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SUMMARY

OVERVIEW

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

Mission

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

Goal

- 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.

This Federal Geothermal Program Research Update reviews the specific objectives, status, and accomplishments of DOE's Geothermal Program for Federal Fiscal Year (FY) 2002. 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 2002 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. A better understanding of the Basin and Range geological systems including the regional structure, rock type and fluid compositions is leading to improved exploration models for western U.S. geothermal systems. Improvements in numerical modeling of reservoirs are continuing, and providing a better understanding of fluid flow in geothermal systems. Development of high temperature tools along with new methods of fracture detection and seismic imaging are being pursued to gain a better understanding of the physical constraints of geothermal reservoirs.

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. 3-D magnetotellurics, noble gas isotope geochemistry, and airborne electromagnetic and gravity surveys are some of the exploration tools being investigated and refined for geothermal resource identification and delineation.

Drilling and completion of wells for exploration, production, and injection accounts for 20 to 40 percent of the cost of generating electricity from geothermal resources. Current geothermal drilling and completion technology 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. Continuing research to avert lost circulation episodes in geothermal drilling is yielding positive results. Advanced drill bits for hardrock drilling applications are under development. Well bore integrity and lost circulation are vexing problems in the drilling and completion of geothermal wells. Research in these areas as well as acid resistant cements and measurement while drilling is showing promising results.

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, performance enhancement and optimization of binary cycles will result from investigations in heat cycle research. This and other research enable better understanding of geothermal power plant costing methodologies. High-temperature, scale-resistant, corrosion-resistant, and thermally-conductive liner materials and coatings are being developed for piping, heat exchanger applications, and energy conversion processes. Nondestructive testing of these types of systems is being conducted. Biotechnology research focuses on solutions that characterize microbiological growth and changes with various processes and environments encountered in the geothermal settings, as well as methods to prevent and repair damage to equipment and facilities from microbiological attack.

I. GEOSCIENCE PROJECTS

TOOLS FOR RESERVOIR CHARACTERIZATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation:	$500K
Cost Share Funding:	$100K

Project Objective: There are two major objectives of this project: (1) measure flow properties of geothermal fluids (steam and water) and geothermal tracers, and (2) develop and distribute new numerical tools for improved reservoir management. Properties that were measured include steam-water relative permeabilities and capillary pressure and adsorptive properties of selected geothermal tracers. Numerical models were constructed that allow a geothermal operator to add simulation of geophysics to the more conventional reservoir modeling, and to estimate reservoir properties via inverse modeling. A more accurate and complete reservoir model is possible using these new tools.

Background / Approach: This project is a combination of experimental and numerical work. The experiments were designed to obtain properties required in accurate reservoir management (including numerical simulation), including steam-water relative permeability and transport properties of geothermal tracers. The numerical work is intended to develop enhanced numerical tools to assist in reservoir management. The specific projects are discussed in more detail below.

The Stanford Geothermal Program has a long history of petrophysical property measurements for the geothermal industry. In FY 2002, that program designed and conducted flow experiments to measure steam-water relative permeabilities in fractured rock. This work is reported elsewhere – see Horne (this volume) for further information.

Vapor phase geothermal tracers are being used increasingly in the geothermal industry to help identify flow paths within the reservoir and design successful injection schemes. However, other than thermal stability, few properties of these tracers (primarily freons and perfluorocarbons) under geothermal conditions are known. Experiments were designed to measure phase behavior and flow characteristics of these tracers. Results from these studies in FY 2001 indicated the potential for their adsorption on geothermal reservoir rock. To quantify this phenomenon, flow experiments were conducted to measure adsorption. The compound under consideration was injected into a sand-filled column initially filled with helium and water. The initial water saturation was varied between 0 and about 22% by volume (a residual saturation). The tracer was injected along with an inert carrier gas (argon), and subsequently displaced with helium. The mean residence time of the PFC and argon can be calculated by integrating the effluent history of the tracers. Because argon partitions negligibly into liquid water and does not adsorb, differences in residence time can be quantitatively attributed to phase partitioning and adsorption. The former is expected and desired; tracer tests can be designed to estimate the liquid saturation from injecting partitioning tracers. The latter is undesirable, and precludes quantitative tracer test analysis using that compound.

