002 results will be presented at the GRC Annual meeting and published in GRC Transactions.

Major Reports Published in FY 2001:

Roberts, J.J., Bonner, B.P., and Kasameyer, P. W., Electrical Resistivity Measurements of Intact and Fractured Geothermal Reservoir Rocks, Twenty Sixth Annual Stanford Geothermal Reservoir Engineering Workshop, 2001.

Major Articles Published in FY 2001:

Roberts, J. J., A. Ramirez, S. Carlson, W. Ralph, W. Daily, and B. P. Bonner, Laboratory and field measurements of electrical resistivity to determine saturation and detect fractures in a heated rock mass, Geothermal Resources Council, Transactions, 25, 681-686, 2001, also Rep. UCRL-JC-143220, Lawrence Livermore National Laboratory, Livermore, CA, 2001.

Roberts, J. J., A. G. Duba, B. P. Bonner, and P. Kasameyer, The effects of capillarity on electrical resistivity during boiling in metashale from scientific corehole SB-15-D, The Geysers, California, USA, Geothermics, 30, 235-254, 2001.

Structural Geology and Geophysics at Dixie Valley, Nevada

Contract/Grant #:	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
DOE HQ Program Manager: Alan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	INEEL Geosciences Research Department 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830
Contracting Organization INEEL Geosciences Research Department 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830	**Principal Investigator(s)** **Name:** Richard P. Smith **Phone:** (208) 526-9896 **Fax:** (208) 526-0875 **E-mail:** rps2@inel.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Jay Nathwani **Phone:** (208) 526-0239 **Fax:** (208) 526-5964 **E-mail:** nathwaj@id.doe.gov		

Project Objective:

Develop a defensible conceptual understanding of the extensional faulting in Dixie Valley and plans for additional geophysical investigations to resolve remaining problems.

Approach/Background:

In previous years, work by David Blackwell on detailed gravity surveys of the area and on temperature logs of new boreholes suggested that a single-fault model for the transition from the Stillwater Range to the downdropped Dixie Valley is not the preferred conceptual model. Field work during FY2000 confirmed this suggestion because abundant geological evidence exists for multiple faults. The approach for this year is to synthesize the geologic information from last year's geologic mapping campaign, information from published literature, and information from existing geophysical surveys to more accurately define the structural setting of the producing reservoir and to develop strategies for more successful exploration for additional geothermal reservoirs in the area.

Status/Accomplishments:

1. Produced synthesis map of geologic and geophysical features in GIS format.
2. Wrote draft of a paper for presentation to the GRC Annual Meeting in August. Paper in review and revision now.
3. Developed a strategy for additional geophysical investigations in the area and obtained a proposal and cost estimate from USGS for a high-resolution aeromagnetic of Dixie Valley to provide a totally independent data-set with a high probability of revealing positions of subsurface faults.

Planned FY 2002 Milestones:

1. Complete interpretations of surface geophysical surveys by the end of April
2. Incorporate borehole lithology and borehole geophysics into the synthesis by end of July.
3. Develop strategy for additional drilling by September 2001.
4. Prepare a manuscript for publication in peer-reviewed journal by September 30.

Major Reports Published in FY 2001:

GIS map entitled "Structure of Dixie Valley, Nevada."

Major Articles Published in FY 2001:

Geologic and geophysical evidence for intra-basin and footwall faulting at Dixie Valley, Nevada; Paper in review for GRC Annual Meeting

FY 2002 – Paper with a similar title for publication in peer-reviewed journal.

Enhanced Data Acquisition and Inversion for Electrical Resistivity Structure in Geothermal Exploration and Reservoir Assessment

Contract/Grant #: DE-FG07-00ID13891, Task 4	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: EE-12	**Performing Organization**	
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	University of Utah Energy & Geoscience Institute 423 Wakara Way, Suite 300 Salt Lake City, UT 84108	
Contracting Organization	**Principal Investigator(s)**	
U.S. Department of Energy Idaho Operations Office 850 Energy Drive Idaho Falls, ID 83401	**Name:** Philip E. Wannamaker **Phone:** (801) 581-3547 **Fax:** (801) 585-3540 **E-mail:** pewanna@egi.utah.edu	
Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Jay Nathwani **Phone:** (208) 526-0239 **Fax:** (208) 526-5964 **E-mail:** nathwaj@id.doe.gov	$286K	

Project Objective:

Our efforts are aimed at reduced drilling costs and increased reservoir base through more reliable technology for exploration and enhanced geothermal systems. Progress requires improvements in density and quality of field EM data, developing refined electrical models and EM modeling algorithms for the geothermal environment, and incorporating independent geological data in cooperative interpretations for EM data. For imaging subsurface resistivity structure, several modes of EM propagation have been used ranging from man-made sources in the time-domain to natural and artificial sources in the frequency domain. Due to the depth of exploration potential and the likelihood of substantial advances in data quality and imaging capability as proposed herein, we are emphasizing the magnetotelluric (MT), CSAMT, and galvanic (DC) resistivity/IP methods. This approach also exploits emergence of new-generation array collection instrumentation for simultaneous MT-DC surveying.

Approach/Background:

One way to improve resistivity structural resolution is by developments in non-linear 2-D inversion of magnetotelluric (MT/CSAMT) and DC resistivity/IP responses. The standard approach is to minimize an objective function $W_\lambda(m)$ which is a weighted sum of data misfit and departure from *a priori* information:

$$W_\lambda(m) = \{(d-F[m])^T C_d^{-1}(d-F[m])\} + \lambda\{(m-m_o)^T C_m^{-1}(m-m_o)\}$$

The inversion of diffusive EM data must be stabilized, and the particular approach is embodied in the choice of the form of C_m. Our novel method is model-adaptive and exploits basic resolution principles of electrical methods such as similitude and fundamental correlations (e.g., conductivity-dimension) to avoid model artifacts, instead of using brute-force smoothing by damping slope or curvature.

Geothermal systems and other earth structure of course can be 3-D so we pursue this modeling capability as well. For adapting our own techniques and allowing efficient technology transfer, we require a straightforward, freely available source code. We have been cooperating with Y. Sasaki of Kyushu University who has provided such a program, implementing the 2nd-order, E-field staggered grid formulation (Smith, 1996; Alumbaugh et al., 1996; Sasaki, 1999, 2001). Currently, we are modifying and applying this algorithm to temporal changes in resistivity structure of geothermal fields with production over time, as described below. Prototype finite EM source and inversion capability have been tested also, and we will be improving upon those.

As a complement to commercial surveying capability, we are completing a multi-station field MT system with unique modes of acquisition and processing which is aimed particularly at eliminating man-made EM interference in already-producing geothermal systems. Increases in productivity and data accuracy are sought through simultaneous band acquisition with multi-site control via digital radio telemetry. We have been formulating a more complete MT noise model for the problem where noises on the inputs (H) and output (E) are correlated.

Status/Accomplishments:

Inversion tests for the 2-D MT case have been run on several sample data sets from Nevada, Utah and New Zealand. In a prominent example from northern Nevada, electrical structures associated with the altered/carbonized ore zone and the silicified carbonates have been confirmed by excavation or drilling. A prototype pole-dipole, DC 2-D inversion program utilizing analogous regularization principles has recently been completed. Program structuring is underway for joint inversion, desirable since the two methods have differing resolving capability when it comes to conductive versus resistive structures.

An example simulation using our 3-D modeling algorithm was given in previous quarterlies for the Oguni system, in cooperation with John Pritchett of SAIC using the STAR P-T-X reservoir simulator. Input to the simulator includes ambient (t = 0) P-T-fluid composition-permeability conditions from available drilling and sampling, together with laboratory data on electrical properties of fluids and bulk mixtures versus P-T-X. After 50 years of production, simulated increases in apparent resistivity due to steam formation and cooler water reinjection reach 40% beyond the initial (t = 0) response, and should be readily detectable in careful repeat MT surveys.

The overall design of the U. Utah/EGI MT system is essentially finished and we are dealing currently with the engineering details to implement the system. The power supply units, interface boards to integrate E-field pre-amplifiers, channel cards, and E-field junction cases for low-impedance measurements are built. Firmware development is advanced in the areas of A/D control, timing control, custom high-speed synchronous serial data links, and paged memory communications protocols. A set of 900 MHz low-power digital spread-spectrum radios was acquired and tested to provide a low-power data telemetry option for system operations. Capability has been developed to measure accurately in ultra-high impedance environments (e.g., recent volcanics). We have developed a complete noise model for such systems which allows separation of non-plane wave noise transfer functions from the MT plane-wave function of primary interest, and implemented three-stage, combined coherence-sorting/jackknife outlier removal.

Planned FY 2002 Milestones:

Current two-dimensional inversion technology will be generalized to joint MT/DC applications, which are complementary in their resolution of subsurface structures. Quantech Geoscience Inc. has recently fielded a system acquiring array MT and DC measurements simultaneously, and we will apply this new-generation system and our inversion capability to basic structural and resource problems at the Dixie Valley thermal area. We will be modifying the prototype finite source 3-D code by incorporating the accurate and versatile Green's functions from our long-standing integral equations algorithm. Our inversion approach will be able to accommodate the results of focused electrical array research by A. Tripp, also supported by DOE/OWGT. It is our intention to provide a compact, easy-to-use 3-D platform which is completely in the public domain for both private and academic use.

Major Reports Published in FY 2001:

We opt for peer-review publications.

Major Articles Published in FY 2001:

Wannamaker, P. E., P. P. DeLugao, and J. A. Stodt, 2001a, Two-dimensional inversion of magnetotelluric data using a-priori models and resolution principles of diffusive electromagnetics, Geophys. J. Int., in prep.

Wannamaker, P. E. , J. M. Bartley, A. F. Sheehan, C. H. Jones, A. R. Lowry, Trevor A. Dumitru, Todd A. Ehlers, W. S. Holbrook, G. L. Farmer, M. J. Unsworth, D. B. Hall, D. S. Chapman, D. A. Okaya, B. E. John, and J. A. Wolfe, 2001c, Great Basin-Colorado Plateau transition in central Utah: An interface between active extension and stable interior, in The Geological Transition: Colorado Plateau to Basin and Range, Proc. J. Hoover Mackin Symposium, ed. by M. C. Erskine, J. E. Faulds, J. M. Bartley and P. Rowley, Utah Geol. Assoc./Amer. Assoc. Petr. Geol. Guideb. 30/GB78, Cedar City, Utah, September 20-23, 1-38.

Wannamaker, P. E. , G. R. Jiracek, J. A. Stodt, T. G. Caldwell, A. D. Porter, V. M. Gonzalez, and J. D. McKnight, 2001b, Fluid generation and movement beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric (MT) data, J. Geophys. Res., in press.

Wannamaker, P. E., and W. M. Doerner, 2001, Crustal structure of the Ruby Mountains and southern Carlin trend region, northeastern Nevada, from magnetotelluric data, Ore Geology Reviews, in press.

Recency of Faulting and Neotectonic Framework in the Dixie Valley, Nevada Geothermal Field and Other Geothermal Fields in the Basin and Range

Contract/Grant #: DE-FG07-00ID13891, Task 4	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**	
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	University of Nevada, Reno San Francisco State University	
Contracting Organization Center for Neotectonic Studies MS 169 University of Nevada, Reno Reno, NV 89557	**Principal Investigator(s)** **Name:** Steven G. Wesnousky **Phone:** (775) 784-6067 **Fax:** (775) 784-1382 **E-mail:** stevew@seismo.unr.edu	
Project Officer / Monitor **Name:** Carol Von Lente **Phone:** (208) 526-1534 **Fax:** (208) 526-5548 **E-mail:** vanlencl@ida.doe.gov	**DOE Funding Allocation** $212K	**Cost Share Funding**

Project Objective:

The motivation of this project is to understand factors controlling the location of mineable geothermal fields in Nevada. It is generally recognized that springs and geothermal fields are commonly located along or in close proximity to active faults. Critical to the potential of active geothermal fields are physical conditions that maintain pathways for fluid flow. We hypothesize that, in addition to simply the presence of active faults, that the past history of earthquakes and the resultant redistribution of stresses in the earth's crust plays a role in controlling the stresses that maintain pathways for fluid flow and, hence, the location of mineable geothermal sites along active fault zones. Toward examining this hypothesis, we have mapped the geometry of active faults and examined the paleoearthquake history along faults in the vicinity of the Dixie Valley, Beowawe, and Brady geothermal electric power generating sites in Nevada.

Approach/Background:

Our approach has been to map Quaternary deposits and emplace trenches along active faults in the vicinity of each of the power plants to define both the geometry and paleoearthquake history of the faults. The purpose of the observations is to define the timing and rupture extent of past earthquakes on faults in the vicinity of the power plants. Elastic dislocation models are then constructed to incorporate the past history of events in the region and compute stress changes and, in particular, the Coulomb Failure Function, in the region of the power plant sites.

Status/Accomplishments:

We have finished our initial mapping, geomorphic analysis, and paleoearthquake studies at each of the localities. We are currently awaiting completion of laboratory analysis of samples collected to date geologic deposits and, hence, place better limits on the age of past earthquakes in the Beowawe and Brady areas. We observe in each area that, although each site is clearly located along an active fault, it is not so clear that the sections of fault with the power plants ruptured in the most recent earthquakes. When modeling our observations, we find that the paleoearthquake history of fault ruptures has moved the faults in the vicinity of the power plants closer to failure. This may provide a mechanism for keeping fluid pathways open and, in part, explain the present location of the successful geothermal facilities.

Planned FY 2002 Milestones:

We will this spring and summer to finish our analysis and synthesize our results to be published to the broader scientific community in a professional journal article and to present at the annual 2003 Workshop on Geothermal Reservoir Engineering.

Major Reports Published in FY 2001:

Lutz, S. J., S. J. Caskey, D.D. Mildenhall, P.R.L. Browne, and S.D. Johnson, Dating Sinter Deposits in Northern Dixie Valley, Nevada-The Paleoseismic Record and Implications for the Dixie Valley Geothermal System. PROCEEDINGS, Twenty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 28-30, 2002.

Major Articles Published in FY 2001:

None

Geothermal Resources Exploration and Definition

Contract/Grant #: DE-AC04--94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
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Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s):** **Name:** Norman R. Warpinski **Phone:** (505) 844-3640 **Fax:** (505) 844-7354 **E-mail:** nrwarpi@sandia.gov	
Project Officer / Monitor **Name:** Dan Sanchez **Phone:** (505) 845-4417 **Fax:** **E-mail:** dsanchez@doeal.gov	**DOE Funding Allocation** $1,500K(DOE awards to industry) $175K (Sandia support)	**Cost Share Funding** 80/20 cost sharing on industry awards

Project Objective:

The Geothermal Resource Exploration and Definition (GRED) project is a cooperative DOE/industry project to find, evaluate, and define additional geothermal resources throughout the western United States. The ultimate goal is to aid in the development of geographically diverse geothermal resources and increase electrical power generation from geothermal resources in the continental United States. This is accomplished through cost-share cooperative agreements between DOE and private industry to minimize the risk in locating and testing new resources.

Approach/Background:

The project was initiated in April 2000 with a solicitation for industry participation. Proposals were evaluated in July 2000, and seven successful candidates were notified in August 2000. While the awards are provided directly by DOE, Sandia National Laboratories provides technical oversight over the projects and some limited support for appropriate activities. Current awardees are (1) Mt. Wheeler Power Co., Rye Patch NV project, (2) Noramex Corp., Blue Mountain NV project, (3) Utah Municipal Power Agency, Cove Fort, UT project, (4) Calpine's Siskiyou Geothermal Partners LP, Fourmile Hill, CA project, (5) SB Geo, Inc, Steamboat Springs, NV project, (6) Coso Operating Company LLC, U-Boat, NV project and (7) Lightning Dock Geothermal Inc., Lightning Dock, NM project.

Projects are divided into three phases consisting of geophysical exploration, drilling of a test well, and evaluation of the well performance. In Phase I, the awardees have the opportunity to perform sufficient geophysics to select an optimum drill site. However, some projects are sufficiently advanced that no additional exploration work is required and only an exploration report is needed to document the site potential. In Phase II, a test well is drilled, cored, logged and otherwise evaluated. In Phase III, detailed testing of the resource is performed.

Status/Accomplishments:

The Nevada Rye Patch project focuses on the development of an abandoned high-temperature geothermal site. Subsequent geophysical work has identified two target sites that could be sufficient to power the plant. Phase II was completed by re-entering a pre-existing shallow well that had severe lost-circulation problems, using new foam technology to seal off the zone, and continued drilling to the target depth of 2110 ft, penetrating a limestone reservoir. An initial flow test was run that gave excellent results and additional evaluation will be performed during Phase III testing in FY02.

The Nevada Blue Mountain project is a geothermal site that was identified during gold exploration. A 2,000 ft well will be drilled to confirm the existence of a high-temperature geothermal reservoir associated with overlapping spontaneous potential, resistivity, and shallow temperature gradient anomalies, and to determine the reservoir's production characteristics. It is expected that drilling should start in mid-winter.

The Utah Cove Fort/Sulphurdale project is concerned with locating and drilling a test well to explore the western extension of the Cove Fort-Sulphurdale geothermal area. The geophysical exploration consisted of resistivity, ground magnetic, and microgravity surveys that suggested the presence of fault structures and low resistivity zones, possibly indicating a major upflow zone for the geothermal system. A well was sited and drilled to a depth of 2,000 ft in the fall of 2001 and results are now being analyzed for decisions on future efforts.

The California Fourmile Hill project near Glass Mountain is the focus of exploration work to characterize its resource. A Phase I temperature gradient well was drilled in September 2001 to finalize the assessment of the site, reaching a total depth of 4417 ft. Temperature logging of the well will be performed during the fall of 2001.

The Nevada Steamboat project investigates the existence of a shallow boiling reservoir in the northern Steamboat Hills and Steamboat Springs area. Two slim-hole wells were drilled during March and April of 2001, reaching total depths of 2,000 and 973 ft. Several fracture zones were encountered with noticeably large fracture apertures observed in recovered core. Data from these two wells indicate that a large thermal zone with high-temperature fluids exists at a relatively shallow depth. Testing of this reservoir will continue into FY 2002.

The Nevada U-Boat project involves the geophysical exploration of the deep geothermal resource beneath the Steamboat KGRA using seismic and gravity studies. The objective is to constrain the location of the deep fault system and productive zone at this site. The geophysical exploration consisted of 3-D surface seismic, microseismic, and gravity surveys, with results currently being processed and interpreted. All data will be correlated to obtain the most probable fault-system geometry and site a test well.

The New Mexico Lightning Dock KGRA is currently used only for heating applications, but it is believed that higher temperature waters are present in deeper fault systems. The Phase I exploration work includes gravity, resistivity, and aeromagnetic surveys that were completed in the fall of 2001 and are now being evaluated. It is believed that major lineaments cross the geothermal region, providing pathways for movement of the hot water. The geophysical activity is aimed at optimum siting of a test well to contact the fault intersection.

Planned FY 2002 Milestones:

Since not all projects will advance through all three stages, milestones are based on at least four of the projects completing the full resource assessment. At least four of the projects will be awarded Phase III funds by March 2002. The major milestone is to have the resource assessed for at least four projects by September 2002.

Major Reports Published in FY 2001:

Rye Patch Geothermal Resource, Pershing County, Nevada, Phase I Report, Geothermal Development Associates, Reno, NV, October, 2000.

Geothermal Exploration Activities at the Steamboat Springs KGRA, Phase I Report, SB Geo, Inc, Reno, NV, C. Goranson, October 2000.

Blue Mountain Geothermal Area, Phase I Report, Noramex Corp., Carson City, NV, October 31, 2000.

Structural Controls for the Animas, NM Geothermal Resource, Special Technical Progress Report, Lightning Dock Geothermal, Inc., Las Cruces, NM , R.L. Bowers and R.A Cuniff, March 22, 2001.

Ground Magnetic and Electrical Resistivity Surveys, Cove Fort-Sulphurdale Geothermal Area, Utah, Utah Municipal Power Agency, Spanish Fork, UT, H.P. Ross and C.E. Mackelprang, June 8, 2001.

Integrated Geophysical Study of the Steamboat Geothermal Field, U-Boat Prospect, Wahoe County, Nevada, Confidential Phase I report, Optim LLC, W. Honjas and S. Pullammanappallil, August 2001.

Major Articles Published in FY 2001:

None

Drilling

Acoustic Measurement-While-Drilling

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Sandia National Laboratories (SNL) P.O. Box 5800 Albuquerque, NM 87185-1033
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s)** **Name:** Douglas S. Drumheller **Phone:** (505) 844-8920 **Fax:** (505) 844-3952 **E-mail:** dsdrumh@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	$559K	$350K–Fossil Energy Program $300K–Extreme Eng. $200K–Baker Oil Tools

Project Objective:

Our goal is to complete the construction of a new Measurement-While-Drilling (MWD) tool that can be deployed in drilling operations, thus enabling pressure-while-drilling, steering, and other operations in situations where mud-pulse telemetry provides insufficient data rate or does not work. This project will be terminated and fully documented this year.

Approach/Background:

The development of an advanced drilling system hinges upon effective methods for communicating drilling and navigation parameters between the drill bit and the surface. The industry standard is communication by mud-pulse telemetry. Unfortunately this technology only communicates one way from the bit to the surface, it has a very slow data transfer rate, and it will not work in either high-temperature regimes, vapor-dominated wells, or under-balanced drilling operations. Thus, it has limited use in the geothermal industry. However, an alternative technology exists. It communicates information using stress waves that propagate through the steel drill pipe. As such, the condition or even the total absence of drilling fluids does not directly affect the communication signals. Additionally, communication rates are easily adjusted to optimize data transmission rates and ranges, and the hardware is easily adapted to two-way communication. We have already designed, deployed, and licensed our second-generation telemetry system to industry for deployment in production wells. Several companies have purchased licenses to our latest, third-generation drilling tool, and several others are in various stages of license negotiations.

Status/Accomplishments:

Three generations of acoustic telemetry tools have been built and successfully fielded in both test wells and commercial operations. These tools have been designed for both drilling and production applications. For example, a production-monitoring tool was successfully fielded in a commercial well in Mississippi and subsequently licensed to Baker Oil Tools. Our latest tool is designed for drilling applications. Two field-tested prototypes exist. One recently drilled a 2700-ft well in Alberta, Canada. It was recovered in perfect condition after transmitting annulus pressure and temperature data to the surface continuously throughout the entire drilling project. Two companies have a commercial license to this tool.

This drilling tool has been designed to operate at 200 °C and transmit data at rates up to 50 baud. Indeed, data compression methods could be employed to raise the effective transmission rate to near 200 baud, which is ten to one-hundred times greater than current MWD systems. The virtue of the design is that it is entirely based on high temperature electronic components and transducers and has no mechanical moving parts. The active transducer is a PZT ceramic with a Curie temperature of 350 °C. However, the existing tools have low-temperature versions of the logic boards, and due to funding constraints we will be unable to complete construction and field the high-temperature components. We are terminating this project this year. Outstanding subcontract commitments for the wireless surface acoustic receiver will be completed, the DSP algorithms will be implemented and documented, and a final report will be issued to provide a sufficient information basis to geothermal drilling service vendors who wish to commercialize this technology.

Planned FY 2002 Milestones:

Field test low-temperature acoustic tool in static environment	(C)	Oct 01
Field test low-temperature acoustic tool under actual drilling conditions	(C)	Nov 01
Lab test wireless surface acoustic receiver	(I)	Mar 02
Field test wireless surface acoustic receiver	(C)	Jun 02
Upgrade DSP algorithms and conduct above ground test	(I)	Aug 02
Final report on acoustic tool	(I)	Sep 02

Major Reports Published in FY 2001:

Wave Impedances of Drill Strings and other Period Media, U.S. Patent application.

Major Articles Published in FY 2001:

Wave Impedances of Drill Strings and other Period Media, Journal of the Acoustic Society of America (in review).

Diagnostics-While-Drilling

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s)** **Name:** John Finger **Phone:** (505) 844-8089 **Fax:** (505) 844-3952 **E-mail:** jtfinge@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	$1,316K	N/A

Project Objective:

The principal Diagnostics-While-Drilling (DWD) objective is a Proof-of-Concept test that will demonstrate the value of real-time near-bit data for greatly enhancing drilling rate-of-penetration and overall bit performance in hard formations.

Approach/Background:

The program must demonstrate DWD to the drilling industry so that we can validate and quantify its benefits and can stimulate the flow of private resources into development of an economical high-speed data link for geothermal drilling applications. There are many possible forms of demonstration, but we have chosen a Proof-of-Concept (POC) test that focuses on bit dynamics (forces and motions at the bit) to support the PDC bit-development program in its effort to improve PDC performance in hard (e.g., geothermal) formations. The POC will be conducted at GTI's Catoosa test site and will be divided into two phases: in Phase I we will use the DWD system components in a trial run to gather baseline downhole data for both roller-cone and PDC bits, but in Phase II we will operate two identical PDC bits drilling through the same interval of hard rock as Phase I. In Phase II, the driller will not use DWD data for control with the first bit, but for the second one he will use DWD feedback to improve performance.

The three major components of the DWD system for the POC are: a downhole measurement tool, a data link to the surface, and equipment to analyze and display data at the surface. Because we do not yet know which parameters are most important to optimize bit performance, we will attempt to make a full suite of downhole measurements – three-axis and angular acceleration; weight, torque, and bending at the bit; rotary speed (both by magnetometers and by integration of angular acceleration); annulus and drillpipe pressure; and temperature. The data link for the prototype system will be a wet-connect wireline, which is similar to a conventional wireline down the inside of the drill pipe, except that it incorporates an electrical swivel so that the bottom part of the wireline can rotate relative to the top segment. The surface hardware/software will decommutate the stream of digital data coming up the wireline, archive the data in permanent storage, perform certain manipulations (such as Fast Fourier Transforms) on the data, and display it to the driller in graphical form.

Sandia has formed a Technical Advisory Committee to review program plans and results, so that we can be assured of the project's relevance and sound technical approach. The TAC meets approximately three times a year and comprises representatives of the geothermal, oil and gas, drilling, and service industries.

Status/Accomplishments:

Delays in contracting and design definition have pushed the POC into FY02, but we have added two pre-Catoosa activities to the original schedule. After the downhole sub is completed, it will be vibration-tested in the Sandia vibration labs, and after the vibration tests are complete the complete system, including downhole electronics and surface display, will be tested in the Reed-Hycalog drilling laboratory in Houston. Status is: 1) design complete and mechanical parts of measurement sub under fabrication; 2) high-speed (200^{+} k-baud) data transmission demonstrated through wet-connect wireline; 3) definition complete for data decommutation system, some components on hand; 4) requirements defined for surface display system; and 5) test plan complete for POC and follow-on PDC bit tests.

Planned FY 2002 Milestones:

Proof-of-Concept Test

Evaluate in-house data de-commutation and display capabilities	(I)	Dec 01
Perform Phase I benchmark DWD tests at GTI/Catoosa	(C)	Apr 02
Conduct initial Phase II tests on PDC bits at GTI/Catoosa	(I)	May 02
Document initial POC results	(I)	Jun 02
Phase II - Comparison of diagnostics-while-drilling (DWD)	(K)	Aug 02

Develop Field-Ready System

Write development plan for field-ready system	(I)	Jun 02
First conceptual design for field-ready system	(C)	Sep 02
Organize industry DWD cost-share mechanism	(I)	Sep 02

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

"Component Technologies Build DWD Framework", *The American Oil & Gas Reporter*, November 2000, pp. 111-118

"Smart Technologies Revolutionize Drilling Techniques", *SANDIA TECHNOLOGY*, Spring 2001, pp. 3-6

Cost Database and Simulators

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s)** **Name:** John Finger **Phone:** (505) 844-8089 **Fax:** (505) 844-3952 **E-mail:** jtfinge@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	$245K	N/A

Project Objective:

Major objectives of this project are: 1) Develop baseline data for geothermal drilling cost in different reservoirs; 2) Improve the ability to model the drilling process and predict drilling costs; and 3) Use modeling and data to assess the impact of technology improvements and to guide research within the Program.

Approach/Background:

Sandia National Laboratory (SNL) has developed a model for estimating the cost of drilling a specific well, but we have not had enough actual field data to calibrate this model for various scenarios. This has been the case because operators have traditionally been very reluctant to release cost data. In FY01, however, a considerable amount of well data became available from major US operators and much of it is in an electronic format (RIMBase) that makes analysis much simpler. This data set will support two of the following activities.

GEODRIL – This program, developed by Maurer Engineering, calculates the pressure, temperature, and velocity of drilling fluid at all points in the drill pipe and in the annulus during drilling. This is useful in defining the downhole environment that tools and electronics must survive.

PayZone – This code, written by Cooper Consulting, models the well drilling process, including bit and drilling fluid selection, casing, drilling parameters, etc. It can show the effect of different well designs on drilling time and cost, and can simulate improved drilling technology to assess its effect. Originally developed for oil and gas drilling, it has been modified to reflect geothermal conditions, including rock types and higher temperatures.

RIMBase – RIMBase is a cost-reporting and database system for drilling operations that identifies time and cost for various drilling activities and also provides performance data such as bit life, rate of penetration, and equipment reliability.

Status/Accomplishments:

GEODRIL – Complete; CDs of code, with user manuals, have been delivered from Maurer Engineering.

PayZone – Some of the well-cost data acquired for the database also contains enough performance information that it is useful for calibrating PayZone. These files have been delivered to Cooper Consulting.

RIMBase – Sandia has developed relationships and signed Non-Disclosure Agreements with the three major US geothermal operators. We have received the following well files in RIMBase format from Calpine and CalEnergy: Geysers (27 files), Salton Sea (125 files), Cerro Prieto (47 files), and Newberry (2 files). Many more records (including other operators) are available in paper copies.

Planned FY 2002 Milestones:

Transfer paper-based well files into RIMBase	(I)	Feb 02
Complete test of PayZone against well data	(I)	Mar 02
Complete compiled RIMBase database on well cost	(C)	Aug 02

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Evaluation of Flow Tool

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s)** **Name:** Ronald D. Jacobson **Phone:** (505) 845-9675 / (505) 844-6720 **Fax:** (505) 844-3952 **E-mail:** ranorma@sandia.gov jahenfl@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

Our objective was to test the PhotoSonic fiber-optic-based logging tool in a geothermal well. If the tool was successful, we were to help PhotoSonic market the tool to the geothermal industry by providing a third party field evaluation.

Approach/Background:

The PhotoSonic fiber-optic-based logging tool was developed to measure pressure, temperature, steam quality, and mass flow rate of the steam fraction during steam-flood operations for enhanced oil recovery. But would it work inside a geothermal well? All of the PhotoSonic specifications said that it would work and work well. However, PhotoSonic had little actual field experience and no geothermal experience.

Stated Tool Specifications

Temperature – 0-400C, up to 7 hrs
Pressure – 0-20 Mpa
Steam Quality – 0-100%(Derived in part from pressure and temperature readings)
Flow (No moving parts) – 0-25 tons/hour (Derived pipe dimension and steam quality values to estimate)

Our approach was to impress upon PhotoSonic how harsh the geothermal environment really is. We then selected a geothermal well, which provided a good test location for this new tool. We contacted the well owner (Steamboat Springs) and arranged a test.

Prior to the actual PhotoSonic test log, we logged the well using our PTS tool. This insured that the well was clear and provided accurate pressure and temperature profiles.

Status/Accomplishments:

The tool was deployed within two geothermal wells at Steamboat Springs. The results are summerized below.

- Temperature readings were about 3°F higher than Sandia's readings but could be recalibrated.
- Pressure was 10% higher than Sandia's readings. Again this was a calibration issue.
- Flow was not measured. The PhotoSonic tool incorporates a motion sensor to ignore flow while the tool is moving. This motion sensor will greatly restrict this tool's use in geothermal wells. We suggested removing this feature from the design.

Planned FY 2002 Milestones:

PhotoSonic will supply logging tools and support personnel. Sandia will supply the logging equipment and calibrated Pressure/Temperature/Spinner (PTS) tools for comparison. The Sandia PTS tool will be used to benchmark the performance of the PhotoSonic tool. The results will be analyzed for accuracy and/or weaknesses.

Major Reports Published in FY 2001:

None

Wellbore Integrity and Lost Circulation

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala Phone: (202) 586-4198 Fax: (202) 586-8185 E-mail: Raymond. LaSala@ee.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s)** Name: A.J. Mansure Phone: (505) 844-9315 Fax: (505) 844-9315 E-mail: ajmansu@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala Phone: (202) 586-4198 Fax: (202) 586-8185 E-mail: Raymond. LaSala@ee.doe.gov	$511K	$145K

Project Objective:

The lost circulation technology program area focuses on two objectives: 1) developing hardware, software, and procedures for detecting and characterizing lost circulation zones to reduce costs by quickly and accurately determining the optimum treatment and procedure; and 2) developing materials, hardware, and procedures for cost-effective treatment of lost circulation zones. In particular, 1) as part of lost circulation detection, mud pump pressure and/or vibration signatures should be monitored to identify changes in pump efficiency and impending pump failures, and 2) a simple, low-cost lost-circulation control technology – "deployable from the back of a pick-up" is needed: polyurethane grouting.

Approach/Background:

Lost circulation is one of the most persistent problems associated with geothermal drilling, and accounts for roughly 10-20% of the total cost of drilling a typical geothermal well. It occurs when drilling mud is lost to the formation during drilling. It can result in numerous drilling problems such as; stuck drill pipe, damaged bits, slow drilling rates, and collapsed boreholes. Furthermore, plugging lost circulation zones is difficult and can be a very costly element of drilling a geothermal well.

Monitoring drilling circulating systems to determine problems such as lost circulation, washouts, etc. is complicated by a lack of a practical, accurate method of measuring inflow. A variety of commercial meters have been evaluated, but none found to be suitable for drilling conditions. The Rolling Float Meter (RFM -- an outflow meter) can be calibrated to inflow calculated from pump stroke counts; however, changes in pump efficiency often occur more frequently than the problems identified from differences in inflow and outflow. A rig system for identifying changes in pump efficiency would be useful as part of a system to detect lost circulation and other wellbore hydraulics problems.

Plugging lost circulation zones remains a very difficult and costly part of drilling geothermal wells. In civil engineering, polyurethane is becoming the material of choice for dam remediation projects and sealing boreholes with large voids and high inflows, conditions associated with the worst lost circulation problems. Advantages of polyurethane grout are that the viscosity and setting time can be controlled to fit the job. The grout can be engineered to have a low viscosity while being pumped and then gain strength in a short period, minimizing "waiting-on-cement" and the potential for the plug to be washed out.

Status/Accomplishments:

The concept of monitoring mud pumps to determine if changes in efficiency and impending failure was demonstrated as an alternative to costly inflow meters. This concept is not currently being reduced to practice.

In prior years, commercially available civil engineering polyurethanes were demonstrated in the lab to form leak-proof pressure-resistant plugs suitable for a chemical grouting of lost-circulation zones and for borehole stabilization. Best practices for controlling the placement of polyurethane plugs were identified and thus field demonstration of polyurethane grouting was the next logical step in commercialization of this technology.

Commercially available polyurethanes will work at the temperatures of most geothermal lost-circulation zones. However, plugging lost circulation in depleted reservoirs will require new polyurethane formulations. Potential formulations for these conditions have been identified.

In FY01 polyurethane grouting was successfully applied to a lost circulation zone in a geothermal well at Rye Patch, NV. Previously, failure to seal this zone resulted in the temporary abandonment of the well after twenty cement plugs, including 15 conventional, two thixotropic, and three with foam cement, were unsuccessful. Polyurethane grouting has been successfully used in core drilling operations (slim holes) to stop lost circulation and stabilize boreholes; however, previous attempts to apply polyurethane grouting to large diameter geothermal boreholes have not been successful. The techniques applied to grouting with polyurethane at Rye Patch were adapted from civil engineering technology where polyurethane is becoming the grout of choice for sealing high cross flows. The success of the grouting of the loss zone at Rye Patch was a result of applying the best practices developed in prior years.

Steps to accomplishing the successful polyurethane grouting job at Rye Patch included 1) choosing the right polyurethane formulation for the drilling conditions at Rye Patch and testing the material to verify the appropriateness of the material. 2) Designing a deployment system suitable for the rig and drilling technologies used at Rye Patch and the laboratory testing of the deployment system components to verify their functionality in a geothermal environment. 3) Procurement and fabrication of the deployment system. 4) Close coordination between the operator, drilling contractor, chemical company, grouting company, and development team. 5) Adherence to good drilling practice. 6) Both a design and operations plan the included contingencies. 7) and, a little luck -- several aspects of the contingency plans had to be used, but the borehole favored us with a favorable packer location without which the job would have been difficult.

The polyurethane grouting at Rye Patch was a success and the system used could be applied economically to other geothermal lost circulation. However, as one would expect there were many lessons learned that will be applied to improve and simplify the system. When the system used at Rye Patch was developed, the request to drill thorough depleted reservoirs had not been made. The challenges of going deeper and hotter, require that the design of such a system starts over again rather than develop as an evolution of the existing system.

Planned FY 2002 Milestones:

Downselect to "best" polyurethane grout formulation, Feb. 2002
Field demonstration of simplified polyurethane grouting system, June 2002
Comprehensive assessment of wellbore-integrity state-of-the-art, April 2002
Identification of candidate wellbore-integrity system for lab or field test, Sep. 2002

Major Reports Published in FY 2001:

Mansure, A.J.; and Westmoreland, J.J.: October 2000, "Plugging Lost-Circulation Zones with Polyurethane: Controlling the Process," Geothermal Resources Council Transactions, Vol. 24.

Mansure, A.J.; Westmoreland, J.J.; Staller, G.E.; Jacobson, R.D.; Libengood, H.; Smith, E.; Galbreadth, D.; and Rickard, B.: "Polyurethane Grouting of Rye Patch Lost Circulation Zone," Geothermal Resources Council Transactions, (October 2001), 24

Rickard, W.M.; Johnson, B.; Mansure, A.J.; and Jacobson, R.D.; "Application of Dual Tube Flooded Reverse Circulation Drilling to Rye Patch Lost Circulation Zone," Geothermal Resources Council Transactions, (October 2001), 24.

Major Articles Published in FY 2001:

Polyurethane Grout Seals Rye Patch Well, Geothermal Resources Council Bulletin, (May/June 2001), Vol. 30 N3.

High Temperature Instrumentation and Tools

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s):** **Name:** Randy Normann **Phone:** (505) 845-9675 **Fax:** (505) 844-3952 **E-mail:** ranorma@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	$90K	$15K

Project Objective:

Distributed Temperature System (DTS) uses fiber to measure temperature. However, fiber degradation starts within the first 24 hrs when placed with a geothermal well! This makes DTS systems unpractical. Our objective is to solve the degradation problem.

Approach/Background:

Earlier testing of wellbore degraded fiber gave a strong indication of hydroxide (OH) molecules being created inside the fiber. Hydroxide is a well-known fiber degradation mechanism created by exposing the fiber to free hydrogen at temperature. Sandia studied three possible sources of free hydrogen:

1. From the wellbore fluid
2. From the stainless steel tubing
3. From the fiber's outer jacket of polyimide

In FY 2001, a number of fibers were tested following an exhaustive background research in reducing hydroxide molecules within optical fibers. Sandia tested some potential fibers where phosphorous and germanium was not used to dope the fiber. Early research had indicated that phosphorous doping accelerated hydroxide (OH) growth in the fiber. Phosphorous is used to aid in fiber production and is not needed by the fiber for optical reasons. Germanium is used to create an improved optical wave path by grading the fiber's optical index (this is called Graded Index, GI). Graded index fiber has many times the light transmission capabilities of non-graded index, called Step Index.