Work has also continued in the development of numerical tools to increase the industry's ability to effectively manage geothermal resources. The reservoir model, TETRAD, has been coupled with geophysical models developed by SAIC. Results from a TETRAD simulation can be "post-processed" by using TETRAD output (saturation, mole fraction, temperature profiles, etc.) as input to the geophysics models. This new capability will provide the user the ability to impose additional constraints on the history matching process and thereby obtain a more accurate reservoir description. Geophysical models coupled to TETRAD include microgravity, DC resistivity, magnetotellurics (MT), and self potential (SP). This task primarily involved writing new subroutines within TETRAD to output the desired information.

The models discussed above run in a "forward" mode. That is, the input is assumed known, and the simulation results are reservoir response to known initial conditions and field operations. This is typically not the case. Input to a numerical simulation is a combination of data readily measured or estimated (e.g., heat flux, pressure profiles) and data ranging from difficult (fracture spacing) to impossible (permeability distributions) to determine, and simulation output is therefore a predicted response to an assumed initial condition. The initial conditions (including reservoir properties of permeability, etc.) are not considered "known" until simulated reservoir response (e.g., production) agrees with observations. To accurately estimate reservoir properties, a (typically large) number of history matching simulations are conducted. Work was undertaken in FY 2002 to automate this process of estimating reservoir properties (aka, Automatic History Matching, Inverse Modeling, and Parameter Estimation Modeling). The "calibrated" reservoir model is then used in optimizing field operations.

Status / Accomplishments: Laboratory experiments with fluorocarbons indicate that many compounds previously identified as potential geothermal tracers adsorb to silica (a ubiquitous mineral found in geothermal reservoirs). At zero liquid saturation and low (23ºC) temperature, a trend of increasing adsorption with increasing tracer molecular weight was observed. Adsorption increases at elevated temperature. However, at nonzero liquid saturations the liquid apparently shields the sand from the tracer, and reduces adsorption. This suggests that, under saturated conditions, some of the fluorocarbons may be used as geothermal tracers. However, if superheat conditions prevail, the tracers adsorb and interpretation becomes difficult.

One example of these results is given below in Table 1. In these experiments, the sand column was heated to 60ºC, and the injectate was saturated with moisture at 23ºC. Because the gas is undersaturated with moisture at 60ºC, the sand column dries out during the experiments. A series of 5 experiments were conducted for each of the tracers reported below. One can readily see the effects of sand column dry-out as the experiments proceed; for example, the mean residence time of R134a in Experiment 3 is 21%

larger than in Experiment 1. After the 3rd experiment, the sand column was re-humidified with 200 microliters of liquid. Residence time of all tracers in Experiments 4 and 5 is essentially the same as argon, showing the effect of a liquid saturation. From these experiments, it appears that fluorocarbons may be used in saturated two-phase reservoirs, but superheated conditions preclude quantitative interpretation. A more complete discussion of these experiments is given by Maxfield et al. (2003).

Table 1: Summary of sand column experiments. Carrier gas humidified at 23°C; sand column heated to 60°C.

Retention Time (min)							Retardation Factor Relative to Argon					
							Adjusted for Temperature and Initial Humidity					
Compound	Inject #1	Inject #2	Inject #3	*	Inject #4	Inject #5	Inject #1	Inject #2	Inject #3	*	Inject #4	Inject #5
Argon	34.2											
R134a	34.2	38.4	41.6	*	34.0	32.2	1.00	1.12	1.21	*	0.99	0.94
MPentane	35.0	41.4	51.6	*	34.1	32.2	1.02	1.21	1.50	*	0.99	0.94
DMHexane	48.9	94.6	203	*	36.6	33.9	1.42	2.75	5.90	*	1.07	0.99
*Between injections #3 and #4, 200 microliters of water was injected onto the top of the column followed by 400 cc of helium.												

A version of TETRAD has been modified to write an output file containing data required for the geophysical models. This revised code has been made available to TETRAD's developer, and is expected to be released in FY 2003. The code has been validated against a synthetic dataset provided by SAIC. In that test case, prolonged production from a geothermal field, coupled with injection of cooler fluid on the flank of the field, resulted in substantial differences in gravity over time. The problem was simulated using TETRAD, with output postprocessed using the SAIC models. TetGeo results compared favorably with the SAIC results. The revised model is discussed by Shook (2002a).

Version 1 of an inverse model for TETRAD (Tet^{-1}) was also completed in FY 2002, and is being tested on a geothermal field in collaboration with the field operator. The revised code will be made available to geothermal operators in FY 2003. Preliminary results from the code development and testing are given by Shook (2002b). A simple geothermal example was used to test the new model. The domain was 2-D and square. Permeability and porosity were constant within each quadrant of the domain. Simulated production and tracer test data were used to estimate the four values of permeability and porosity. Results of the test case are given below in Table 2. As seen in the table, parameters estimated from Tet^{-1} are in good agreement with the true properties. The software is being further refined and more automated in FY 2003. A version of the code will be released in FY 2003.