In FY 2001, laboratory testing was completed using four different test fibers. Two fibers showed significant promise. The fiber that showed the most promise was sent to Pruett Industries for evaluation with the York DTS instrument. It worked for short distances. The lack of a graded index limited the fiber to a few hundred feet.

Following these results, a manufacture started a production of phosphorous free fiber, graded index fiber.

Status/Accomplishments:

A fiber was successfully demonstrated in oven testing to be highly resistive to hydrogen deformation.
A non-graded index fiber was tested using a DTS system in a 250C steam well. This fiber showed a resistance to hydrogen deformation.
Fiber Guide, (a fiber manufacture) is now producing a high-temperature version of the phosphorous free fiber, which was resistive to hydrogen deformation.

Planned FY 2002 Milestones:

We will purchase several kilometers of this NEW fiber from Fiber Guide and test it within a geothermal production well.

Major Reports Published in FY 2001:

Results of this work were published both at the Stanford Workshop and in the GRC Bulletin.

High Temperature Electronics

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033	
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s):** **Name:** Randy Normann and Joseph A. Henfling **Phone:** (505) 845-9675 / (505) 844-6720 **Fax:** (505) 844-3952 **E-mail:** ranorma@sandia.gov jahenfl@sandia.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	**DOE Funding Allocation** $600K	**Cost Share Funding** $45K

Project Objective:

1. To complete the first production run of the Sandia developed high temperature Application Specific Integrated Circuit.

2. To perform a demonstration of an SOI logging tool, within a geothermal well without using any heat shielding.

3. To assist Pruett Ind. in the production of their first Geothermal pressure, temperature and spinner logging tool designed at Sandia.

4. To assist DOSECC in the production of their first Geothermal core-tube-data-logger. This tool was developed at Sandia for geothermal applications.

Approach/Background:

The ASIC (Application Specific Integrated Circuit) is an integrated circuit which enables high-temperature electronics developed for aircraft engines to be used in geothermal logging tools. This was a major development effort consuming most of our resources in fiscal year 2000. In fiscal year 2001, we received the first production ASICs. These first ASICs were successfully tested 250 degrees Celsius however, expect them to continue operating up to 300C.

The major development effort of 2001 was to use the ASIC in an actual logging tool. Again this was successful. Two tools that were commercialized in 1999 and 2000 required support from Sandia in order that the tools would be successful in industry. These tools were the core-tube-data-logger and the PTS tool.

Status/Accomplishments:

1. The ASIC functions exactly as designed and has been successfully demonstrated up to 250 degrees Celsius. We expect this device to continue to operate up to 300 Celsius.

2. A pressure and temperature logging tool was demonstrated. This tool logged a geothermal well for 40 hours at 240 degrees Celsius without heat shielding! There was however a drift in the temperature measurement which we believed to have been caused by free hydrogen within the well. We have redesigned the tool to reduce this effect.

3. Pruett Industries has built a number of pressure, temperature and spinner tools based on the Sandia design and using Sandia software. This tool is very successful with Pruett Industries now logging geothermal wells world wide.

4. Sandia has provided to DOSECC complete core-tube-data-logger mechanical designs, electronics and software. DOSECC is continuing to evaluate marketing strategies on this tool. One strategy is to build tools and rent them to drilling operators. The other strategy is to build a tool as a onetime sell to the future well owner.

Planned FY 2002 Milestones:

1.	Conduct long-term well profile testing of SOI tool	(C)	Nov 01
2.	Complete documentation on first SOI tool	(I)	Dec 01
3.	Provide first prototype electronics to industrial partners	(C)	Feb 02
4.	Conduct high-temperature workshop with industry	(I)	Jun 02
5.	Develop agreement for use of SOI EEPROM with Fraunhofer Institute	(I)	Aug 02
6.	Assist in field testing with industrial partners	(I)	Aug 02
7.	Release data on additional SOI components at GRC	(I)	Sep 02

Major Reports Published in FY 2001:

None

Design Criteria and Structural Response Analysis for Well Cements

Contract/Grant #: DE-AC02-98CH10886	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	**Principal Investigator(s):** Name: A. J. Philippacopoulos and M. L. Berndt Phone: (631) 344-6090 Fax: (631) 344-2359 E-mail: ajph@bnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala Phone: (202) 586-4198 Fax: (202) 586-8185 E-mail: Raymond. LaSala@ee.doe.gov	$165K	

Project Objective:

The objective of this project is to develop a comprehensive design and implementation approach for geothermal well cements through employing detailed experimental testing confirmed by numerical modeling.

Approach/Background:

The success and life expectancy of a geothermal well rely on the initial and sustained integrity of the completion cement. The current design criteria specified for geothermal well cements oversimplify the mechanical property requirements. Minimum unconfined compressive strength at 24 hours is typically specified yet the structural capability of geothermal cements strongly depend on additional properties such as elastic modulus, strength under tensile and multi loading scenarios, and the time- and temperature-dependent nature of these properties. This is in addition to other considerations such as formation properties, in-situ stresses and well operating conditions. Currently, there is a lack of understanding of the nature of the stress regime in the vicinity of geothermal wells and analytical methodology is required to describe how cements actually behave in-situ. A more intelligent approach to well cementing operations that takes into account these factors is needed in order to select the best materials, prevent failure and reduce overall costs. It is particularly important to consider and compare the structural response of cements that have recently been developed as alternatives to conventional mixes. Ongoing studies by the oil and gas industry are reaching similar conclusions. The results from the research conducted so far clearly demonstrate that adequate materials characterization and selection of cements for the completion of all types of wells (i.e., geothermal, oil and gas) should be based on rigorous engineering analysis.

Our research involves comprehensive testing to determine material properties and their range of applicability for conventional and advanced geothermal well cements. The results obtained from the testing program are subsequently used in numerical modelling studies to predict and compare the performance of wells completed with different cement types. The cements include standard Class G/silica flour mixes in addition to lightweight and latex-modfied mixes that are used in geothermal cementing operations. Since our research has clearly shown that tensile strength is also critical for the performance of the well, the properties and response behaviour of fibre reinforced cements are also studied. A variety of cement formulations are being tested for compressive properties under unconfined and triaxial loading, tensile behaviour, elastic modulus, Poisson's ratio and thermal properties. Our modelling studies consider a reasonable range of application. They cover simple annular continuous models up to detailed finite element models. Our fundamental approach is to include all significant components of the system so that casing-cement-formation interaction effects are incorporated into computation of the system response. This means that stresses and deformations due to pressure and temperature conditions developed in the interior of the well take into account key system interactions. Detailed parametric variation studies are being carried out using a range of cement properties resulting from our material testing program. To simplify the process, formation properties are varied in relation to the cement properties so that permutations of stiff /soft cements with soft/stiff formations are considered.

Status/Accomplishments:

Mechanical and thermal property measurements on standard Class G/silica flour, latex-modified and lightweight cement formulations were conducted. These properties were subsequently used in thermal and pressure stress analysis. The potential improvements in cement tensile strength that can be achieved by fibre reinforcement was investigated. For this purpose, a range of different fibres was selected for initial screening tests. Three fibre types were delineated for further investigation based on significant tensile strength enhancement. Ongoing research is focused on more detailed mechanical properties and the response behaviour of geothermal wells completed with fibre reinforced and lightweight cements. In addition, different cement formulations are being characterized for thermal diffusivity in order to perform transient thermal stress analysis. A set of initial one dimensional (axisymmetric) models were investigated. Subsequent development of two-dimensional models was completed. Static analysis for pressure conditions and steady-state thermoelastic analysis of double cased geothermal wells produced good results. Dynamic pressure analysis is expected to be carried out during the fourth quarter of the program while, transient thermoelastic analysis is an ongoing task. Some preliminary results from the latter task were recently obtained by simulating the temperature rise whithin the geothermal well by step functions. The findings of our research are being discussed with Halliburton Energy Services and collaborative testing and analysis are planned. As part of the technology transfer activities, the results obtained to date have been presented at the 2001 GRC Annual Meeting, two papers have been submitted to Geothermics and an abstract has been submitted to the 2002 SPE Meeting.

Planned FY 2002 Milestones:

Complete detailed mechanical and thermal property characterization of fibre reinforced cements	Jul 02
Complete numerical modeling to support development of design approach	Aug 02
Peer reviewed paper, describing results of experimental and modeling studies	Sep 02

Major Reports Published in FY 2001:

A.J. Philippacopoulos and M.L. Berndt, “Engineering Analysis of Materials for Remediation of Geothermal Wells,” BNL 68266, April, 2001.

Major Articles Published in FY 2002:

A.J. Philippacopoulos and M.L. Berndt, “Mechanical Property Issues for Geothermal Well Cements, Geothermal Resources Council Transactions,” Vol. 25, 119-124, San Diego, 2001.

Hard-Rock Drill Bit Technology

Contract/Grant #: **DE-AC04-94AL85000**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**
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Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s):** **Name:** David W. Raymond and Jack L. Wise **Phone:** (505) 844-8026 / 844-6359 **Fax:** (505) 844-3952 **E-mail:** dwraymo@sandia.gov ; jlwise@sandia.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond.LaSala@ee.doe.gov	$1,219K	$408K (in kind)

Project Objective:

This project promotes innovations in the design and operation of drag bits and related hardware suited to the hard-rock drilling environments typical of geothermal sites. The research effort achieves improvements in bit technology through complementary advances in the areas of *drag-cutter mechanics and materials* and *bit mechanics and design*. The focus is on bits with fixed cutters that feature ultrahard PDC (polycrystalline diamond compact) or TSP (thermally stable polycrystalline) overlays.

Approach/Background:

The activities for this project are divided among five separate tasks: (1) PDC Cutter Development and Testing, (2) Self-Induced Bit Vibrations, (3) PDC Bit Development and Testing, (4) Mudjet-Augmented PDC Bit, and (5) Bi-Center PDC Bit with Real-Time Control. For each task, Sandia's in-house resources are employed and supplemented, as appropriate, by outside laboratory and field-testing capabilities. Unique Sandia testing resources include the Hard-Rock Drilling Facility (HRDF) and the Linear Cutter Test Facility (LCTF). Bit performance and wear are computationally simulated and new designs are generated using the Sandia-developed PDCWEAR code. Industry and/or university involvement in each task is actively maintained, thereby incorporating additional technical expertise and capabilities. The following paragraphs address the tasks individually.

Task 1 - PDC Cutter Development and Testing: A database of cutting-force and wear measurements from LCTF and HRDF tests is being constructed to show the influence of cutter design parameters on wear and durability, ultimately leading to the identification and production of optimal designs for geothermal drilling. Several cutter manufacturers (US Synthetic, Dennis Tool Company, and Technology International) have been supplying cutters with selected compositions and geometries for evaluation.

Task 2 - Self-Induced Bit Vibrations: Sandia is working with the University of Louisiana to characterize and control self-induced bit vibrations (i.e., chatter) that cause impact damage to PDC cutters and contribute to reduced rates of penetration during geothermal drilling. Measurements of cutting force, wear, and vibration intensity are made on the HRDF, which has been modified to provide adjustable levels of axial and torsional compliance and to allow the introduction of axial damping.

Task 3 - PDC Bit Development and Testing: Sandia is partnering with several bit manufacturers (Diamond Products International, Reed-Hycalog, Security DBS, and Smith International) to plan and implement a field demonstration of state-of-the-art PDC bits in a hard-rock formation that simulates a geothermal setting. Controlled, heavily instrumented drilling tests will proceed in conjunction with Sandia's Diagnostics-While-Drilling (DWD) proof-of-concept tests. Offsetting benchmark data will be acquired for conventional rollercone and PDC bits.

Task 4 - Mudjet-Augmented PDC Bit: A cooperative effort is under way between Sandia, Security DBS, Dynaflow, and Terra Tek to develop and demonstrate a new PDC bit that uses high-pressure mudjets directed at the cutter/rock interface to enhance the cutting process. Activities include the design of new wear-resistant, resonating/cavitating nozzles, fabrication and testing of a prototype mudjet bit, single-cutter testing with a high-pressure nozzle to characterize the cutter/nozzle/rock interaction, and production and field verification of an optimized mudjet bit.

Task 5 - Bi-Center PDC Bit with Real-Time Control: Montana Tech has been working under Sandia contract to model, optimize, and control bi-center PDC bits for geothermal drilling. Combined testing and modeling efforts are characterizing the dynamic interaction of the bi-center bit, BHA (bottomhole assembly), and rock formation, leading to improved bit designs and the development of a neural network for real-time lithology recognition and drilling control.

Status/Accomplishments:

During 2001, Sandia's continuing work on synthetic diamond drill bit technology received a DOE Energy 100 Award , which honored this effort as one of DOE's top 100 scientific and technical accomplishments. Specific FY01 accomplishments follow:

Task 1 - PDC Cutter Development and Testing: The first six lots of cutters with different combinations of design parameters were fabricated by U S Synthetic and subjected to extensive LCTF cutting-force tests at Sandia and drop-impact and abrasion tests at U S Synthetic. Drilling tests on Technology International TSP cutters demonstrated that proprietary treatments yield improved fracture toughness. Dennis Tool Company delivered eight different claw-cutter configurations for test and analysis.

Task 2 - Self-Induced Bit Vibrations: An HRDF instrumented sub was built and calibrated to allow time-resolved weight on bit (WOB) and torque on bit (TOB) measurements during drilling. A laminated rock sample with alternating soft and hard layers was constructed and drilled to reveal mechanisms of cutter damage at rock interfaces. Measurements of stick-slip torsional vibrations were obtained for a PDC bit running in hard rock, and the coupling between axial and torsional vibration modes was examined.

Task 3 - PDC Bit Development and Testing: Negotiations were initiated between Sandia and several bit manufacturers regarding the terms of a single-lab, multi-partner Cooperative Research and Development Agreement (CRADA) that will apply to upcoming joint field demonstrations of PDC bits in a hard-rock formation. A draft Statement of Work for the CRADA was prepared and submitted to the industry partners for review and comment. To support the joint development of a stabilized PDC bit by RA-TECH and DOWDCO, surface vibration data were acquired during production drilling in an Oklahoma gas well.

Task 4 - Mudjet-Augmented PDC Bit: Polycrystalline diamond orifices were machined, and brazed nozzle assemblies survived flow testing. Drilling with the prototype mudjet bit using these nozzles demonstrated a 30% increase in rate of penetration (ROP) relative to drilling with conventional nozzles. Offsetting drilling data were obtained with a rollercone bit. Analysis of the drilling data confirmed that PDC bits yield significant cost savings per foot relative to rollercone bits. Hardware design and fabrication, including work on new nozzle configurations, was initiated to support planned jet-augmented, single-cutter tests on the LCTF.

Task 5 - Bi-Center PDC Bit with Real-Time Control: Work was performed at Montana Tech to take time-resolved data for forces acting on PDC cutters and bits during drilling, to optimize PDC bit designs for hard rock, and to develop a neural network for optimizing ROP on the basis of field data. A final report was issued on the bi-center PDC bit efforts.

Planned FY 2002 Milestones:

Task 1:	Complete additional cutter testing for fundamental parameter study	(I)	Apr 02
	Report results on claw-cutter optimization project	(I)	Sep 02
	Document new results for fundamental parameter study	(C)	Sep 02
Task 2:	Demonstrate an in-line axial damper for the HRDF	(I)	Jun 02
	Determine effects of damping on bit performance and cutter failure	(I)	Sep 02
Task 3:	Establish working agreement (e.g., CRADA) with bit manufacturers	(C)	Nov 01
	Receive "best effort" bits from bit companies	(C)	Jul 02
	Complete drilling demonstrations (3 phases) with DWD program	(I)	Sep 02
	Complete report on drilling demo results	(I)	Sep 02
	Complete report on stabilized PDC bit field tests	(I)	Sep 02
Task 4:	Complete test fixture design	(I)	May 02
	Assess PCD orifice fabrication via direct sintering process	(I)	Sep 02

Major Reports Published in FY 2001:

K. W. Johnson, C. Link, and M. B. Ziaja, "Modeling and Development of a Bi-Center PDC Bit Design," Final Report: Period of Performance June 1, 1998 to September 30, 2001, Montana Tech of The University of Montana, September 2001.

Major Articles Published in FY 2001:

D. Raymond, "Mudjet-Augmented Diamond Bit Demonstrates Drilling Rate Improvements in Hard-Rock Formations," Geothermal Resources Transactions, 2001.

Near-Term Research and Development Industry Collaborative Projects Operators Solicitation (and Outstanding GDO Projects)

Contract/Grant #: **DE-AC04-94AL85000**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033
Contracting Organization U.S. Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185-5400	**Principal Investigator(s):** **Name:** Allan R Sattler **Phone:** (505) 844-1019 **Fax:** (505) 844-3952 **E-mail:** arsattl@sandia.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond.LaSala@ee.doe.gov	$379K (FY 01) $436K (approx., prior year)	$600K

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) projects.

Approach/Background:

This project funds 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, because the geothermal industry is small and represents a limited, specialized market and the technical well-construction challenges it faces are among the most difficult in the indsustry.

The approach is to solicit jointly funded projects addressing near term drilling and well maintenance related needs of industry. The projects are selected using a competetive and 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 must include a geothermal operator as a major participant. The Laboratories will provide support for each project (instrumentation, analyses, etc) as needed under Project 2.2.1.1.

This project also entails managing, adding value to, and completing the FY 00 solicitations and the outstanding GDO projects. With the exception of the FY 01 solicitation, all funds involved in contracts are prior year funds and all financial figures listed represent only the unloaded DOE/Sandia share, the industry share is at least as large as the DOE/Sandia share, but usually much greater. With the exception of the FY 00 solicitation and, of course, the recent FY 01 Operator Solicitation ($185K), the remaining projects in this section are outstanding GDO projects, with the exception of one consulstant

Status/Accomplishments:

The FY 01 solicitation was prepared and sent out to a wide distribution in industry and four proposals were received. These proposals were graded by the personnel from the Sandia Geothermal Department and DOE (as a non voting member) and two proposals were selected for awards . Work statements were written for those proposals selected and offers were made to the two selected offerers selected as FY 01 ended.

Design, and Test of a Hybrid Drill bit, Thermasource, FY 00 Solicitation ($50 K remaining in FY 01)--Zones have been identified at the Bottle Rock Portion of the Geysers (Thermasource is the operator as well as being the main sub contractor for bit testing). The historical drilling data was reviewed and the drill bits were designed and manufactured. Thermasource is waiting upon the completion of a rather long permitting process to begin operation and power production in that portion of the Geysers and of course, the attendant testing of the hybrid drill bit.

Slimhole Well Testing and Comparison of Geothermal Power Potential between a Slimhole and a Full Size Well Trans Pacific, FY 00 solicitation, ($50K)--Progress has not been made on this project as there are delays in concluding an agreement between Trans Pacific and the governments of Nicaragua or/and Honduras.

Development of a Foam Cement Retainer/Packer and Development of Optimum Procedures for Deploying Foam Cement Caithness and Weatherford Completion Systems, Outstanding GDO Project, ($31K), --Inflation tests and drilllability tests of the foam cement retainer/packer at the Weatherford Completion were successful. There was an early failure in the inflation test but design changes corrected the difficulty. The change of the Coso Field from Cal Energy to Caithness and the upheavals in the oilfield service industry have caused delays in this work.

Foam Cement Log Interpretation, Cal Energy , Outstanding GDO Project ($100K)--Wells were identified in the CalEnergy Imperial Valley Geothermal Field where Schlumberger was to recalculate the logging data with new algorithims (at no cost to DOE/Sandia) and a literature search on foam cement was concluded. Buy outs of portions of Cal Energy with attendant management changes have caused delays in commencing with the work.

Improved Mud Hammer for Geothermal Drilling, Novatek, Outstanding GDO project ($12.5K)--A universal mud hammer suitable for high temperature drilling was designed and fabricated. After completion of the hammer fabrication, the contract between Sandia and Novatek was closed, and the project was "formally" terminated as all funds have been expended, but close contacts remain. Subsequent testing of the mud hammer was conducted at Tera Tek, under NETL sponsorship, and there are one or two points on a drilling curve that show exceptional ROP at low horsepower for this mud hammer. Further analysis of the data, especially in the parameter space where very high ROP is evident, is being investigated. This was a highly leveraged project, with considerable NETL funding for both Novatek and Tera Tek for testing and for very closely related hammer development.

Adding a Milling Capability to the Valve Changing Tool, Smith International, Outstanding GDO Project ($17.5K) -- A milling capability was added to the valve changing tool and the tool was awaiting a field test. Because of the long delay in obtaining this field test, the contract between Sandia and Smith International was closed by mutual agreement. Nonetheless, Smith International extended Sandia an open invitation to witness the field test whenever it was to be conducted.

Insulated Drill Pipe, Drill Cool ($14K) Outstanding GDO Project--A test was run on (interior) coated insulated drill pipe and from a thermal standpoint the insulation was comparable to the "standard" double walled insulated drill pipe. As a result of field testing some joints of 2 7/8-inch coated drill pipe, questions of the durability of the coating remain. A possible fix, exterior coating, is being considered.

Bill Rickard (consultant, $5K)-- Mr. Rickard assisted Sandia in the preparation of a GRC paper on the successful deployment of polyurethane foam at Rye Patch and providing GWB consultants with elaborate records of the two GRED Rye Patch Cementing Operations. (Under separate contract, Mr. Rickard was prominent in the drilling and polyurethane foaming at Rye Patch.)

Planned FY 2002 Milestones:

Oct 02--Complete FY 01 solicitation. Due to delays in completing the contracts this milestone had to be moved from FY 01. There are no other major milestones but internal milestones are maintained for project tracking.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Near-Term Technology Development/Industry Assistance

Contract/Grant #: DE-AC04-94AL85000	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Allan Jelacic **Phone:** (202) 586-6054 **Fax:** (202) 586-8285 **E-mail:** allan.jelacic@hq.doe.gov	Sandia National Laboratories (SNL) PO Box 5800 Albuquerque, NM 87185-1033
Contracting Organization	**Principal Investigator(s)**
ALO Albuquerque Operations Office	**Name:** George E. Staller **Phone:** 505-844-9328 **Fax:** 505-844-9315 **E-mail:** gestall@sandia.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** 202-586-4198 **Fax:** 202-586-8185 **E-mail:** raymond.LaSala@ee.doe.gov	$152k	$15k

Project Objective:

Assist the geothermal industry with near-term problems related to well construction and maintenance in an effort to reduce well costs and improve viability of the US geothermal industry.

Approach/Background:

Work with industry to evaluate and troubleshoot Laboratory and industry developed technology for geothermal drilling applications. Provide technical consultation and assistance on the operation and installation of devices such as the rolling float meter, mud density meters, data-acquisitions systems, software, etc. Test and evaluate industry-produced instruments at the Wellbore Hydraulics Flow Facility, during field operations, and at an industry partner's facility when requested. Assist geothermal operators with difficult well-logging operations when appropriate.

Development of technologies as a result of the Geothermal Drilling Program such as the Rolling Float Meter, the Pressure/Temperature Spinner Tool, Insulated Drill Pipe and others require technical support to ensure their successful entry into the US geothermal drilling industry. Additionally, geothermal operators and well-service companies periodically seek assistance from Sandia to evaluate new products and solve near-term drilling problems. Examples include tough well-logging jobs, special data acquisition techniques, and data analysis.

Status/Accomplishments:

The contract for the Circulation Monitoring System (CMS) was completed. Cooperative field evaluation tests with geothermal industry users were conducted and the CMS software was evaluated at Sandia with field data supplied by geothermal drilling industry service companies. The newly completed CMS operation manual was utilized during these evaluation tests to verify system operation and manual soundness.

Test results were documented for new lost circulation materials supplied by the geothermal industry and evaluated using Sandia's modified API bridging-materials tester. These materials were then compared with materials previously evaluated at Sandia using the same techniques and test equipment.

Technical consultations with various potential industry RFM users were conducted. Where possible RFM equipment was loaned to industry users for field evaluation studies. Requests for procurement of RFM equipment and cooperative field tests were forwarded to industry sources that are currently manufacturing and providing these instruments for geothermal drilling applications.

Geo Hills Associates provided technical consultation/interface on International Energy Agency issues and the U.S. Geothermal Drilling Industry cost database study.

Planned FY 2002 Milestones:

This work was not funded in FY02.

Major Reports Published in FY 2001:

P.J. Gronewald, A.J. Mansure, and G. E. Staller, August 2001, "Indonesian LCM Evaluation Tests using a Modified API Bridging-Materials Tester", Sandia Report SAND2001-2400.

Major Articles Published in FY 2001:

P.J. Gronewald, A.J. Mansure, and G.E. Staller, August 2001, "Indonesian LCM Evaluation Tests using a Modified API Bridging-Materials Tester", Poster presented at annual Geothermal Resources Council meeting and published in the GRC Transactions, Vol. 25, Page 93.

Acid-Resistant Cements

Contract/Grant #: DE-AC02-98CH10866	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000
Contracting Organization	**Principal Investigator(s)**
Chicago Area Office	**Name:** Toshifumi Sugama **Phone:** (631) 344-4029 **Fax:** (631) 344-2359 **E-mail:** sugama@bnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** raymond.lasala@ee.doe.gov	$140K	$300K

Project Objective:

The objective of this project is to further increase the resistance of CaP cement to acid and to validate long-term autoclave tests of fiber-reinforced cements.

Approach/Background:

Calcium aluminate phosphate (CaP) cement was developed at BNL as a CO_2-resistant cement for wells exposed to temperatures up to 280°C.This work was done in collaboration with Unocal and Halliburton Energy Services. With our collaborators, we successfully used CaP cement to complete geothermal wells in Indonesia. As a result, this cement was commercialized under the trade name "ThemaLock Cement" by Halliburton Energy Services in 1998. In 1999-2000, the commercialized cement became increasingly popular, and was employed in completing many geothermal wells in the United States and Japan. Consequently, this technology received a "2000 R&D100 Award". In 2001, emphasis focused on improving two properties of this CaP cement: One was its acid resistance in the well's surface groundwater at ~ 90 degrees C; the other was its toughness-associated mechanical behavior. The latter property prevents the development of stress cracking caused by low thermal expansion of the cement during the passage of superheated geothermal steam and fluid through the cement-sheathed steel pipes in the injection wells. BNL and Halliburton undertook 6-mo.-acid-exposure tests of newly formulated Al_2O_3-rich CaP cement system. The results showed that a total loss of wight in this new cement system caused by acid was 27 %, corresponding to 20 % less than that of the conventional CaP cement. Also, the data demonstrated that 80 % of the total weight loss occurred in the first month of exposure, reflecting a weight loss of 21.6 % in 30 days. Since the ultimate goal of resistance to acid is less than a 5 wt% loss after a 30-day immersion, a further improvement in the cement is needed to achieve this goal.

BNL investigated ways of preventing the development of microcracks generated by shrinkage and their propagation caused by a low thermal expansion of the cement. One approach then was to incorporate high-temperature stable fibrous materials into the CaP cements to create a composite structure. In this work, carbon microfibers were used as one of the potential materials. The fiber-reinforced cements had the fracture toughness of 0.053MN/m3/2, corresponding to an improvement of ~ 135 % over that of non-reinforced specimens.

Status/Accomplishments:

Over the past four years, CaP cement has been used in a total of twenty-four geothermal wells in Indonesia, Japan, and the United States and is becoming increasingly popular for completing geothermal, oil and gas wells worldwide. In fact, Hallibuton sold a total of 266,700 IBS CaP cement from January through October 2001. This amount corresponded to an increase of ~ 15 %, compared with that in the same period last year. In developing superior acid-resistant CaP cements that show less than a 5 wt% loss after immersion for 30 days in a 90 degrees CH_2SO_4 solution (pH 1.2), we are evaluating the effectiveness of two anti-acid admixtures, water-dispersible high-temperature silicon emulsions and alkaline metal hexafluoro compounds. The physico-chemical factors contributing to lessening the acid erosion of the immersed cement will be investigated, including phase identification and the development of any microstructure in the cement bodies. Integrating all this information will provide us with an ideal formulation for better acid-resistant CaP cements. The newly formulated cements then will be delivered to Halliburton for their independent evaluation before beginning field trials. More recently, BNL succeeded in developing a much tougher CaP cement composite than the carbon microfiber-reinforced composites. Incorporating an advanced Al_2O_3 ceramic microfiber into the CaP cement, we assembled a new composite system. This composite displayed a fracture toughness of 0.06 MN/m3/2, which is 13 % higher than that of the carbon microfiber-reinforced one. Six-month autoclave validation tests of cement composites reinforced with the two high potential fibrous materials, carbon and corumdum, are currently been undertaken. Our focus will be on monitoring the changes in toughness-related properties as a function of autoclave exposure time. Contingent upon the results from the in-house autoclave durability tests, a full-scale field demonstration at Bakersfield, CA, by Halliburton will evaluate its performance in actual use and refine its formulation as necessary.

Planned FY 2002 Milestones:

Complete short-term acid resistant test	Mar 02
Complete delivery of new acid-resistant cement systems	Apr 02
Complete report describing the results of all tests for acid-resistant cement system	Jun 02
Complete 6-month autoclave validation test for fiber-reinforced cement systems	July 02
Complete report describing all the results of testing for fiber-reinforced cements	Aug 02

Major Reports Published in FY 2001:

T. Sugama, L.E. Brothers and L. Weber, “Calcium aluminate cements in fly ash/calcium aluminate blend phosphate cement systems: Their role in inhibiting carbonation and acid corrosion at a low hydrothermal temperature of 90°C” September 2001.

Major Articles Published in FY 2001:

T. Sugama, L. Weber and L.E. Brothers, “Ceramic fiber-reinforced calcium aluminate/fly ash/polyphosphate cement at hydrothermal temperature of 280°C”, Journal Advanced in Cement Research, 13 (2001) 381-391.

III. ENERGY SYSTEMS RESEARCH AND TECHNOLOGY (ESR&T) PROJECTS

Non-Destructive Testing of Corrosion- and Erosion-Induced Damage in Geothermal Piping

Contract/Grant #: DE-AC02-98CH10886	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	
Contracting Organization Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	**Principal Investigator(s):** **Name:** M. L. Berndt and A. J. Philippacopoulos **Phone:** (631) 344-6090 **Fax:** (631) 344-2359 **E-mail:** allan@bnl.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	**DOE Funding Allocation** $275K	**Cost Share Funding**

Project Objective:

The objective of this project is to evaluate improved methods for non-destructive detection of corrosion and erosion-induced damage in geothermal piping systems with emphasis on long range, on-line techniques.

Approach/Background:

Industry responses from our Survey of Operation and Maintenance (O&M)-Related Materials Needs in Geothermal Power Plants (BNL 65677) indicated a specific need for improved non-destructive testing (NDT) methods to detect and monitor damage in piping systems caused by corrosion and erosion-corrosion. Conventional practice is to use ultrasonic wall thickness measurements to determine metal loss. Pipe insulation is removed and the tests are performed in a point-to-point fashion on the pipe exterior. Such tests only give an assesment of pipe condition directly at the measurement point. Thus, damage in adjacent areas may go undetected and result in failure and unscheduled maintenance. BNL initiated a new research project in FY01 to address the need for better NDT methods. The overall goal of the research is to achieve cost savings and improved reliability for geothermal facilities. Our research involves: (a) theoretical investigation of NDT methods as applied to specific problems encountered in geothermal facilities; (b) field demonstration and evaluation of NDT methods with emphasis on on-line, long range techniques; and (c) integration of the results from NDT with remaining strength and life assessment. The purpose of long range methods is to rapidly screen the pipe condition a significant distance from a single location. Methods being considered can give 100% volumetric coverage and do not require extensive removal of insulation. Following long range inspection, conventional NDT (e.g., ultrasonic wall thickness measurements, radiography) can be used to map and quantify the extent of metal loss in the identified area. The project also supports efforts in reliability centered maintenance programs employed by the geothermal industry.

Status/Accomplishments:

In FY01 BNL's NDT program for evaluating corrosion and erosion-corrosion of geothermal piping systems focused on experimental and modeling studies with the objective of applying more reliable and cost effective methods for condition assessment. Several samples of corroded and eroded piping removed from geothermal power plants were studied to determine the morphology and distribution of defects. The pipe segments are ranging between 6 up to 24 inches in diameter and were obtained from diferent parts of geothermal plants including production and re-injection wells. The results from this task are being applied in our investigation of long range ultrasonic methods that can detect such damage in geothermal plants. The samples were also subjected to conventional ultrasonic wall thickness tests. The latter were carried out parametrically with the aim to assess the resolution that is needed to obtain accurate spatial distribution of the observed corrosion and erosion-corrosion.

We completed an in-depth review and evaluation of current applications of ultrasonic guided waves by different industries. Application of low frequency guided waves for NDT of both internal and external corrosion in piping is relatively recent and its use in refineries, chemical plants and other industries is growing. Our review included (a) methodologies of wave propagation and (b) experimental confirmation using different techniques for inducing ultrasonic guided waves in pipes as well as their detection. We concluded that similar methodologies to those currently employed by the oil and chemical industry will also have major benefits to the geothermal industry. The specific requirements related to geothermal piping were compared to the requirements of ultrasonic guided wave inspection. These include potential limitations due to high temperature as well as wave propagation issues.

Under this program BNL is working with several different geothermal power plant operators to arrange field demonstrations and evaluation. Two different transducer types are being considered: piezoelectric and magnetostrictive. In addition, numerical modeling studies are being conducted to gain thorough understanding of the application to geothermal piping and in support of the field tests. Research is also being performed on remaining strength and life assessment subsequent to NDT.

Planned FY 2002 Milestones:

Complete analysis and report on remaining strength and life prediction methods	Feb 02
Visit geothermal power plant to discuss NDT issues and field tests	Mar 02
Complete field evaluation of guided wave method	Aug 02
Document numerical modeling, experimental and field evaluations	Sep 02

Major Reports Published in FY 2001:

M.L. Berndt, Non-Destructive Testing Methods for Geothermal Piping, BNL 68166, March, 2001.

Major Articles Published in FY 2001:

None

Plant Performance Enhancement and Optimization

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401
Contracting Organization National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	**Principal Investigator(s):** **Name:** Desikan Bharathan **Phone:** (303) 384-7418 **Fax:** (303) 384-7495 **E-mail:** Desikan_Bharathan@nrel.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	$200K	

Project Objective:

The project objectives are: 1) to assess system-wide performance and economic characteristics of operating geothermal electric power plants, 2) to identify short and long term performance improvement options and determine their economic viability, and 3) to implement feasible cost-effective measures to generate case studies of successful implementations.

Approach/Background:

Power plants that take a comprehensive, plant-wide, systems approach to increasing energy conversion efficiency, production capacity, and improving its sustainability are of interest. Specifically, chosen projects will result in the adoption of best available and emerging technologies using a variety of tools, information, process engineering techniques, and support systems. The plants would conduct the assessment by initially profiling the entire plant's energy requirements and energy-intensive processes in the form of an energy audit using state-of-the-art process modeling tools. Further assessments would then focus on specific components or systems that would offer the largest cost savings and return on investment. Assessment methodologies and strategies that aim to discover opportunities where the plant's investment in energy conversion efficiency and capacity are maximized are of most interest.

The project goal in supporting plant assessments is to develop case studies that illustrate the benefits of adopting a plant-wide, systems approach strategy across an entire production facility. The summary results, successes, and experiences from these assessments will be published to encourage U.S. geothermal power generators to adopt and implement plant-wide systems approach to increasing energy conversion efficiency, capacity, improve reservoir sustainability, and overall economics for power generation from geothermal resources.

Status/Accomplishments:

The task characterizes the performance of geothermal power plants and investigates methods to enhance their overall performance from a system point of view. One opportunity is to improve the chemistry for the hydrogen sulfide abatement. A chelating agent, Iron chelate, is normally used in the conversion of hydrogen sulfide to soluble thiosulfate. The chelate captures atmospheric oxygen and makes it available for eventual oxidation of the sulfur. Chelate concentrations of 10 ppb are commonly used in the circulating water in the power plants at The Geysers. The chemical costs turn out to be as much as one quarter of the power production cost. With process improvements, there is a potential for reduction of this cost, by decreasing the concentration and the use of chelate substantially.

Calpine Corporation, in collaboration with PG&E Chemical Services group is looking into modifying the oxygenation process for improving the abatement chemical use. NREL will participate as part of this research team in an effort to investigate potential means for reducing the consumption of chemicals in the abatement process. NREL will develop a detailed three-dimensional model of the flow field using a computational fluid dynamics (CFD) model. NREL researchers will identify areas of major resistance to the oxygenation process in the cooling tower risers. NREL may propose modifications to the risers to improve the diffusion of the injected atmospheric air into the circulating water stream. Different options will be considered for evaluation of their practicality.

Planned FY 2002 Milestones:

Develop CFD model of the flow riser for the cooling tower at Unit 11	(I)	June 02
Evaluate alternative arrangements for improved oxygen diffusion and uptake	(C)	Sept 02

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

Continued discussions with Calpine engineers on the various methods by which the chelate consumption may be reduced.

Co-Production of Silica and Other Commodities From Geothermal Fluids

Contract/Grant #: W-7405-Eng-48	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Raymond LaSala Phone: (202) 586-4198 Fax: (202) 586-8185 E-mail: Raymond. LaSala@ee.doe.gov	Lawrence Livermore National Laboratory (LLNL) 700 East Avenue P.O. Box 808 Livermore, CA 94551	
Contracting Organization	Principal Investigator(s): Name: Bill Bourcier Phone: (925) 422-3745 Fax: (925) 422-7438 E-mail: bourcier1@llnl.gov	
Project Officer / Monitor Name: Raymond LaSala Phone: (202) 586-4198 Fax: (202) 586-8185 E-mail: Raymond. LaSala@ee.doe.gov	DOE Funding Allocation $150K	Cost Share Funding

Project Objective:

Develop technologies for extracting marketable silica and other commodities from geothermal fluids.

Approach/Background:

Produced geothermal brines contain large quantities of dissolved silica that often forms scale in power production facilities. The goal of our current work is to develop methods to extract the silica to avoid scaling and produce a marketable by-product. Later work will focus on extraction of other valuable brine constituents such as lithium. The additional revenue obtained through cascaded use of the geothermal resource can reduce the cost of geothermal power.

Previous work has shown that silica precipitation from geothermal brines can be induced by changing the pH, adding salts, and/or cooling. However, the silica produced in on-site tests, for example at CalEnergy's Salton Sea site, was found unsuitable for targeted commercial uses, especially the valuable high-end uses such as rubber filler. The silica was contaminated with unwanted elements, had unacceptably low surface area, and for yet unknown reasons was found to be unreactive in tests and therefore unsuitable for market use.

The purpose of our project is to develop silica extraction technologies that produce marketable silicas from geothermal fluids. We first identify industrial partners interested in pursuing silica extraction tests at their sites. We then perform laboratory tests of simulated site fluids to develop an understanding of the silica precipitation process for that particular fluid and geothermal field. The results of these tests provide estimates of silica yields, precipitation rates, and how silica properties vary with precipitation conditions. These results are used to develop the silica extraction test plan for each site. The plan is focused on generating silicas with properties that match those of commercial silicas. The field work test plan is then carried out at each site using a mobile test facility in order to collect silica samples precipitated over the desired range of test conditions. The silicas are then partially characterized on-site in the mobile test facility, and additional samples archived for later more detailed analysis at LLNL, and sent to industrial end users for real product testing.