Table 2. Summary results for Tet^{-1} example problem.

In 9 Iterations:	True Properties		Estimated Properties		Max Relative Error
	k_i	φ_i	k_i	φ_i	
Region 1	50.	0.05	49.95	0.05	0.1 %
Region 2	150.	0.025	150.1	0.025	0.07%
Region 3	250.	0.075	249.9	0.075	0.04%
Region 4	100.	0.04	100.03	0.04	0.03%

Reports & Articles Published in FY 2003: None.

Reports & Articles Published in FY 2002:

Shook, G. M., "Preliminary Efforts to Couple TETRAD with Geophysics Models," Trans., 27th Stanford Workshop on Geothermal Reservoir Engineering, Jan. 2002.

Shook, G. M., "An Inverse Model for TETRAD: Preliminary Results," Trans., Geothermal Resources Council, Vol. 26, Sept. 2002.

Presentations Made in FY 2002:

Shook, G. M., "Preliminary Efforts to Couple TETRAD with Geophysics Models," Trans., 27th Stanford Workshop on Geothermal Reservoir Engineering, Jan. 2002.

Shook, G. M., "An Inverse Model for TETRAD: Preliminary Results," Trans., Geothermal Resources Council, Vol. 26, Sept. 2002.

Planned FY 2003 Milestones: Measurement of relative permeability and other petrophysical properties is expected to continue by the Stanford Geothermal Program in FY 2003; however, it is no longer funded by this project.

A detailed description of laboratory testing of the vapor-phase tracers has been submitted for publication to Geothermics (Maxfield 2003). These studies have shown potential problems with the vapor-phase tracers selected to date. Therefore, we have designed a numerical study to elucidate geothermal tracer properties that allow for quantitative interpretation of tracer tests. Results expected in FY 2003 include ranges of partition coefficients acceptable for tracers, and methods to predict thermal velocities from two-phase tracer tests.

Version 1 of Tet^{-1} will be released to interested TETRAD users in FY 2003 for further testing and use. Work will continue in including the geophysical models with TETRAD in inverse modeling. This new suite of models ($TetGeo^{-1}$) will be available for beta testing in FY 2003.

SOLUBILITY AND PHASE EQUILIBRIA OF FLUOROCARBON TRACER CANDIDATES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: U.S. Department of Energy
Office of Geothermal and Wind Technologies
DE-AC07-99ID13727

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DOE Funding Allocation: $175K

Cost Share Funding: None

Project Objective: A family of geothermal tracer candidates was previously identified and further studies were initiated to determine behavior of the tracer candidates at geothermal conditions. Preliminary tests indicated that there was some adsorption of some of the tracer candidates on the solid matrix. In order to verify these preliminary findings the tracer candidates were diluted in helium and passed through a packed sand column. Helium was used as both the diluent and carrier gas through the sand column. The mobility and inert nature of the tracer candidates was compared to argon to determine if they qualified as conservative tracers. The objective of this work was to determine if the tracer candidates were conservative and any conditions under which adverse interactions occur.

Background / Approach: Geothermal tracers are used to provide information on flow paths between injection and production wells and also information on the overall operation and performance of geothermal fields. Tracer compounds must meet several criteria to be useful in field applications. The tracer compounds should not be present at appreciable levels in the field under study. They should flow with the bulk fluid being monitored, be stable at reservoir temperatures, detectable at low concentrations and have minimal environmental impact.

Although a number of tracer compounds have been explored for geothermal applications, many of these compounds do not meet all of the desired selection criteria. For example, chlorofluorocarbons, which were used in The Geysers from 1990 to 1997, have been phased out of production due to their negative environmental impact. Isotopes, such as deuterium, tritium, and ^{18}O, can be prohibitively expensive and environmentally questionable. Propane, helium and bromide may have background levels that are too high for practical uses in certain locations. Consequently, new tracers, which meet all of the selection criteria, are needed.