Status/Accomplishments:

During FY2001 we carried out laboratory silica extraction tests in preparation for field tests to be performed in FY2002. We will conduct our first field campaigns at the Mammoth and Coso geothermal fields in collaboration with Mammoth Pacific L.P. and Coso Operating Company, respectively. We also have plans to include CalEnergy's Salton Sea and Covanta Energy's Heber fields in later tests. We have conducted laboratory tests of simulated fluids for the Mammoth, Coso, and Salton Sea fields.

Work on simulated Mammoth fluids suggests that we can precipitate about half the contained silica by adding 10 mmol magnesium chloride to the geothermal fluid. The precipitation is rapid and is mostly complete in only a few minutes at 60°C. Mammoth plans to use spent geothermal brine as make-up water for the cooling unit, and silica scale forms as the geothermal fluids are cycled repeatedly through the system. Removal of the silica will eliminate the scaling problem as well as generate additional revenue if a marketable by-product can be produced.

Tests on simulated Coso fluids showed that raising the pH of the acidified brines (Coso uses the brine acidification process to control silica scaling) from 5 to 7 precipitates high surface area silica (~400 m2/g) and extracts about half the contained silica. Adding more base tends to extract additional silica from the fluid. Silica precipitation is also rapid and takes only a few minutes at 80°C. This information helps to constrain the fluid residence time in the reactor used for our field tests.

Silica precipitation tests using simulated Salton Sea geothermal fluids were performed by adding sodium carbonate to raise the pH and induce precipitation. Silica precipitates previously generated using lime to raise the pH were too iron-rich for most commercial markets. Using sodium carbonate causes precipitation of a separate iron carbonate phase in addition to the silica phase, and reduces the iron content of the silica precipitate. This technique produces a much cleaner silica product, and also a metal-rich side stream for additional metals extraction. We plan to further test this process on-site.

We have gathered data on and characterized commercial silicas for comparison with the properties we measure for our geothermal silicas. Useful commercial silicas have high surface areas (~50-400 m2 /g) and are chemically homogeneous. Silica applications include rubber additives, paper coatings, dessicants, odor control products, and various getters in the chemical cleanup industry. We have established technical contacts from the rubber industry and colloidal silica distributors to help identify optimum material properties and likely markets for our produced silicas. Samples collected during our field work will be sent to their laboratories for additional testing that is more specific to the desired application.

For FY02 we have been awarded additional funding for this project from the California Energy Commission (CEC). DOE funding will be used as the required 20% matching contribution. The funding will be used to assemble a mobile test unit and carry out the on-site tests at Mammoth and Coso. The test unit will contain the stirred reactor and all analytical equipment (e.g. particle size and colorimetric silica analysers, pH and conductivity probes etc.) needed to perform the field tests.

Planned FY 2002 Milestones:

Report on field test of silica extraction at the Mammoth site (tentative May 2002, contingent on arrival of CEC funding)

Report on field test of silica extraction at the Coso site (tentative August 2002, contingent on arrival of CEC funding)

Major Reports Published in FY 2001:

Bourcier, W. L. and S. I. Martin (2001). Co-production of silica and other commodities from geothermal fluids. Livermore, Lawrence Livermore National Laboratory, 17 pages, annual report to DOE.

Major Articles Published in FY 2001:

Bourcier, W. L., S. I. Martin, et al. (2001). Developing a process for commercial silica production from geothermal brines. Geothermal Resource Council Transactions, v. 25, p. 487-491.

Component Development for Ammonia/Water Power Cycles

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	
Contracting Organization National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	**Principal Investigator(s):** **Name:** Vahab Hassani **Phone:** (303) 384-7464 **Fax:** (303) 384-7495 **E-mail:** vahab_hassani@nrel.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	**DOE Funding Allocation** $415K	**Cost Share Funding**

Project Objective:

The overall objective of this work is to improve the resource utilization and to reduce the cost of electricity generation form medium- to low-temperature geothermal resources. The specific objective of this project is to study the performance of an absorber/cooler used for heat rejection in cycles that use ammonia/water as working fluid. Currently such an absorber/cooler is not commercially available. The results of this study will provide valuable information to U.S. heat exchanger manufacturers to design most efficient heat rejection units.

Approach/Background:

Our approach in this work is to reduce the cost of electricity generation from geothermal resources by reducing the power cycle capital and maintenance costs through development of inexpensive and efficient components such as the heat rejection component for the power cycle. This work targets systems that utilize ammonia/water as the working fluid, such as the Kalina cycle. Some of the analysis carried out at NREL shows great promise. In some of these cases, brine effectiveness increase is as high as 20% which will result in reduced cost of electricity generation. These new power cycles require development of new components (e.g. absorber/cooler for the heat rejection side) and laboratory or field testing for proof of concept.

A state-of-the-art ammonia/water condensation test facility was assembled at NREL in FY99 to provide the capability of testing condensation of ammonia/water vapor mixtures in various heat rejection configurations such as single shell and single tube (water cooled) and plate-fin (air-cooled). This facility is designed to simulate the condensing portion of a plant. During FY99 and FY00, NREL researchers successfully carried out tests during which heat and mass transfer data were collected for condensation of ammonia-water mixtures at various pressures and concentrations. Several reports and papers (presented at GRC) were published to disseminate the results of our studies. Our testing of the shell and tube configuration showed that heat transfer coefficients can be increased by as much as three fold if mean liquid solution from boiler side is introduced into the condensing section. This is a significant improvement over conventional condensation processes currently used. It is important to note that no heat exchanger manufacturer have designed or built an air-cooled condenser for ammonia/water vapor mixture condensation. Hudson, one of the U.S. largest air-cooled heat exchanger manufactures, is currently working with Exergy to design and built the first air-cooled condenser for one of the Kalina cycles. This design is a single pass fin and tube heat exchanger in horizontal orientation. It is very important to note that this is a cross-flow setup and it will have a smaller log mean temperature difference (LMTD) compared to the counter-current flow. The efficiency of the cycle (or its brine effectiveness) reduces significantly and the initial cost increases considerably if the counter-current cooling is not used because more air should be pumped and more surface area should be provided to make up for the low LMTD.

It is important to note that the horizontal installation of the condenser causes phase separation inside the tubes. Separation of liquid and vapor should be prevented as much as possible because the thermodynamic equilibrium in the component is lost resulting in incomplete condensation. To prevent this situation in horizontal condensers, additional heat exchange area should be provided or non-condensed vapor (mostly ammonia) should be vented out of the component. Addition of extra surface area will mean additional cost and fan power operation. The venting of the excess ammonia from the component would mean that the concentration of the cycle is constantly changing which results in an in-efficient system and is not viable solution. Another approach to prevent liquid and vapor separation is to create annular flow regime inside the tubes. This would require proper distribution of liquid and vapor into each tube and additional pumping power to create such flow regime.

To address the above design issues, NREL researchers have been exploring the innovative idea of using plate-fin air-cooled absorber/coolers. There are several considerations that make plate heat exchangers preferable to the tube & shell heat exchangers. The most important one being that the heat exchanger should be installed vertically to allow for proper mixing of the vapor and liquid to achieve thermodynamic equilibrium while allowing the lean aiding flow to wet the contact surface for an effective absorption process during the heat rejection. This could be achieved more readily by using plate heat exchangers rather than shell and tube. Additionally, for achieving a high effectiveness, a true counter-current flow should be established in the heat exchanger. This is almost impossible with a very long (almost 60 ft) shell and tube heat exchanger. Current designs of tube-fin heat exchangers have cross-flow configurations. Our design for the plate-fin heat exchanger indicates that the plate height can vary between 4 ft to 10 ft. In pursuit of this idea, NREL has built a prototype air-cooled plate-fin heat exchanger. We have completed our first set of tests and a comprehensive report has been completed and submitted to DOE and is available as NREL technical report for U.S. industry to review.

Our approach in this year's activity will encompass the following:

1. Actively pursue close collaboration with a major U.S. heat exchanger manufacturer for proper technology transfer. We have brought Dr. Ken Bell on board as a consultant to NREL to help us modify the existing design of the plate-fin heat exchanger and introduce this technology to U.S. industry.

2. The protoype built at NREL is designed and built such that it will enhance the condensation process of ammonia/water vapor mixture exiting the turbine by introducing a lean liquid mixture to the vapor stream, allowing the vapor to be absorbed into the liquid stream rather than direct condensation of the vapor stream. We will modify the existing liquid and vapor distribution system such that it will be more feasible for mass production.

3. In a parallel activity, NREL is collaborating with HTRI for incorporation of single tube in shell data to HTRI software. HTRI is using NREL's data to model ammonia/water condensation. Their model will be available in their software package for industry use.

Status/Accomplishments:

During the past several months, NREL has completed some modifications to the existing plate-fin configuration. NREL has also completed a comprehensive set of tests, collecting data on pure steam condensation in plate-fin heat exchanger setup. This data will be very useful in comparing the performance of such heat exchanger to existing tube-fin units. NREL and HTRI have been working together to model tube and shell data into HTRI code. This project is in progress and will be completed in Sept. 2002.

Planned FY 2002 Milestones:

- Award of a subcontract for design modifications, and technology transfer to U.S. industry.

- Summary of Progress on development of an air-cooled plate heat exchanger.

- Review of NREL work on the air-cooled plate condenser by industry consultants.

- Completion of implementation of NREL's data in HTRI's code.

Major Reports Published in FY 2001:

Ammonia/Water Condensation Tests: Plate-Fin Heat Exchanger (Absorber/Cooler)

Major Articles Published in FY 2001:

None

Geothermal Direct Use Field Verification

Contract/Grant #:	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401
Contracting Organization National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	**Principal Investigator(s):** **Name:** Russell Hewett **Phone:** (303) 384-7463 **Fax:** (303) 384-7495 **E-mail:** russell_hewett@nrel.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
Name: Raymond Fortuna, U.S. Department of Energy **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** raymond.fortuna@ee.doe.gov	$505K	$271,200 by three subcontractors developing innovative direct use projects

Project Objective:

"Direct use" covers use of a geothermal resource directly for the following applications: industrial process heat and hot water, agricultural process heat, and heating and/or cooling for buildings. The Direct Use Prioject covers technology development, market assessment, field verification, and testing and evaluation relating to geothermal direct use technology. In addition, the task includes providing technical support and assistance services to the DOE/NREL Geothermal Energy Program, project operators, potential users of geothermal direct use projects and project developers. Also, geothermal direct use covers applications that involve use of spent geothermal fluid cascading from other applications, such as geothermal power plants. The goal is to facilitate market acceptance and deployment of geothermal direct use technology (utilizing low-to-medium temperature geothermal resources) as a technically feasible, practical and cost-competitive energy option in the United States. Traditionally, the thrust in the Geothermal Program has been to conduct research and technology development activities to develop large-scale geothermal power plants (i.e., plants greater than 10 megawatts) – focussing on high-temperature geothermal resources. Since, there are a much larger number of lower temperature geothermal resources in the United States than higher temperature sources, stimulation by the Program of the use of the lower-temperature resource for direct use applications (rather than electricity) could vastly increase the number of geothermal resources which would be put to beneficial use. The thrust in the Direct Use Field Verification Project is to improve the technology base and bring in engineering innovation for: (a) use of low-to-medium temperature resources; (b) various applications; and (c) new geographical regions. The objective of this task is to increase the use of low-to-medium temperature geothermal resources by: (1) developing concepts for innovative, "pioneering" direct use geothermal plants that have better economic performances, greater reliability and better "user-friendliness" than today's operating facilities; (2) validating proof-of-concept of their capabilities by constructing and operating them in pilot implementation., and (3) providing technical outreach support to encourage independent direct use projects.

Approach/Background:

One thrust in the Direct Use Field Verification Project is to improve the technology base and bring in engineering innovation for: (a) use of low-to-medium temperature resources; (b) various applications; and (c) new geographical regions. In FY2001, NREL conducted a competitive solicitation to establish multiple collaborative, cost-shared, innovative direct use projects -- each project to be implemented at a site for which a characterized geothermal resource was available for use by the proposing organization. The objective in the solicitation was to fund three-to-five projects that, ideally: (a) included projects in regions or states in which there are few or no projects; (b) included new applications of the technology; and (c) provided sites to field validate proof-of-concept of the technical performance, economic performance and long-term O&M performance of direct use systems for various applications. The solicitation resulted in selction of five organizations for collaborative projects.

The other major thrust in the project is establishing and operating at least two centers of excellence for the NREL/DOE Geothermal Program to provide technical assistance services, technology transfer support and outreach for the following target audiences: (a) developers of geothermal direct use projects; (b) developers of small-scale geothermal power plants; (c) users of small-scale geothermal power plants and direct use systems; (d) organizations interested in formulating geothermal project concepts and determining their technical and economic feasibility; and (e) organizations in the actual process of implementing turnkey projects. During FY2001, NREL conducted a competitive solicitation in which two organizations were awarded three-year "Geothermal Direct Use Technical Support, Testing and Evaluation Support and Analytical Tools Development" subcontracts. The goal is providing technical and other support to the above mentioned target audiences -- as well as local/state/Federal policymakers -- to facilitate market acceptance and penetration.

Status/Accomplishments:

As a result of the competitive solicitation "Development and Field Verification of Innovative Geothermal Direct Use System Concepts" (RFP No. RAA-1-31402), NREL selected five organizations with which to establish subcontracts to design, construct, operate and evaluate the performances of innovative geothermal direct use projects. They are as follows: (a) AmeriCulture; (b) I'SOT; (c) Idaho Water Resources Research Institute/University of Idaho; (d) City of Klamath Falls Oregon; and (e) SKS Properties.

Each project is organized into two phases. Phase I (approximately six months) involves: (a) formulating the optimized design for the system (including performance monitoring instrumentation); (b) estimating its installed cost; (c) assessing its expected technical and economic performances; and (d) developing the draft business plan, including the market plan for using the system.

Phase II (which will last about 36 months) involves: (a) finalizing the design for the system and completing all permitting; (b) constructing the system and installing the performance monitoring equipment; (c) operating the system and monitoring its performance for 24 months; (d) collecting and analyzing the performance monitoring data; (e) defining and conducting a technology transfer/outreach effort; (f) determining the "lessons learned" from pilot operation and specifying recommended R&D efforts to make the system concept as compatible as possible with the end-use and economically competitive. Three of the awardees (I'SOT, University of Idaho and SKS Properties) are conducting their Phase I projects. NREL is in the process of completing award of subcontracts to AmeriCulture and the City of Klamath Falls.

During FY2001, through the competitive solicitation "Geothermal Direct Use Technical Support, Testing and Evaluation and Analytical Tools Development" (RFP No. RAA -131490), NREL selected two organizations to receive three-year subcontracts. They were: (a) Geo-Heat Center of the Oregon Institute of Technology (Klamath Falls, OR); and (b) Cooperative Extension Energy Program of Washington State University (Olympia, WA). Each subcontract involves: (a) providing geothermal direct use technical support to DOE, NREL, project operators, prospective project developers and local/state/Federal policymakers; (b) collecting and analyzing operational and maintenance (O&M) data from operating projects; (c) conducting near-term research, testing and evaluation efforts relating to commercially-available equipment to improve cost-effectiveness and user-friendliness; (d) developing, cataloging and documenting geothermal direct use software; and (e) generating a database of direct use project case studies. During FY2002, technical assistance services were provided to over 100 organizations. In addition, over 2.0 million "hits" were recorded on the website for the technical assistance project.

Planned FY 2002 Milestones:

(1) Completion of Phase I of the subcontracts by the five organizations that were awarded subcontracts through the "Development and Field Verification of Innovative Geothermal Direct Use System Concepts" Solicitation (Aug 02)

(2) Completion of a "draft" CD documenting relevant spreadsheets and programs applicable for direct use project design and analysis and a report in WORD providing documentation regarding the software by OIT and WSU (Sep 02)

Major Reorts Published in FY 2001:

Lund, John, "Final Report: Geothermal Direct Use Technology Technical Support", Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, OR, October 2001.Jot

Major Articles Published in FY 2001:

None

Enhanced Heat Rejection Systems

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	
Contracting Organization National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	**Principal Investigator(s):** **Name:** Chuck Kutscher **Phone:** (303) 384-7521 **Fax:** (303) 384-7540 **E-mail:** chuck_kutscher@nrel.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond.LaSala@ee.doe.gov	**DOE Funding Allocation** $325K	**Cost Share Funding**

Project Objective:

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, combinations of air and water-cooled condensers, and improved water-cooled condensers. Our goal is to reduce electricity cost 0.5-cent per kWh.

Approach/Background:

Because of the thermodynamics of operating power cycles at typical geothermal resource temperatures, approximately 90% of the heat extracted from the ground must be rejected to the environment. As a result, 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 clean 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 40% due to elevated air temperatures.

NREL has developed spreadsheet and other computer-based models to evaluate the impact of improved condenser designs and operation strategies. One key result to date has suggested that the use of lower design flow rates in air-cooled condensers can reduce the total electricity cost. NREL has used the models to compare different fin designs for air-cooled condensers, and we have identified potential performance improvements in using plate fins in place of helically wound fins. In particular, research efforts have included the prototype construction of a new plate fin design that uses perforations to increase local heat transfer on the fin surface. We are working with Super Radiator Coils, a manufacturer of plate fins to compare the heat transfer and pressure drop performance of both plain plate fins and perforated plate fins to helically-wound fins. Work on improved fins is motivated by the fact that thermal resistance is higher on the air side than the working fluid side. However, hydrocarbon condensation is relatively inefficient compared to steam condensation, so improvements to tube-side heat transfer also warrant consideration.

NREL developed a spreadsheet to compare the cost and performance of various options for evaporatively pre-cooling air. This work has shown that the use of a deluging system or Munters packing 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 are also investigating ways to combine water cooling with air cooling and, in cooperation with the Field Verification task, we are investigating the potential advantages of using evaporative condensers instead of shell-and-tube condensers at the new Empire 1 MW power plant.

Status/Accomplishments:

- Reviewed responses to CBD announcement soliciting industry partners. Based on NREL contacts with numerous manufacturers, identified Super Radiator Coils as interested partner and began collaboration

- Completed Fluent runs to better define heat transfer coefficients in perforated fins and incorporated new correlations into our Visual Basic model.

- Completed literature search and detailed spreadsheet model comparing four evaporative precooling systems and completed report. (September 1, 2001)

- Provided technical support to Mammoth Pacific in their efforts to understand the performance of their evaporative pre-cooling system and arranged to make a site visit to take measurements (visit was made on October 2, 2001).

Planned FY 2002 Milestones:

Establish a CRADA with Super Radiator Coils	(C)	Mar 02
Fabricate two transpired plate fin-and-tube heat exchanger prototypes and a non-perforated plate fin-and tube	(I)	Mar 02
Obtain independent test results on the heat exchanger prototypes and decide on next steps for improving overall air-cooled condenser performance	(C)	Apr 02
Assist power plant operators with development of evaporative cooling systems	(I)	May 02
Incorporate a series evaporative condenser into spreadsheet model of cooling enhancements	(C)	Jul 02
Complete paper on various evaporative pre-cooling methods, including series cooler and deluging finned and non-finned tubes	(I)	Sep 02

Major Reports Published in FY 2001:

Report on spreadsheet analysis comparing four different means for evaporatively pre-cooling the air to air-cooled condensers (September 2001)

Major Articles Published in FY 2001:

None

Field Verification Project

Contract/Grant #:	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	
Contracting Organization National Renewable Energy Laboratory (NREL) 1617 Cole Blvd Golden, CO 80401	**Principal Investigator(s):** **Name:** Chuck Kutscher **Phone:** (303) 384-7521 **Fax:** (303) 384-7540 **E-mail:** chuck_kutscher@nrel.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond.LaSala@ee.doe.gov	**DOE Funding Allocation** $770K	**Cost Share Funding**

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 in the FY 2000 solicitation.

Approach/Background:

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. Only Milgro-Newcastle requires locating and drilling a production well. Phase I work on all three projects began in FY 2001. The DOE Golden Field Office with NREL providing a technical monitor is managing the Exergy-AmeriCulture project. The other two projects are managed by NREL, with each also having an NREL technical monitor. NREL assembled a design review team including NREL personnel and outside consultants to participate in design reviews.

Status/Accomplishments:

- Empire Phase I design review and report were completed April 2001
- Exergy-AmeriCulture Phase I design review and report were completed August 2001
- Milgro-Newcastle completed electrical resistivity profiles in May 2001 and completed report on two slim holes in August 2001.
- NREL provided technical design support via ASPEN modeling to the Empire and Exergy Phase I efforts.

Planned FY 2002 Milestones:

Empire:

Empire Phase II design review	(C)	Aug 02
Begin Empire construction	(I)	Sep 02

Milgro:

Complete final slim hole	(I)	Jan 02
Complete production well	(I)	Feb 02
Preliminary design review	(C)	Sep 02

Exergy-AmeriCulture:

EA process complete	(C)	Apr 02
Begin ordering equipment	(I)	Sep 02

Major Articles Published in FY 2001:

Empire Phase I Design Report, April 2001.
Exergy-AmeriCulter Phase I Design Report, August 2001.

Major Articles Pbulished in FY 2001:

None.

Silica Scale Inhibition

Contract/Grant #: W-7405-Eng-48	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Lawrence Livermore National Laboratory (LLNL) 700 East Avenue P.O. Box 808 Livermore, CA 94551
Contracting Organization	**Principal Investigator(s):** **Name:** Raold Leif **Phone:** (925) 422-2469 **Fax:** (925) 422-0208 **E-mail:** leif1@llnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: **Phone:** **Fax:** **E-mail:**	$300K	

Project Objective:

Inhibit the formation of silica scale in geothermal power plants.

Approach/Background:

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 its 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. Effective and economical scale control can reduce the operations and maintenance costs associated with preventing scale formation and/or removing and disposing of scale. 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.

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). Antiscalants, or inhibitors, intervene in 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 evaluate 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. We will develop a relatively rapid, reliable and robust sampling and experimental protocol for evaluating inhibitor formulations. We will obtain a basic understanding of the effect of the inhibitors and, by on-site sampling and analysis techniques, better define the initial chemical and physical state of the brine at the point of inhibitor addition to better select appropriate inhibitors.

To achieve our goals, we conduct laboratory and field tests of commercially available silica scale inhibitors. We first screen the inhibitors in laboratory tests to determine their effect on silica reactions, and then conduct on-site field tests of the most promising inhibitors in collaboration with industrial partners. We are assembling a mobile test facility containing required analytical equipment for on-site testing in FY02. Our ability to monitor brine chemistry, silica concentration and particle size of precipitated silica during the laboratory and field tests allows us to study some of the more difficult aspects of controlling silica scale using polymeric antiscalants, such as thermal stability of the additives, dispersant behavior as a function of brine chemistry and solution temperature, dosage response of additives, and effectiveness of dispersants as a function of particle size. Our independent evaluations of the products of multiple vendors is complemented by a more complete understanding of inhibitor action. Our mobile testing facility will allow us to better characterize the system to which the inhibitor is added. The state of polymerization at the point of treatment is a critical factor in choosing a threshold inhibitor or dispersant. The presence of rock "dust" or other sources of nucleation sites in the incoming geothermal brine must also be considered, and can be tested with our mobile testing facility.

Status/Accomplishments:

In FY01, we conducted laboratory experiments to screen commercial inhibitors for their ability to inhibit silica scale in geothermal brines by acting as threshold inhibitors and/or dispersants. A number of inhibitors, originally designed for reverse osmosis and cooling water applications, were included in the testing. Water soluble polymeric silica scale inhibitors were used, and in particular the polyacrylate class of homopolymers, because these polymers exhibit the thermal stability necessary for higher temperature geothermal applications. Our research suggests that antiscalants originally targeted for low temperature reverse osmosis and recirculating cooling water applications have the potential for inhibiting silica polymerization, and hence silica scale.

The laboratory scaling experiments used to evaluate the effectiveness of scale inhibitors were conducted at room and elevated temperatures in stirred batch reactors using both simple control solutions and complex simulated geothermal brines. Experiments focused on a simulated, medium salinity Coso brine in preparation for the planned FY02 field testing campaign at the Coso geothermal field (Coso Operating Co.). The kinetics of silica polymerization was tracked by measuring monomeric silica using the silicomolybdate method, and total silica was quantified by atomic absorption. The size distribution of amorphous silica particles was measured by dynamic light scattering. Additional analytical measurements, employed as needed, included elemental analysis of scale deposits and 29Si NMR of the solutions and scales.

In FY01 we also established a wide number of industrial contacts and collaborators which include Philippine Natl. Oil Corp.-Energy Development Corp. and inhibitor manufacturers/distributors (BetzDearborn, FMC, Goodrich, PerLorica, Biolab, Nalco). Field tests of antiscalants will occur in conjunction with on-site silica extraction tests at the Coso and Mammoth (Mammoth Pacific L.P.) geothermal fields in FY02 (see LLNL project "Co-production of silica and other commodities from geothermal fluids). Initial work in FY02 is focused on the laboratory screening of inhibitors for Mammoth. Mammoth plans to use spent geothermal brine as make-up water for the cooling unit, and silica scale forms as the geothermal fluids are cycled repeatedly through the system.

We also purchased a particle size analyzer in FY01 that is specially designed for silica particle analysis that we can take with us into the field for the on-site tests as well as use in the laboratory.

Planned FY 2002 Milestones:

Complete first field test of anti-scalants at Mammoth	(I)	May 02
Complete second field test of anti-scalants at Coso	(I)	Aug 02

Major Reports Published in FY 2001:

Lief, R. and Roberts, S., 2001, Silica Scale Inhibition: Annual Progress Report: submitted to DOE, October 2001.

Major Articles Published in FY 2001:

None

Advanced Processes for Geothermal Brine Multiple Resources

Contract/Grant #: **DE-AC02-98CH10886**	**Contract/Grant Period:** **FY 2001**

Sponsoring Office Code: **EE-12**	**Performing Organization**	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	
Contracting Organization Brookhaven National Laboratory P.O. Box 5000 (Building 526) Upton, New York 11973-5000	**Principal Investigator(s):** **Name:** Mow Lin **Phone:** (631) 344-3064 **Fax:** (631) 344-7905 **E-mail:** mow@bnl.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	**DOE Funding Allocation** $100K	**Cost Share Funding** $120K

Project Objective:

As part of the overall Geothermal Energy Research program which is aimed at the development of economical geothermal resource production systems, the aim of the Processes for Geothermal Brines and Residues effort is the development of economic and environmentally acceptable methods for treatment of geothermal by-products and their conversion to commercially viable products. This includes treatment of geothermal mineral rich precipitates (MRPs) and mineral rich brines (MRBs) into silica products. Successful commercialization of end products should generate revenues, which will offset the overall costs of geothermal power production. The anticipated net result is minimum or no waste disposal and increased revenues. Geothermal silica R&D is a two fold approach: 1) Production of quality silica, and 2) Prevention of scaling.

After the extraction of silica, the chemical properties of the injection brine change. The reduction of silica concentration reduces silica scale formation in injection piping, booster pumps and injection wells thus further reducing the operational costs of geothermal power production.

This R&D effort is conducted in collaboration with Caithness and industrial groups and educational institutions.

This work may support, at a minimum level or concurrently as appropriate, the Technology Transfer and Science Education missions of the Department of Energy.

Approach/Background:

Geothermal brines vary greatly in mineral content. In general, due to to the high salt concentration and its associated complex chemistry, it is very difficult to recover minerals selectively and accomplish it economically from high salinity geothermal brines. However in the low salinity brines, the quality of starting materals is superior due to the lack of ion-complexes and lack of significant interfering species when process streams are implemented. Because of this high quality resource the processing becomes significantly more cost-efficient and attractive. In high quality low salinity brines, species such as borate, silica, lithium, cesium and others can become commercially attractive materials for extraction.

Status/Accomplishments:

The program was under funded. However, a process was designed for a pilot plant test conducted in Dixie Valley, NV. The plant tapped from the primary reinjection line was tested at brine feed of 5 gallons per minute at a temperature of 230 degree F and pressure of 140 psig. The silica product is high in purity and surface area. The overall yield is about 60%.

The process has won the R&D 100 award in 2001

Planned FY 2002 Milestones:

Study and modification of the process will be conducted for geothermal brines from the Coso, Steamboat, Beowawe reservoirs.

Major Reports Published in FY 2001:

Reports were sent to DOE.

Major Articles Published in FY 2001:

Mineral Recovery: A Promising Geothermal Power Production Co-Product, Mow S. Lin, Eugene T. Premuzick Wei M. Zhou, and Stuart D. Johnson, Geothermal Resources Council Transactions, Col. 25, Autust 26-29, 2001.

Mitigation of Impact of Off-Design Operation

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830	
Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** **Name:** Greg Mines **Phone:** (208) 526-0260 **Fax:** (208) 526-0969 **E-mail:** minesgl@inel.gov	
Project Officer / Monitor **Name:** Joel Renner **Phone:** (208) 526-9824 **Fax:** (208) 526-0969 **E-mail:** rennerjl@inel.gov	**DOE Funding Allocation** $140K	**Cost Share Funding**

Project Objective:

The project supports the geothermal program objective of reducing the levelized cost of electricity. The task objective is to identify and evaluate methods of minimizing the effects that operating at off-design conditions have on the power generation from geothermal binary power plant, and to define operational schemes that will increase plant revenues and minimze operating costs.

Approach/Background:

Because geothermal binary power plants utilize a relatively low energy source, their performance is significantly impacted by changes either in the heat source (brine) or sink (ambient) temperatures. This is particularly true of binary plants using air cooled condensers where the total available energy (the maximum ideal power that can be produced between heat source and sink) decreases by up to 40% during a summer day, when typically the demand (and market value) for power is the highest. Similar, though smaller, decreases in the total available energy occur with a decline in the resource temperature.

In this task, investigators are analytically examinimg the operation of an air-cooled binary plant to identify methods by which a plant operator can minimize the impact of these changes on component and plant performance, increasing the power available for sale. One approach considered was to cycle production from the resource, over-producing during periods of high revenues and cutting production during periods of low demand to allow the resource to recover. A concurrent approach identified how the plant performance was being limited, and evaluated technologies that could alieviate those limitations. In these analytical studies, investigators have modeled a binary plant, based upon the design of existing plants. The model predicts performance of each of the plant components at a given off-design condition, allowing the operating conditions to be identified which provide the optimum net power production. The analysis also allows investigators to identify the components or portions of the power cycle where the total available energy is being consumed (or rate of consumption is increasing). This allows investigators to target specific parts of the power cycle where improvements in performance will increase the net power production. It is envisioned that the techniques and methods that are developed will have application to both exisitng power plants and new plant designs to provide operational flexibility that will increase revenue streams and extend resource life. As concepts are identified with the potential to increase power production at the off-design conditions, investigators will work with industry to incorporate these concepts.

Status/Accomplishments:

Investigators have evaluated cycling resource production in response to market demand and the potential benefit of this cycling on revenue streams (using historical deregulated power price data in California). These studies identified scenarios where an operator could increase revenue streams, while decreasing the total brine usage. Results were presented at the 2000 annual Geothermal Resources Council meeting.

Models have been developed of binary plants that are similar to the Holt-designed plants at Mammoth and Steamboat. In FY 2001, the models were moved from EXCEL spreadsheets to an ASPEN Plus process simulator. This change allowed more detailed plant simulations to be conducted, accounting for pump curves, changes in heat transfer coefficients, changes in turbine performance, frictional losses, etc.. The move also facilitated the use of a second law, or available energy, analysis of the modeled plant conditions. This type of anlaysis allows one to identify which portions of the cycle are largest "consumers" of available energy, and are most likely to have the largest benefit if their performance could be improved. The modeling effort first examined the impact of changes in the ambient temperature on plant performance at the design brine conditions. Results indicated that the ability of the plant to convert the available energy in the brine to power (net) degrades as the air temperature rises (the 2nd law efficiency decreases with the ambient air temperature). This result was also obtained at off-design brine conditions, though the magnitude of the decrease in the 2nd law efficiency changed at the different brine scenarios. Results for the different off-design brine conditons indicate the 2nd law efficiency increases at a given air temperature as the brine flow rate decreases (with a constant brine temperature). Converseley, for a fixed brine flow rate, 2nd law efficiencies of the modeled plant decreased (at a given air temperature) with the brine temperature. The increased irreversibilitiy associated with the decreased turbine efficiency has one of the largest impacts on plant performance at the off-design conditions evaluated.

Investigations are currently examing concepts with the potential to improve performance. One concept evaluated was the use of modified turbine inlet condtions (reduce the constraint on turbine inlet superheat). These modified inlet conditions are an operational change and incur minimal cost to the plant. Their projected beneficial impact on performance increases as the brine conditions deviate (especially temperature) from design. Their impact is also largest at the cooler ambient conditions. At air temperatures (80 – 100 F) typical of summer days, they have minimal benefit. These types of expansions have been applied and used in the operation of the binary plants near Mammoth Lakes CA.

The use of variable frequency drives (VFD) to better manage parasitic power loads in the power plant has also been evaluated. At design brine conditions, the potential benefit does not warrant the cost of using the VFD's to off-set the impact of the varying ambient temperatures. At off-design brine conditions, their impact on net power becomes more significant. The modeling suggests there would be more benefit to using this device on the working fluid pumps than condenser fans. In addition to providing an effective method of managing the parasitic loads, the VFD's provide the operational flexibity to reduce or increase plant output in response to demand. Investigators continue to examine different potential schemes for improving plant performance, including the practicality of varying turbine speed to maximize efficiency.

Planned FY 2002 Milestones:

Mar 02 Report 2nd law analysis of binary plants and benefit of concepts identified with potential to mitigate impact of off-design operation

Jul 02 Complete study of 2nd law analysis of flash-steam plants and evaluation of concepts that minimize impact of off-design operation.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Power Plant Costing Methodology

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** **Name:** Greg Mines **Phone:** (208) 526-0260 **Fax:** (208) 526-0969 **E-mail:** minesgl@inel.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
Name: Joel Renner **Phone:** (208) 526-9824 **Fax:** (208) 526-0969 **E-mail:** rennerjl@inel.gov	$90K	

Project Objective:

The objective of this task is to develop a methodology for providing representative costs for the different types of energy conversion systems used for the generation of electrical power.

Approach/Background:

The viability and future growth of the domestic geothermal industry is contingent upon reducing both operating and capital costs. While historical costs in terms of $/KW installed, provide a relative perspective on the overall plant costs, they do not easily allow one to evaluate how performance, design or cost improvements will lower costs. In this task, investigators are developing methods to determine the costs of power plants in detail sufficient to assess the large cost items and the impact of research on the cost of these plant components/systems. The methodology being developed is based upon publicly available costing information and commercially available software. As the methodology is developed for a type of energy conversion cycle, this conversion system is modeled using, where possible, the equipment specifications from commercial plants to assure that component sizes and materials are typical of those used in geothermal facilities. The modeling activity establishes process flows, temperatures, pressures and components sizes necessary to produce a desired power output. The costing methods are then applied to the model results to derive component, system and plant costs. The costs are then refined using confidential, industry supplied cost information for the plant type of interest.

Status/Accomplishments:

Efforts to date have focused on developing a method to establish costs for binary power plants having a design and construction typical of those used by the industry. The initial effort in this task was to model an air-cooled binary power plant (15 MW) using the ASPEN Plus process simulator. The model results were based upon the design brine and ambient conditions for existing commercial plants. Predicted components sizes were compared to those indicated on equipment specifications obtained from plant operators. The review of publicly available cost information indicated this information was dated, and did not provide the desired detail. Rather than attempt to update and modify existing costing methods (like the value-analysis), a commercial software package (ICARUS PE) was purchased. This software package interfaces with ASPEN to obtain the information it requires to develop component and plant costs. It also allows users to modify input to provide additional detail on equipment and costing factors. Investigators used ICARUS and the ASPEN results to develop costs for the 15 MW air-cooled binary plant. The resulting costs were transmitted to binary plant operators and developers for review and comment. The industry feedback was then used to "calibrate" the costing methodology (the ICARUS cost model). A report on the development of the costs for these plants was drafted and forwarded to peers for review. Comments have been received, and will be incorporated into a report to be issued in FY 2002.

Planned FY 2002 Milestones:

May 02 Develop methodology to obtain costs for flash-steam plant.

Sept 02 Incorporate methodology to estimate well field costs into plant costing method.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Removal of Non-Condensable Gases From Binary Power Plants

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830
Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** **Name:** Chuck Mohr **Phone:** (208) 526-9552 **Fax:** (208) 526-4017 **E-mail:** mohrcm@inel.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

Validate the use of a membrane-based technology as a cost-effective means for continual removal of non-condensable gases from binary power plant condensers. Successful development of this technology will minimize the performance penalty associated with these gases and will reduce the working fluid loses associated with current removal methods.

Approach/Background:

Discussions with operators of binary geothermal plants, combined with review of the operating procedures for such plants, has identified a process inefficiency that results from the presence of non-condensable gases (NCG's) in the condensers of the plants. The NCG's elevate the condenser pressure, reducing the turbine pressure drop and decreasing turbine output. NCG's are gradually introduced into the system and accumulate in the condenser, gradually decreasing turbine output. This inefficiency is recognized by the industry, and it is alleviated by periodic purging of condenser vapors to remove the NCG's. However, during the buildup of the NCG's to the concentration at which purging is performed, the plant operates at gradually decreasing efficiency. Industrial contacts expressed considerable interest in a system that would maintain a low concentration of noncondensibles in the condenser vapors by continually removing them, rather than allowing them to increase to where purging was needed. INEEL engineers suggested that a membrane-based system would be capable of performing this continual removal.

Beginning in the '80s, membranes have been developed by Membrane Technology and Research (“MTR”, Menlo Park, CA) to separate condensible organic vapors from noncondensible gases. MTR has applied the process based on these membranes to separating NCG's from several organic vapors, but not those of interest to the geothermal industry. Developing the technology for geothermal application involves demonstrating that these membranes are effective in separating air from the specific working fluids used, and then engineering and testing an integrated system that will operate effectively under conditions anticipated in geothermal plants.

In working to apply this technology to binary power plant operations, investigators utilized the approach of first quantifying the magnitude of the NCG buildup, and then identifying the gas consitituents and introduction rates. This information is used to size, design and construct a prototype unit that will be field tested to validate its ability to remove the NCG's continuously, with reduced working fluid losses. Industry participation is critical to conducting the field validation test.

Status/Accomplishments:

The concept of using a membrane system for continual removal of non-condensable gases was evaluated using a two-step process. First, operating data from a from binary power plant was analyzed to estimate the dependence of turbine output on condenser pressure. Combined with the condenser pressure history of the plant, an overall benefit of a continual low NCG content in the condenser was estimated and the resulting increase of power output and revenue was calculated. Testing of membranes for this application was done in early FY01 via a subcontract to MTR. Two membranes were tested; an organic-selective membrane and an air-selective one. These tests showed that both of these membranes were well suited to this application. Using the data from these tests, a conceptual design was prepared and analyzed. Incorporating the plant performance data indicated that this membrane system would be capable of increasing plant output by two to seven percent. Because of the low rate of introduction of air into the condenser vapor (on the order of several grams air per hour), only a small membrane system will be needed, hence it should be low-cost compared to its potential benefit in increased plant output and revenue. Approval was obtained form DOE to proceed to full-scale prototype testing, and MTR was subcontracted to build the prototype and support installation and testing.