Fluorocarbons have many properties that suggest they are suitable for use as geothermal tracers. Fluorocarbons are considered to be environmentally acceptable, thermally stable, detectable at low concentration levels, and have insignificant background levels. Hydrofluorocarbons and perfluorocarbons have been explored as tracers for a wide variety of applications outside of the geothermal world including: monitoring air pollutant transport, leak detection, ocean transport study, indoor air quality study and medical applications. In subsurface environments, fluorocarbon tracers have been used in microbiological characterization in subsurface basalts and sediments, the characterization of natural gas reservoirs and as partitioning tracers to estimate NAPL contamination.

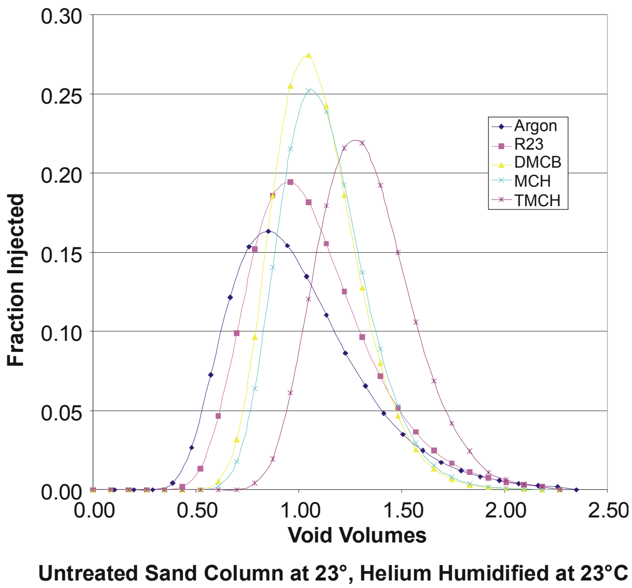
The present work is focused on the transport of fluorocarbon compounds in the vapor phase. Fluorocarbons explored include two hydrofluorocarbon freons, [trifluoromethane (R-23) and 1,1,1,2-tetrafluoroethane (R-134a)] and five perfluorocarbons, [perfluorodimethylcyclobutane (DMCB), perfluoromethylcyclopentane (MCP), perfluoromethylcyclohexane (MCH), perfluorodimethylcyclohexane (DMCH), and perfluorotrimethylcyclohexane (TMCH)]. Previous work at the INEEL suggested that there might be some retention of the perfluorocarbons on the stationary phase. This study characterizes the retention of these compounds on a fixed bed of washed sea sand with helium as the mobile phase at 23°C. The effect of sand moisture content is examined.

This work found that fluorocarbon retention is strongly affected by sand moisture content, causing the compounds to flow with the bulk fluid when the sand is saturated with water, but they are significantly retained by the solid phase when the sand is thoroughly dried.

Status / Accomplishments: The first temporal moment for argon was in good agreement with the column pore volume, and the mass balance for argon was calculated to be within 5%.

In the untreated sand both freons had very similar first temporal moments to argon, deviating by only 5%. The perfluorocarbon first temporal moments deviated somewhat from argon resulting in retardation factors of 1.08 – 1.32. A retardation factor of greater than 1.20 is considered nonconservative. Two of the perfluorocarbons (DMCH and TMCH) were close to or beyond the boundary considered conservative under these conditions.

Some of the sand was heated overnight at 100°C, which resulted in 0.06% weight loss of the sand and this drying had a large effect on the retardation of the perfluorocarbons. The only tracer that was not dramatically affected by the dry sand was R23. All the other tracers were significantly delayed, one did not even begin to elute after more than 10 void volumes of carrier gas were passed through the column. This observation brings into question the transport characteristics of the tracer in the superheated region of the geothermal field. As the steam is superheated it becomes a ‘dry steam’ or a dry gas. Under these conditions the tracers could be slowed or stopped by their interaction with the dry rock matrix. This would cause a huge error in the tracer test interpretation which assumes conservative character of the tracer.



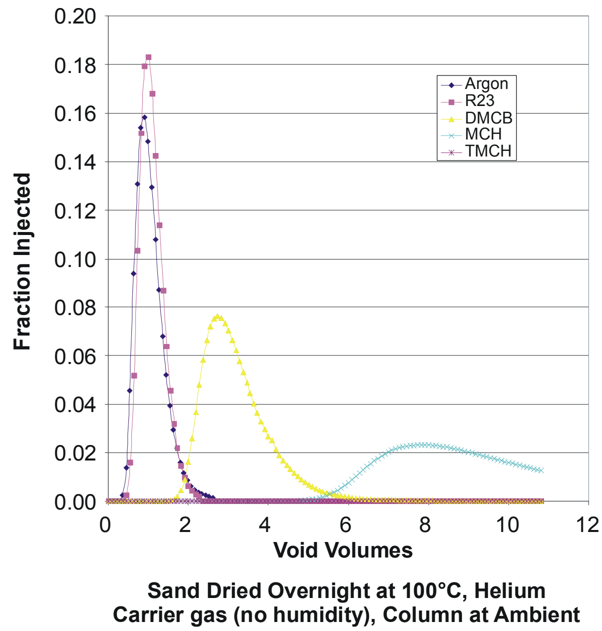


Figure 1. Figure 2.