Two commercial geothermal plants (Mammoth and Steamboat) have volunteered to host tests of the prototype. These two plants will allow the prototype to be tested with two different working fluids, isobutane and isopentane. Both the air- and organic-selective membranes will be tested in the prototype. MTR and INEEL personnel have met at the first test site and coordinated siting, power, condenser vapor and liquid return hookups, and details concerning monitoring and data acquisition. Delivery of the prototype to the Steamboat plant is expected in late February 2002, where it will be tested in an isopentane working fluid system.

Planned FY 2002 Milestones:

Complete fabrication of prototype system and deliver to Steamboat facility	Mar 02
Complete first prototype membrane test at Steamboat	Aug 02
Present test results at Geothermal Resources Council technical meeting	Aug 02
Complete installation of prototype system at the Mammoth facility	Sept 02

Major Reports Published in FY 2001:

“Continual removal of non-condensable gases for binary power plant condensers” by Charles Mohr, (presenter), Greg Mines, and Kit Bloomfield; presented at the 2001 Geothermal Resources Council annual meeting (San Diego, CA, August 2001).

Major Articles Published in FY 2001:

None

Improved Coatings for Geothermal Pipes

Contract/Grant #: DE-AC07-99ID13727	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
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Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
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Project Objective:

In support of the geothermal program goal of reducing the cost of producing power from geothermal energy this effort will reduce the maintenance cost due to corrosion. This task investigates the functionality of thermally sprayed coatings for geothermal applications as a substitute for costly bulk materials. Both the technical feasibility and the potential to reduce costs will be validated so that geothermal companies can directly acquire the services from coating companies. The cost reduction of using interior coatings vs bulk alloys is considered a 10:1 reduction due to capital costs and labor savings.

Approach/Background:

Extreme geothermal operating environments force the use exotic materials for piping and components, or require frequent replacement of these components if standard materials of construction are used. The application of thermal spray coatings on exposed steel (or other commonly used alloys) surfaces has the potential to provide the same corrosion and scaling protection as the exotic materials, but at a lower cost. This activity addresses the issues industry has faced in using these coatings, including their application to internal surfaces, appropriate coating materials, and the associated economics. The greatest issue preventing the geothermal industry from using thermal spray has been the inappropriate selection of a coating for a particular environments because of lack of materials evaluation beforehand. The resulting failures inhibit the future use of thermal spray coatings in this or other applications. The general approach is to establish a thorough understanding of the operating environment and materials evaluation before the coatings material is selected. The primary task will be to develop the methodology for the materials evaluation and the application of the coating, that will allow a geothermal user to develop the specification that will result in the successful procurement of a thermal spray coating.

The capability to spray coatings down the interior of piping has just recently been developed. This capability has the potential to be used in the field to repair or "retrofit" existing piping systems, as well as in the fabrication of new pipe. The INEEL will support the development of this capability to thermally spray coat the inside of piping and vessels in geothermal applications. The INEEL is bringing the prototype system out of the shop floor to the field and increasing its capacity up to industrial scale. Both the geothermal industry and the coating manufacturers need the performance data from the tests to produce a fabrication specification. The INEEL is recognized as having the technical experience to design the tests and analyze the coatings against the performance requirements.

Status/Accomplishments:

In FY2001, working arrangements were established with operators at the Salton Sea and The Geysers to test these coatings under actual operating conditions. Preliminary meetings were held with the facility staff engineers to identify areas of the plants that would benefit from robust interior coatings. Requirement documents were produced that described the environment and process conditions. Based on these conditions, a materials evaluation report was created for a specific application recommending materials and methods to apply the materials. A test plan to evaluate the recommended materials was created,and then reviewed and approved by CalEnergy. As part of this effort a coupon tree for material testing was also designed and included in the review and approval process by CalEnergy. This level of analysis and preparation were necessary to ensure that the performance requirements were be met by the fabrication specification for the corrosion coupons. The response by the operating engineers in the geotheraml industry has been very positive.

Both the coupons of the four materials selected for testing at CalEnergy and coupon tree for holding the coupons were fabricated at Flame Spray Industries under the direction of Zatorski Coating Company.

Interfacing with CalEnergy and Calpine engineers also provided initial data for evaluating the economics of using these piping sections currently fabricated with exotic materials. The potential cost savings is illustrated by comparing a pipe spool fabricated with an exotic material at a cost of $20,000, with the estimated $3000 cost for an equivalent carbon steel pipe ($1,000), thermally spray coated with the same nickel alloy ($2,000).

A presentation was made to National Association of Corrosion Engineers (NACE) members in September 2001 at a Western Regional Conference in Portland, OR. The presentation discussed the selection of materials and particular thermal spray approach. The discussion raised many ideas about full scale operations of coating operations in the field.

Planned FY 2002 Milestones:

Remove the coupon tree at the Salton Sea facility; evaluate the materials.
Fabricate piping section with selected material and install at Salton Sea facility.
Install piping spool at Calpine facility.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Geothermal Plant Process Monitoring

Contract/Grant #: DE-AC07-99ID13727	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**	
DOE HQ Program Manager: Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	Idaho National Engineering and Environmental Laboratory 2525 North Fremont Ave P.O. Box 1625 Idaho Falls, ID 83415-3830	
Contracting Organization U.S. Department of Energy-Idaho Operations 850 Energy Drive Idaho Falls, ID 83401	**Principal Investigator(s):** **Name:** Judy K. Partin **Phone:** (208) 526-0260 **Fax:** (208) 526-5327 **E-mail:** jk6@inel.gov	
Project Officer / Monitor **Name:** Greg Mines **Phone:** (208) 526-0260 **Fax:** (208) 526-0969 **E-mail:** minesgl@inel.gov	**DOE Funding Allocation** $260K	**Cost Share Funding** $15 Industry In-Kind

Project Objective:

The objective of this program is to lower the cost of geothermal power production through the development and verification of low maintenance instrumentation for the real-time detection and control of various process parameters.

Approach/Background:

Geothermal plants contain gaseous 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 or the consumption of energy. They are also conservatively applied, in part because the targeted species are only measured periodically. Examples of these processes include the over-application of iron chelate to ensure hydrogen sulfide emissions from cooling stacks remain within the regulated limits or excessive steam washing to remove particulate and reduce chloride concentrations to levels that will not damage plant components. Steam washing reduces the steam's energy content and may also contribute to erosion damage and scaling by adding moisture to the system. Losses in turbine efficiency due to scaling can approach 5%, or $650,000 in lost revenue per year for a 50 MWe plant, while the cost to replace a damaged turbine is on the order of $5,000,000. The overuse of chemicals for abating hydrogen sulfide in a typical plant is estimated to cost $75,000 to $100,000 annually. In addition, the existing data collection techniques used to control these processes are labor intensive and cannot be performed in all process streams of interest, resulting in reduced operational efficiency and increased costs.

This project is directed at the identification, proof-of-concept testing, and field demonstration of new instrumentation capable of performing reliable, on-line measurements for geothermal process control applications. These instruments exploit new techno-logies that have been developed for the telecommunications industry and include new solid state diode lasers, large bandwidth, high sensitivity detectors, and low loss optical fiber components. Initial efforts were aimed at evaluating systems for the real-time monitoring of hydrogen sulfide in geothermal process gas streams. A system, based upon a frequency-modulated laser spectro-scopy technique, has been successfully developed and fielded that is capable of measuring process hydrogen sulfide levels at the part-per-million level. A similar instrument has been evaluated for the detection of hydrogen chloride in steam.

In FY-2001, the work was expanded to investigate the application of improved light-emitting diode technologies for measuring the moisture content of steam and the development of a particulate characterization system based upon new high-performance diode-pumped laser technologies.

Status/Accomplishments:

A hydrogen sulfide monitoring system, based upon near-infrared, frequency-modulated diode spectroscopy was successfully demonstrated at the Northern California Power Agency Unit 2 in November 2001. The system sampled a slip stream from the treated vent gas exciting the Stretford system and operated for periods up to ten weeks with no operator intervention. The instru-ment readings tracked with levels measured with the plant's Houston Atlas instrument within the known uncertainities of the two devices, employing an automated calibration system that periodically introduced a certified sample from a gas cylinder.

The testing and evaluation of a hydrogen chloride monitor, also based upon the near-infrared, frequency-modulated diode spectroscopy, was conducted in collaboration with Thermochem, Inc. using a steam loop at their facility located in Santa Rosa, California in June 2001. These experiments indicated two problems with the instrument that need to be addressed before the system can see wide use as an on-line hydrogen chloride detection system for plant steam. First, the spectroscopic line-broadening of near-by water vapor lines produced interferences with the 1.793 micron absorption band used for detection; and second, the hydrogen chloride tended to adhere to the stainless steel sampling cell creating a residual, or background, signal. Testing was performed at lower pressures to determine if the water interferences could be eliminated or minimized. Operation at pressures of around 1/3 atmosphere did allow detection limits in the 50-100 ppm range to be achieved. While some production wells produce hydrogen chloride in this range, the typical level of interest is in the 0.1-10 ppm range.

New diode laser technology is becoming available that operates in a region of the electromagnetic spectrum that allows access to stronger absorption bands for species such as hydrogen sulfide and hydrogen chloride, with less water vapor interference. In addi-tion to addressing limitations with the current hydrogen chloride device, this technology could allow the development of an ultra-sensitive (ppb) hydrogen sulfide monitor for cooling tower stack applications. The program is actively monitoring these develop-ments and looking for strategic opportunities to improve our monitoring capabilities. A presentation detailing our work on "New Developments in On-Line Hydrogen Sulfide and Hydrogen Chloride Monitors" was made at the Power Plant Optimization of Operations and Maintenance Workshop held in conjunction with the Geothermal Resources Council 2001 Annual Meeting in San Diego, California, August 23-29, 2001.

The feasibility of developing a new generation steam densitometer, incorporating improved semiconductor emitter and detector technologies, was also investigated. For this effort, a laboratory-scale steam loop was set-up using the output from a facility steam generator, typically used for autoclaving biological materials. The steam was then piped through a tube furnace, operated at the saturation temperature for drying, and then vented into a one-meter optical test cell placed in-line with a throttling calorimeter, providing an independent measurement of quality. Five light emitting diodes, selected for their varying responses to the presence of steam and water, were tested over a quality range of 96-100%. Signal changes in excess of 50% were recorded for some of the diodes over this range, making them good candidates for use in a prototype instrument. Unfortunately, variations in the steam supply prevented us from determining if the devices could operate with sufficient precision and accuracy. In order to address these issues and complete the prototype development, a new steam generator has been specified and procured for use with the project.

A task was also initiated to investigate a new monitoring capability that is based upon the interaction of small particles with a high-energy laser pulse. When a particle is introduced into the focal volume of such a laser, the particle is vaporized producing a luminous plasma and a pressure wave, or acoustic signal. The spectroscopic analysis of the plasma can be used to determine the elemental composition of the particle and the amplitude of the acoustic signal, as a function of the laser energy, can be used to determine the particle size. The particle concentration, or number density, can then determined by measuring the number of signals generated as a function of laser shots for a given energy. In proof-of-concept studies, spectral and acoustic signals were successfully collected from both laboratory standards and field samples containing low density (ppm) suspensions of sub-micron silica, iron and alumina particulate. Potential applications include the detection of well dust, mineral precipitation, or metallic wear in components.

Planned FY 2002 Milestones:

Complete the steam densitometer development, identify a field site and conduct field evaluation of the technology.

Redesign the particulate characterization instrumentation to include a compact, remote sampling head for field deployment.

Major Reports Published in FY 2001:

None

Major Articles Published in FY 2001:

None

Microbiological Research in Geothermal Plants

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Project Objective:

The objective of this program is to investigate the impacts of microbiological activity on the efficient operation of geothermal power production facilities and to support the industry in identifying and mitigating these effects.

Approach/Background:

The high densities of microorganisms found in geothermal facility cooling systems may impact their operational efficiency either directly by reducing heat transfer in condensers and cooling towers, or indirectly by altering the interfacial chemistry of metallic substrates influencing corrosion. In addition, microbiological activity may reduce the effectiveness of corrosion inhibitors, protective coatings, or other chemical treatments used in the plants. The economic impact of this activity has been estimated to be as high as $500,000 annually for a 100MWe plant. In spite of the high costs associated with biofouling, few plants have biological monitoring programs in place. Most facilities either apply treatments on a pre-defined schedule, or on an as-needed basis corresponding to the visual evidence of growth, creating the potential that either too much or too little biocide will be added to the process stream. The inefficient use of these expensive chemicals may result in increased organism tolerance to these treatments and require more costly countermeasures, including the application of expensive coatings; or in some cases, the replacement of components.

Initial studies have been directed at characterizing microbiological activity using conventional sampling and evaluating commercially-available methods for performing in-plant monitoring. Techniques included selective culturing or most probable number (MPN), total organic carbon (TOC), adenosine triphosphate (ATP), direct cell (DC) counts, phospholipid fatty acid analyses (PLFA), denaturing gradient gel electrophoresis (DGGE), and electrochemical measurements. Instruments based upon two of these techniques, a BIOSCAN ATP luminometer and a BiGEORGE electrochemical monitor, have been deployed at geothermal facilities, providing timely data on the level of total microbial activity. Changes in environmental or process conditions may trigger and sustain significant microbial growth in the plants. Consequently, recent studies have concentrated on investigating how microbial consortia from geothermal facilities utilize and cycle nutrients from steam impurities, chemical additives, and component substrates for metabolic activity; and in turn, what role these activities play in initiating or promoting biofilm formation on plant substrates. This information is needed to improve data trend analyses from existing devices and could also lead to the development of improved treatment strategies and measurement probes targeting specific organisms or their activities in the plant.

Not all of the microorganisms found at the geothermal facilities are detrimental, in fact some may actually possess characteristics of economic importance. Organisms called extremophiles, thrive in hostile environments, such as those found in hot springs, high pressure vents in the ocean. In this task investigators are determining whether extremophiles are also present in geothermal plants. In order to survive in these environments the organisms may develop enzymes with unique biochemical characteristics. The biomedical field and other industries spend several billion dollars a year on enzymes for applications ranging from the production of sweeteners and improved detergents to the diagnosis of infectious and genetic diseases. The interest in enzymes found in extremophilic bacteria derives from the fact that standard enzymes stop working when exposed to heat or other adverse conditions, and therefore the manufacturers that rely on them must often take special steps to protect the proteins during reaction or storage. By remaining active when other enzymes would fail, enzymes from extremophiles can potentially eliminate the need for those added steps, greatly reducing separation and purification costs. If organisms with unique properties exist at the plants, then the products derived from these organisms could be very valuable, and could represent a new, potentially lucrative revenue stream for the geothermal industry.

Status/Accomplishments:

An extended field deployment and evaluation of the BiGEORGE Electrochemical Biofilm Monitor is in progress at the Bonnett Geothermal Plant located near Cove Fort, Utah. The instrument was installed in a cooling tower circulation line to the condenser and has been continuously operated since January 2001. The instrumental readings have tracked changes in microbial activity in the plant; and in particular, correctly indicated two microbiological blooms occurring in the cooling tower system during March and July 2001. The program is continuing to work with the facility to evaluate the device performance and to integrate the use of the instrument into plant operation and chemical treatment protocol.

A laboratory bioreactor instrument was set-up and tested, and a series of scoping experiments were performed to investigate how microorganisms found at geothermal plants respond to changes in the physiochemical properties of their environment. The bio-reactor allows one or more experimental conditions to be varied as function of time so that a complex environment can be broken down into a series of known perturbations. In these on-going experiments, iron and sulfur reduction by geothermal organisms are being evaluated as a function of changes in oxygen, pH, and temperature in order to simulate a range of conditions experienced in the plants. (Sulfur utilization is of interest since it is produced as an impurity in the resource. Iron is found in the steel formulations used in plant components and is also added as a chemical treatment for reducing sulfide emissions from the plants.)

A protocol for applying and testing molecular probes for tracking specific activities in bacteria found in geothermal water samples and biofilms has also been developed using the fluorescence in situ hybridization (FISH) technique. Two different oligonucleotide probes, targeted for sulfate-reduction activity, were procured and tested with laboratory and field samples.

A brief survey was also performed to investigate the potential for extremophile-based product development at the geothermal plants. DGGE analyses indicated that organisms identified in the literature to be extremophilic are present at some of the plants we have investigated. Sampling on the hot side of the condenser at the Bonnett Geothermal Power Plant indicated the presence of activity. Additional sampling is planned in 2002 to characterize bacteria from the hot environments at other plants to determine if unique organisms are present. The longer term goal of this effort is to develop programs through laboratory, university and industrial collaborations to isolate, identify and commercialize products utilizing these organisms, and concurrently to develop licensing arrangements for the plants to share in the profits from these products.

Planned FY 2002 Milestones:

Complete in-plant biofilm monitoring study.

Complete probe selection and associated laboratory testing for monitoring specific microbial activities.

Major Reports Published in FY 2001:

P. A. Pryfogle, "Nutrient Cycling Study", INEEL Report, August 2001.

Major Articles Published in FY 2001:

None

Enhancement of Air-Cooled Condensers

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
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Project Officer / Monitor **Name:** Greg Mines **Phone:** (208) 526-0260 **Fax:** (208) 526-0969 **E-mail:** minesgl@inel.gov	**DOE Funding Allocation** $190K	**Cost Share Funding** $125.6K, NEDO ~ $10K, McElroy

Project Objective:

The objective of this project is to improve air-cooled condenser heat transfer performance (overall heat transfer coefficient) by ~15%, resulting in lowering component cost without increasing the air-side pressure drop and fan parasitic power consumption.

Approach/Background:

The 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 in 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. The investigators have identified two concepts, vortex generators on tube fins and/or oval tubes to increase heat transfer performance, which have potential of improving the condenser performance and reducing its size. 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. Testing is being used in conjunction with computational fluid dynamics (CFD) modeling to identify those configurations that provide the best heat transfer. Investigators are using input from tube manufacturers on ease of manufacturing in identifying a suitable tube-fin configuration. Currently, INEEL is focusing the effort on the vortex generators with circular tubes, because oval tubes are likely to be more expensive to manufacture and less likely to achieve initial commercial success. In conjunction with the research work at INEEL, the investigators are pursuing industrial support for the commercial development of these concepts. This work has been complemented by a grant provided by the New Energy and Industrial Technology Development Organization (NEDO), a Japanese government agency under the Ministry of Economy, Trade and Industry (MITI). In addition to funding, the grant is providing investigators with access to the results and progress of the work being done by others other recipients of NEDO grant from in Japan and India.

Status/Accomplishments:

During FY2001, all the laboratory-scale single tube experiments for oval tubes without and with vortex generators were completed. Heat transfer measurements were obtained using a transient technique, which allowed very accurate determinations of local heat coefficients on the fin surface. Corresponding experiments for cylindrical tubes were completed during previous year. Comparative heat transfer performance of the single tube tests results can not be the single deciding factor in selecting a particular design. Laboratory scale experiments were performed for simulated tube bundles with and without vortex generators to measure pressure drop (friction factor) for various competing concepts. A CFD code, Fluent, was used to model cylindrical tubes with vortex generators and oval tubes under the corresponding experimental conditions. The numerical results from the modeling effort provided reasonable matches to the observed thermal performance of both the circular and oval tube configurations. Also an annual meeting was held of all the international researchers funded by NEDO to exchange their independent results. Results from our Japanese collaborators indicated that under some specific cases of cylindrical tubes with vortex generators, it is possible to obtain small improvement in heat transfer (~10%) with significant (~30%) reduction in pressure drop. These results confirmed that our objective of improved heat transfer with minimum increase (or even decrease) in pressure drop could be achieved. Planning for experimental tests using "single blow technique" with 4 (rows) by 4 (columns) bundles of 1-ft. long tubes was completed. McElroy Manufacturing Company provided finned tubes with various shapes and sizes.

Planned FY 2002 Milestones:

Complete installation and checkout of the test loop used in bench-scale bundle testing	Jan 02
Complete a full set of bench-scale bundle testing with winglets	Apr 02
Finalize arrangement with industrial partner to fabricate the large scale, prototype bundle for field testing	Jul 02.