The effect of tracers from the column packed with damp sand at ambient (23°C) temperature was evaluated. The moisture content corresponded to 6.4% by weight of dry sand. While all of the tracers had retardation factors less than 1.2 and thus were conservative, the freons were retarded more in the damp sand than the perfluorocarbons.

The effect of increased temperature with humidified carrier gas was evaluated. When the carrier gas was humidified at 60°C and the sand column was at 60°C all of the tracers were conservative. When the carrier gas was humidified at ambient and the sand column was at 60°C the perfluorocarbons became increasingly delayed until ultimately they were all nonconservative. Thus even at elevated temperature, humidity is needed for the perfluorocarbons to be conservative. Under geothermal conditions up to mild superheat the perfluorocarbons will be good tracers but at increasing superheat conditions the perfluorocarbons may rapidly become nonconservative. Further testing is needed under these conditions.

Reports & Articles Published in FY 2002: Maxfield, Blake T., Daniel M. Ginosar, Ryan D. McMurtrey, “Evaluation of Fluorocarbon Tracer Retention in Dry and Wet Sand Column Tests,” *Proceedings of the Geothermal Resource Council*, Vol. 26, pp. 841–846.

Presentations Made in FY 2002: Poster, *Evaluation of Fluorocarbon Tracer Retention in Dry and Wet Sand Column Tests,* by Blake Maxfield, Dan Ginosar and Ryan McMurtrey at the Geothermal Resource Council Annual Meeting in Reno, Nevada, Sept. 23–25, 2002.

Planned FY 2003 Milestones: None.

IMPROVED RESERVOIR MANAGEMENT

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DOE Idaho Operations Office Contract DE-AC07-99ID13727

Performing Organization: Geosciences INEEL

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DOE Funding Allocation: $625K

Cost Share Funding: None

Project Objective: The objective of this project is to develop new tools for more accurate, field-scale, simulation studies. These tools include accurate modeling of two-phase flow in wellbores and means of tracking injectate and estimating liquid saturation in reservoirs. Results from these tasks will subsequently be used in field-scale simulation studies that will investigate (a) optimal injection practices, and (b) means of optimizing resource exploitation as constrained by power generation and energy market pricing.

Background / Approach: Field-scale modeling studies were planned to evaluate operational practices, with the goal of improving resource management. This study of the improved reservoir management project models a producing Basin and Range geothermal system (Casa Diablo) by matching a historical temperature decline, which is then used to forward model resource temperature decline under base load and a cycling operation. The resulting resource decline scenarios are used to forecast both electrical production capacity and revenues, using historical energy prices and a typical annual ambient temperature profile. This approach improves understanding of how to increase plant revenues by using cycling to take advantage of changes in on- and off-peak power prices. The study shows that cycling operations can offset temperature decline of the resource, sustaining capacity over the life of the plant.

This work combined the use of both reservoir and energy conversion system simulators to enhance the decision-making process for the combined operation of a resource and its geothermal power plant. The project described how we evaluated whether cycling the geothermal resource could reduce the onset of cooling of the resource without reducing power generation revenues. Our approach was to first develop production profiles for different operating scenarios by using a numerical reservoir simulator, which is the most comprehensive performance prediction tool. Reservoir simulator models permit inclusion of detailed reservoir descriptions, which result in more accurate predictions associated with the different operating scenarios. Plant performance can then be modeled for these production scenarios using steady-state thermodynamic process simulators. This modeling identified plant operating parameters, which optimize power production and revenue streams.