Major Reports Published in FY 2001:

Two reports submitted to New Energy Development Organization (NEDO), Japan per contractual agreement.

Major Articles Published in FY 2001:

J. E. O'Brien and M. S. Sohal, "Heat transfer enhancement for finned-tube heat exchangers with winglets," Proceedings of 2000 ASME International Mechanical Engineering Congress and Exposition, Orlando, FL, November 2000.

T. D. Foust, J. E. O'Brien, and M. S. Sohal, "Numerical and experimental methods for heat transfer enhancement for finned-tube heat exchangers with oval tubes," Proceedings of 35th National Heat Transfer Conference, June 2001, Anaheim, CA

M. S. Sohal and J. E. O'Brien, "Improving air-cooled condenser performance using winglets and oval tubes in a geothermal power plant," presented at the GRC 2001 Annual Meeting, San Diego, CA, August 2001.

Field Demonstration and Evaluation of Lined Heat Exchanger

Contract/Grant #: DE-AC07-99ID13727	Contract/Grant Period: FY 2001

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Contracting Organization Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	**Principal Investigator(s):** **Name:** Toshifumi Sugama, **Phone:** (631) 344-4029 **Fax:** (631) 344-2359 **E-mail:** sugama@bnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

This objective of our work undertaken in collaboration with NREL is to evaluate the technical feasibility of the 40-ft.-long lining apparatus and to fabricate tough polymer composite-lined heat exchanger tubes with excellent thermal conductivity.

Approach/Background:

Stainless steel and titanium alloy heat exchanger tubes used in geothermal binary-cycle power plants offer great protection against corrosion caused by hot brine. However, the corrosion-preventing passive oxide layers that form at 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 these scales adhering to the tube's surfaces, but also entails a substantial amount of time. Thus, this cleaning operation essential for reusing the tubes is very costly. On the other hand, although the rate of corrosion of inexpensive carbon steel-based heat exchanger tubes is considerably higher than that of these expensive high-grade metal alloy tubes, the former possess much greater thermal conductivity compared with the latter. If the carbon-steel tubes could be coated with a thermally conductive material that resists corrosion, oxidation, and fouling, then the capital coast of the heat exchanger, containing on average 800 tubes, would be markedly reduced.

In FY 2000, a five-month field performance evaluation was conducted of 20-ft.-long carbon steel tubes lined with two high-temperature performance polymer coating systems, SiC-filled polyphenylenesufide (PPS)/zinc phosphate (Zn.Ph) primer, and Cr oxide-filled resole-type phenolic polymer. The tests were made in collaboration with NREL at CalEnergy's power plant site. This plant operates at a brine temperature of 110 degrees C. The former lining system possessing excellent thermal conductivity was designed and made at BNL, and the latter known by the trade name "Saekaphen Si 14E" was prepared and supplied by Heresite Protective Coatings Co. At present, Saekaphen Si 14E is most reliable and popular material used as a high-temperature liner worldwide. The tests revealed that the Saekaphen Si 14E liners failed in short-term field tests after only one month. In contrast, the SiC-filled PPS/Zn.Ph liners remained intact. Although our liner displayed an outstanding performance, we wished to enhance its surface hardness and inertness to hydrothermal oxidation to further improve its resistance to abrasive wear and to minimize the deposition of the scales. In FY 2001, BNL designed new thermal conductive PPS/SiC-based material systems possessing excellent abrasive wear and oxidation resistance, and also developed a lining process technology suitable for the new PPS material systems. These new PPS systems contained two specific additives, calcium dialuminate (CDA) to resist abrasive wear and the anti-oxidant polytetrafluoroethylene

(PTFE). Zinc phosphate-primed 20-ft.-long heat exchanger tubes were lined with this new material and an eleven-month-long tests of field performance was conducted at the Mammoth Pacific power plant site operating at brine temperature of 160 degrees C. In addition, BNL installed the state-of-the-art apparatus that is used for lining the 40-ft.-long tubes in a horizontal configuration.

Status/Accomplishments:

The new CDA- and PTFE-modified PPS/SiC liners were analyzed at BNL after the eleven-mo.-long field exposure at the Mammoth. The results revealed that anti-oxidation PTFE additive not only minimized the rate of the scale deposition, but also made the liner's surfaces inert to reaction with the scales. Thus, all the scales deposited on the surfaces were easily removed by hydroblasting at only ~ 18.0 MPa pressure. In addition, PPS satisfactory withstood a 160 degrees C brine temperature and displayed great resistance to the permeation of brine through the liner, thereby expressing its outstanding performance in protecting the tubes against corrosion. Furthermore, CDA added for abrasive wear resistance abated the extent of wear damage during hydroblasting. In contrast, the surfaces of stainless steel tubes were very sensitive to the calcium silicate hydrate and silica scaling, developing a strong adherence to the scales. This strong bond was reflected in the requirement for high-pressure hydroblasting at 55.1 MPa to scour them off from the tube's surfaces. But, even after wards, many scales forming a ~ 2.0 micron thick layer still remained on the oxide layer.

Based upon these very promising results in the field evaluations, Bob Curran & Son Corp. commercialized this PPS-based lining material system under the trade name "CurraLon" . As of January 2002, more than 10,000 heat exchanger tubes were lined with it.

Currently, four 20-ft.-long heat exchanger tubes are being lined with carbon microfiber-reinforced PPS composite material possessing high thermal conductivity and great mechanical properties. They will be sent to NREL for a long-term field validation test at the Mammoth power plant site to estimate the liners'useful lifespan. Further, post-approval tests of the BNL-designed apparatus that is used for lining the 40-ft.-long tubes are being undertaken to determine its technical feasibility and reproducibility of the liners deposited on the 40-ft.-long tubes. The factors to be assessed will include the liner's thickness, surface roughness and its adherence to underlying tube surfaces. In addition, the electorstatic powder coating technology of which there is no requrement of any organic solvents will be developed in collaboration with Bob Curran & Sons Corp.

To ensure that PPS-based coatings adequately protect carbon steel against corrosion and inhibit the scale deposition in different geothermal environments, the field performance tests of the coated test coupons will be performed at Bonnett Geothermal in Cove Fort and at Puna the Geysers in collaboration with NREL and Thermochem, Inc.

Planned FY 2002 Milestones:

Evaluate technical feasibility of 40-ft.-long lining apparatus	Apr 02
Prepare four 20-ft.-long tubes lined with coating materials	May 02
Delivery four 20-ft.-long lined tubes to NREL	Jun 02
Complete validation tests of powder coated tube ends and sheets	Jul 02
Report the results of the laboratory and field test	Sep 02

Major Reports Published in FY 2001:

T. Sugama, D. Elling, and K. Gawlik, "Polyphenylenesulfide-based coatings for carbon steel heat exchanger tubes in geothermal environments", December 2001.

T. Sugama and D. Elling, "The state-of-the-art lining apparatus for 40-ft.-long heat exchanger," July 2001.

Major Art6icles Published in FY 2001:

T. Sugama and K. Gawlik, "Filler materials for polyphenylensulfide composite coatings", GRC 2001 Annual Meeting San Diego, CA, Augaust 2001.

High-Performance Coating Materials

Contract/Grant #: DE-AC02-98CH10886	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization	
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Contracting Organization Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	**Principal Investigator(s):** **Name:** Toshifumi Sugama **Phone:** (631) 344-4029 **Fax:** (631) 344-2359 **E-mail:** sugama@bnl.gov	
Project Officer / Monitor **Name:** Raymond LaSala **Phone:** (202) 586-4198 **Fax:** (202) 586-8185 **E-mail:** Raymond. LaSala@ee.doe.gov	**DOE Funding Allocation** $98K	**Cost Share Funding** $150K

Project Objective:

The objective of this work is to enhance the thermal conductivity of polyphenylene sulfide (PPS) composites and develop technologies that allow the coatings to self-repair and self-heal internal and surface cracks.

Approach/Background:

In 2000, emphasis centered on looking for ways to making PPS more resistant to blasting wear. One strategy was to incorporate hydraulic Al_2O_3-rich refractory (HAR) fillers into it. Although semi-crystalline PPS withstood a hydrothermal temperature around 200 degrees C, some brine permeated through the coating. The permeated brine favorably reacted with the HAR fillers to form a hard crystalline boehmite ceramic in an ~ 20 micron superficial layer. This ceramic layer coexisting with PPS contributed significantly to improving the coating's resistance to abrasive wear. Thus, when the HAR-filled PPS coating was applied to heat exchanger tubes and pipes, the HAR filler played an important role in abating its damage by abrasive wear during hydroblasting, a process which is commonly used to remove scales deposited on the coating's surfaces before the tubes are resued. However, two questions still remained unanswered. One was how to prevent the brittleness that develops in the coating caused by incorporating boehmite ceramic into the flexible PPS. The other concerned the extent of susceptibility of the ceramic layer present in the superficial layer to the deposition of silica and silicate scales. In trying to solve the former problem, in FY 2001 we incorporated chopped carbon fibers, which have great hydrothermal stability and very high thermal conductivity, into the PPS coating. To resolve the second problem, we added anti-oxidant admixture to the coating because the oxide layer formed at the outermost surface site of the metallic and polymeric materials leads to their susceptibiling to silica and silicate scaling.

For the vertical heat exchanger tube sheets, the ideal coatings were required to meet the following material criteria. Those were 1) the formation of a uniform, continuous layer by a paint brush or spray gun, 2) the ability to cure well in moist surroundings at room temperature, 3) hydrothermal stability at temperatures up to 200 degree C, and 4) good adherence to carbon steel surfaces. New-type room temperature-curable flourinated ethylene-propylene thermoset polymer is very attractive as a tube sheet coating because of its excellent thermal stability at 300 degrees C. Thus, in FY 2001, the usefulness of this polymer in protecting carbon steel tube sheet against corrosion was investigated.

Although these high-temperature performance coatings provide outstanding protection to metal against corrosion, one important problem is how to repair any damage caused by micron- and nano-sized cracks generated in the matrix during its service life, and also, how to retard the growth of such cracks.

Status/Accomplishments:

Using the chopped carbon fibers, 7.5 micron diam. x 3 mm long, BNL succeeded in developing a very tough, strong PPS composite coating. This carbon fiber-reinforced PPS composite coating displayed 18.6 MPa tensile strength, 813 MPa tensile modulus, and 3.2 % elongation, corresponding to an improvement of 2.4, 2.6, and 1.5 times, respectively, of those properties of non-reinforced PPS. In addition, the thermal conductivity of the bulk PPS was raised 60 % by adding an appropriate amount of fiber. Further improvement of thermal conductivity and mechanical properties currently is being sought by incorporating a highly graphitized carbon microfiber, 7.5 micron diam. x 100-200 micron long , into the PPS.

Among the several anti-oxidant admixtures of PPS, hydrophobic polytetrafluoroethylene (PTFE) was identified as most effective one in minimizing the degree of brine-caused hydrothermal oxidation of the PPS's surfaces. The reason for this minimal oxidation of the PTFE-blended PPS coating was the presence of a PTFE layer segregated from PPS layer in the top surface of the coating. As a result, this surface not only inhibited the deposition of silica and silicate, but also retained its hydophobic characteristics. So, we recommended PTFE-blended PPS coatings as a potential candidate for use as barriers against silica and silicate depositions on metal structural components in silica-rich brine.

In short-term autoclave validation tests, the new room temperature-curable poly(tetrafluoroethylene)/(hexafluoropropylene) thermoset polymer exhibited adequate protection of the underlying carbon steel against corrosion. However, the superfical layer of the coating suffered hydrothermal oxidation, leading to two undesirable features: 1) an increase in the susceptibility of the coating surfaces to the moisture, and 2) a decline in the thermal stability of the coatings. Hence, we carrried out a 6-month field performance test of small coated coupons to judge whether this material coating is applicable to tube sheet; the study is being undertaken at the Mammoth power plant.

Work is underway to design a smart self-healing composite material that can seal cracks in the matrix and retard their propagation. The self-healing concepts involve two different procedures. One is to incorporate micro- and nano-sized encapsulated healing agents into the composite, and the other is to use hydraulic inorganic fillers, which are capable of crystal growth in hydrothermal environments. A 3-mo. short-term field exposure of panels coated with these smart self-repairing composites will be performed at the Mammoth power plant. It will evaluate their ability to reconstitute failed coating structure and to sufficiently restore the corrosion-preventing barrier.

Planned FY 2002 Milestones:

Validate micro-size graphitized carbon fiber-reinforced PPS composite	Feb 02
Deliver composite-coated panels to Thermochem Corp for scale testing	Mar 02
Complete development of self-healing composite coatings	May 02
Deliver self-healing composite-coated panels to Mammoth for field tests	Jun 02
Report describing results of in-house work and field-evaluation tests	Aug 02

Major Reports Published in FY 2001:

T. Sugama, "Anti-silica fouling coatings in geothermal environments," May 2001.

Major Articles Published in FY 2001:

T. Sugama and K. Gawlik, "Carbon Fiber-Reinforced Poly(phenylenesulfide) Composite Coatings," Polymers & Polymer Composites, 9 (2001) 377-384.

T. Sugama and K. Gawlik, "Poly(tetrafluoroethylene)/(hexafluoropropylene) Coatings for Mitigating the Corrosion of Steel in a Simulated Geothermal Environment," Progress in Organic Coatings, 42 (2001) 202-208.

High-Temperature Polymeric Elastomers

Contract/Grant #: DE-AC02-98CH10886	Contract/Grant Period: FY 2001

Sponsoring Office Code: EE-12	Performing Organization
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Contracting Organization Brookhaven National Laboratory (BNL) P.O. Box 5000 (Building 526) Upton, New York 11973-5000	**Principal Investigator(s):** **Name:** Toshifumi Sugama **Phone:** (631) 344-4029 **Fax:** (631) 344-2359 **E-mail:** sugama@bnl.gov

Project Officer / Monitor	DOE Funding Allocation	Cost Share Funding
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Project Objective:

The objective of this collaborative task with Mammoth Pacific, Inc., is to study the kinetics of the oxidation degradation of the high-temperature elastomer bearing in the down-hole pumps, and to predict its useful lifetime.

Approach/Background:

A serious problem confronting operators at the Mammoth Pacific geothermal power plant is the failure of down-hole pumps which extract the energy resource from the hot geothermal brine reservoirs (~ 150°C). This harsh, hostile environment quickly damages the pumping equipment, particularly the shaft components of the pump. Repairing and replacing the failed pump is very costly and time consuming. Thus, the existing down-hole pumps must be modified to deal with this problem. High-temperature performance polymeric elastomers are very attractive materials to use in the new bearing systems of conventional pumps because they may mitigate damage to the shaft components, and allow the oil lubricant to be replaced by a water one.

IV. GEOPOWERING THE WEST PROJECTS

GeoPowering the West

Contract/Grant #: Multiple	**Contract/Grant Period:** FY 2001

Sponsoring Office Code: EE-12	**Performing Organization**
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Contracting Organization INEEL, R. Neilson, rmn@inel.gov NREL, G. Nix, gerald_nix@nrel.gov SNL, R. Hill, rrhill@sandia.gov	**Principal Investigator(s)** **Name:** Curtis Framel, DOE-SRO **Phone:** **Fax:** 206-553-2200 **E-mail:** Curtis.Framel@ee.doe.gov

Project Officer / Monitor	**DOE Funding Allocation**	**Cost Share Funding**
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Project Objective:

The major new DOE program activity "GeoPowering the West" (GPW) is designed to foster awareness of the availability and benefits of geothermal energy as well as to encourage its implementation for both direct use and electrical generation, throughout the Western United States. The focus is on general education and outreach, resolution of non-technical barriers, and technical assistance for development of projects. The activity focuses on education, awareness, and outreach activities aimed at the range of geothermal stakeholders, which includes industry, government organizations, Native American groups, users, environmental groups, and the general public. The objectives of this task for FY2001 are:

– -to initiate activities which will result in an effective GPW working team.
– -develop a roadmap for GPW
– -provide geothermal resources maps and other information to encourage deployment
– -support educational meetings in targeted states, followed by an active role in the formation of local action groups
– -work with the local action groups to develop and implement action plans
– -assist in any way possible, the implementation of action plans to get GPW off to a positive start and to maintain momentum.

Approach/Background:

GPW is a DOE program activity directed by DOE-HQ and led in the field by Curtis Framel of DOE-SRO. The Geothermal Energy Association, SNL, INEEL and NREL will provide support. Current targeted states include Nevada, New Mexico, and Idaho. A GPW Working Group consisting of representatives from INEEL, SNL, NREL, and DOE-HQ will coordinate performance of this activity. The laboratories will also provide support to DOE and to local state groups. A support laboratory will be assigned for each state, with the intent of holding stakeholder meetings to enhance public awareness and formation of a state working groups to develop and implement a action plans for geothermal development within the states. GEA will assist by setting up appropriate meetings and public forums. The assigned laboratory will work with Mr. Framel to assist and to catalyze the state working group. DOE will encourage state working group formation and operation in each targeted state by providing resources (laboratory assistance, financial support, etc.). The laboratories will provide technical and educational support to the state working groups, including development of strategy and action plans, with the intent of catalyzing new geothermal energy projects. Laboratories will develop and provide information as well as work to support actions to identify and evaluate suitable renewable energy portfolios, implementation of green energy pricing, definition of the benefits of tax incentives, greater use of geothermal by the Federal sector and projects involving Native Americans. The laboratories will work as a unified team, with the individual laboratories taking the lead as appropriate, for specific tasks under this activity based on their skills and capabilities

Status/Accomplishments:

The GeoPowering the West activity began in FY 2001. This has been a year of organizing and getting started There are a number of early successes under the GPW belt: 1) the Nevada stakeholder meeting kickoff and formation of working group was done in a highly visible way that included Senator Reid's participation in this high-geothermal resource state with a geothermal industry cluster, 2) likewise, the Idaho stakeholder workshop hosted by Senator Craig led to the formation of a very active state working group, 3) the formation of the New Mexico working group also included activities directed toward a Renewable Portfolio Standard for the state, 4) Maps and Publications (including Geothermal Today) have been prepared to support the state efforts and for more general public education, 5) a Public Lands Workshop addressed the critical issues of Federal land ownership and the resulting constraints on geothermal development, and 6) the development of a GeoPowering the West Implementation Plan (roadmapping activity), which includes the major thrusts of:

1. Education and Outreach--where information will be revised, developed, and disseminated to educate consumers and stimulate demand for geothermal energy.
2. Federal Participation--where actions to increase Federal geothermal energy use will promote technology maturity and encourage the Federal government to "lead by example."
3. Technology Advancement and Deployment--while the DOE Geothermal Program is the primary mechanism for developing improved technolgies in drilling, exploration, resource characterization, and energy systems, GPW will "cross-connect" such information to customers and users as technical assistance for projects.
4. Exploration and Confirmation--where newly identified and existing resource information is communicated with identification of potential opportunities for geothermal applications (an example of such is the Idaho Geothermal Resource Maps).
5. Policy Incentives--While GPW will not set or promote policies it serves a role to help identify and evaluate policy incentives that can effectively promote geothermal and provide information relevant to these policy incentives.
6. Institutional Improvements--GPW will improve communications between stakeholders and governmental bodies, including Native Americans, by identification of institutional issues that contribute or are detrimental to geothermal development.

The work will be coordinated nationally but implemented on a state basis by the laboratories working with their state working groups.

Planned FY 2002 Milestones:

Hold a 1 day geothermal program for Native Americans in conjunction with the Council of Energy Resource Tribe's Meeting on Sustainability	(K)	Mar 02
GRC Bulleting Inserts	(C)	Qtrly
Approval of Idaho Plans by State Working Group	(C)	Feb 02
Hold a workshop on socioeconomic factors in siting and permitting	(C)	Sep 02
Issue a siting and permitting guide for local and government officials	(C)	Sep 02

Major Reports Published in FY 2001:

Public Lands Workshop Report

Major Articles Published in FY 2001:

Inputs to Geothermal Today.