Status / Accomplishments: Coupling the reservoir and power plant models to predict their combined performance response is very useful, if not necessary, in performing the economic analysis used to make business decisions to maximize project revenues and profits. This investigation illustrated the benefit of quantifying the cost effectiveness of cycling geothermal resources to increase revenues under a competitive or deregulated market pricing structure. The study concludes that by cycling this particular 16-Mwe plant and resource, $250K, or14%, increased revenue can be achieved per year, with 3% less fluid extracted from the resource. For the resource modeled, this reduced production rate resulted in an initial recovery of the resource temperature and delayed the subsequent temperature decline by about 4 years. The hotter fluids produced under this cycling scenario yield a relative increase in future power generation revenues from the plant while delaying the investment (drilling additional wells) necessary to recover power production capacity. The economic benefits identified by this study used power prices from the deregulated power market for base load and cycling operations. These benefits may not be realized by geothermal power producers that receive short-range avoided cost for their power (their original contract), not the prices available from the deregulated power market in California. However, any new geothermal power plants constructed and marketing their power within a deregulated power market should consider design in the wells and power plant that will allow them to capture the opportunities of the elevated power prices during on-peak power demands.

Reports & Articles Published in FY 2002: Bloomfield, K., and G. Mines, 2002, "Predicting Future Performance from Reservoir Management Cycling," *Geothermal Resources Council Transactions*, 79-82.

Presentations Made in FY 2002: Geothermal Resource Council Annual Meeting, September 2002.

Planned FY 2003 Milestones:

Study of relative injection benefits for "generic Geysers" description	Apr 03
Detailed study of NW Geysers site that is using pipeline water for injection	Aug 03
Publication of results at Geothermal conference	Sep 03

ELECTRICAL MEASUREMENTS: FRACTURE DETECTION, TRANSPORT AND FRACTURE EVOLUTION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: W-7405-Eng-48

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DOE Funding Allocation: $370K

Cost Share Funding: EMI/Schlumberger Geo-BILT tool development and deployment support (estimated $100K)

Project Objective: This project consists of two parts that jointly address the Geothermal Energy Program Geoscience R&D goals of characterization and management of geothermal resources, including understanding enhancement of sub-surface fractures, underground flows and reinjection. First, a field deployment of a geothermal-capable electromagnetic logging tool (Geo-BILT) that will produce valuable three-dimensional information about lithology and the nature of reservoir fluids, and will provide data from which the existence and orientation of highly permeable zones within several meters of a wellbore can be inferred. The second part is a laboratory study designed to improve our understanding of the electrical signatures of geothermal rocks, fractures, and permeable zones at high temperatures. This knowledge will be applied specifically to the interpretation of data from the Geo-BILT logging tool as well as to the basic problems of interpreting field geophysical surveys, detection of natural and induced fractures, and reservoir evaluation.

Background / Approach: 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. A second DOE strategy is to develop and demonstrate stimulation methods for the construction of enhanced geothermal systems. There are currently no logging tools that can operate in a geothermal well in order to determine the direction to features at distances of several meters from the borehole. Electromagnetic Instruments, Inc., LLNL, other DOE labs and universities, are collaborating in a project jointly funded by the California Energy Commission and DOE. We have designed, constructed, and are testing an innovative, high temperature, multi-component, multi-frequency and multi-spacing electromagnetic logging tool for geothermal applications. The system is called Geo-BILT.

The accompanying laboratory study focuses on the measurement of electrical resistivity of intact and fractured reservoir rocks. Resistivity methods are primary tools for locating and evaluating geothermal resources and also have considerable potential for evaluation of production and reservoir performance. Rocks exposed to active chemistry in geothermal environments acquire distinctive signatures in physical properties, such as the pressure dependence of the resistivity. The temperature and phase of pore fluid, mineralization, and the effects of low grade metamorphic reactions can alter the electrical properties of the rock, making it possible to detect and characterize these effects from electrical geophysical signatures. The detection of fractures and evaluation of their transport capabilities and knowledge of how these properties change with time are critical to reservoir evaluation and reinjection strategies. Analysis of medium scale field experiments have demonstrated that EM methods such as the Geo-BILT Tool can image fractures and be used to make quantitative estimates of saturation.

Status / Accomplishments: The laboratory studies on electrical resistivity of intact and fractured intermediate volcanic rock samples progressed to the point where the data could be put into a model of temperature and saturation. This model was successfully used in the inversion of a field-scale electrical resistance tomography experiment for saturation. The resulting saturations agreed with independent geophysical determinations of saturation using neutron logging in boreholes. The data and models of electrical resistivity were published in a journal article. Additional experiments are being performed to assess the effects of fracture surface area on water extractability in two-phase systems.

Geo-BILT had been successfully tested in a cool environment at the Lost Hills Oil Field in southern California. This spring, Geo-Bilt was successfully deployed for the first time in a geothermal field, in well 66-21 at Dixie Valley, Nevada by EMI and LLNL. The open-hole section of the well, from about 7,200 to 8,200 ft depth was logged. This interval is a sequence of metasediments interrupted by numerous plutonic and extrusive rocks. Access to the deeper section of the well, where the major fluid entry points are, was blocked.

A number of approaches can be used to interpret data from the Geo-BILT tool. Here, we illustrate its use to determine the strike and dip of nearly planar conductive features intersecting the borehole. To accomplish this, we examine the signal on two horizontal receivers from a signal generated by the vertical source in the tool. These combinations of source and receiver are called "null" measurements because in free-space, a layered medium, or any other situation with azimuthal symmetry, they would detect no signal. Figure 1shows the vector amplitudes of the real and imaginary null signals for 700 ft in well 66-21. The amplitudes have been normalized by the primary signal. In most of the section, the signal is small, but discrete areas with larger signals indicate zones with azimuthal asymmetry.

Analysis of the data from 7,855 to 7,885 ft found the signals are consistent with a planar conductor striking to the north-northeast, and dipping to the east-southeast. The borehole televiewer signal from this interval, courtesy of GeoMechanics International, shows a number of features. In the figure, the televiewer amplitude signal, wrapped into a cylinder, is viewed towards the NNE, the strike direction determined from Geo-Bilt. The televiewer indicates many features in this interval. Three dikes intersecting the well show as thick, light, nearly horizontal features, and several fractures appear as thin light or dark lines. Of these features, only one fracture, shown by the small arrows, dips to the SSE, the direction indicated for the anomalies seen by the Geo-BILT log. Similar results are seen at other depths.

The Geo-BILT log allows us to determine that in well 66-21 there is a set of highly conductive fractures dipping to the ESE. The laboratory measurements place constraints on the nature of these fractures. Given the small apertures indicated in televiewer logs, the conductivity producing the Geo-BILT signal is much larger than that observed in the lab for fluid-saturated fractures. Thus, we conclude that the detected fractures are filled with conductive mineralization. Although these fractures are not currently open, this result suggests that they have been favorable flow patterns in the past.

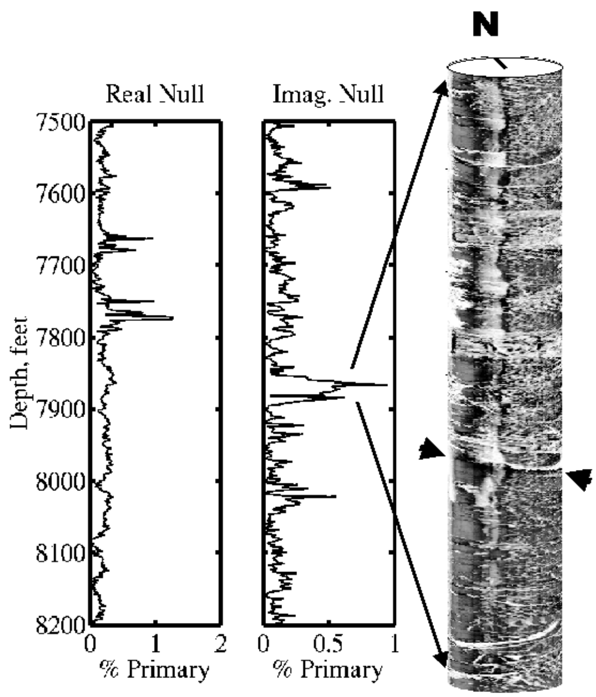

Figure 1. Geo-BILT data from Dixie Valley well 66-21. The data from a null signal pair (vertical dipole source and horizontal dipole receiver), are compared to a borehole televiewer record provided by GMI. The televiewer signal is displayed as if it showed a core viewed along the strike direction determined from the large Geo-BILT signal. The only feature with that strike is the small-aperture fracture marked with arrows.

This deployment shows that an extended EM logging tool like Geo-BILT can provide new information about complex conductivity structures in geothermal fields. Although the Geo-BILT prototype has been successfully deployed in one geothermal well, it failed due to over-heating in a second deployment at Dixie Valley. The prototype has been repaired and is available for use in future DOE or California Energy Commission (CEC) projects. The next planned deployment, supported by the CEC, will be at The Geysers. If appropriate, the Geo-BILT prototype could be deployed by DOE at sites in the future, as long as it survives. EMI is evaluating whether to invest in a production version of this tool in order to offer the service commercially.

With the successful use of the laboratory data to determine the saturation of a field-scale electrical resistance tomography experiment, and the demonstration of the Geo-BILT tool in a geothermal field, we have completed this project. Additional efforts to enhance interpretation methods for EM logging tools will continue in other projects at LLNL and elsewhere. The knowledge gained from this project, and additional laboratory studies that include modeling of the two-phase flow and fracture-matrix interaction, will be applied to EGS systems in a future LLNL project.

Reports & Articles Published in FY 2002:

Roberts, J. J., 2002, "Electrical properties of microporous rock as a function of saturation and temperature," *J. Applied Phys*., 21, 1687–1694.

Roberts, J. J., R. Detwiler, W. Ralph, and B. P. Bonner, 2002, "Fracture surface area effects on fluid extraction and the electrical resistivity of geothermal reservoir rocks," *Geothermal Resources Council Trans*., 26, Annual Meeting, Reno, NV, September 22–25, 411-417.

Presentations Made in FY 2002:

Kasameyer, P., B. Kirkendall, M. Wilt, and R. Mallan, "Borehole electrical measurements at Dixie Valley," *Dixie Valley Geothermal Workshop, Reno, NV, June 13, 2002*.

Mallan, R., M. Wilt, B. Kirkendall, and P. Kasameyer, "3D extended logging for geothermal resources: field trials with the Geo-Bilt system," 2002, *Geothermal Resources Council Trans., 26*, 405–410, Annual Meeting, Reno, NV, September 22–25, 2002.

Roberts, J., R. Detwiler, W. Ralph, and B. P. Bonner, "Fracture surface area effects on fluid extraction and the electrical resistivity of geothermal reservoir rocks," *Geothermal Resources Council*, Annual Meeting, Reno, NV, September 22–25, 2002.

REINJECTION OF CHEMICALLY MODIFIED GEOTHERMAL BRINES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $140K

Cost Share Funding: None

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

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

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

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

Status / Accomplishments: Silica precipitation from reinjected brine is controlled by the rate of polymerization of monomeric silica, rather than transition-state-theory-type kinetic rate laws. Computer models of the temperature and pH dependence of silica polymerization from geothermal fluids supersaturated with silica (owing to steam separation and cooling) have been obtained. The rate of polymerization can be related to the rate of silica precipitation. However, predictions of near-wellbore permeability reduction requires realistic descriptions of the heterogeneities of fluid flow and rock properties at a spatial scale and level of detail that are not captured in most reservoir and reactive transport models. Prediction of the quantity and rate of permeability change, and resulting decrease in injectivity, depends on coupling the rate of polymerization with details of fluid flow and rock properties surrounding the wellbore.

With regard to the influence of fluid chemistry on the mechanical strength of rocks, the basic chemical controls that affect mineral and rock fracture propagation and strength were investigated using data from the literature. The development and testing of hypotheses and conceptual models have been hampered by data limitations. Existing data is largely restricted to studies of single minerals and a limited number of rock types, with limited ranges of physical and chemical conditions and poorly defined fluid chemistry at the mineral interface. It is generally agreed that fluid chemistry affects fracture properties via its effect on the solid/liquid or solid/gas interface. However, the nature of the interfacial parameter or mechanism that exerts the major control on fracturing is not agreed on. Rebinder and others (Parks 1984; Cook 1999) invoke a macroscopic thermodynamic approach that suggests that the energy required to propagate a fracture in a solid is controlled by the surface tension (the surface free energy required to produce a unit of new surface). Because adsorption at an interface reduces surface tension, in theory, adsorption of *any* species should promote fracture initiation and propagation. Other workers invoke microscopic mechanistic conceptual models of the crack tip/fluid or mineral surface/fluid interface. Westwood (1981) hypothesizes that the electrical charge at the solid/liquid interface controls the mobility of dislocations in the solid, and therefore controls surface hardness. At the point of zero charge (pzc), the mobility of dislocations is at a minimum and surface hardness is at a maximum. Other workers suggest that adsorption of chemical species at the crack tip alters the activation energy required for bond breakage, and hence the *kinetics* of fracturing: e.g., the linkage of surface chemistry, mineral dissolution kinetics, and fracture propagation (Dove 1995). Our evaluation of existing data points towards γ_{SL} as a major governing parameter in fracture propagation. The data is less clear on the governing parameter for drilling efficiency. Measurement of the strength and fracture properties of single crystals and monomineralic polycrystalline rocks is required to test and refine the extant hypotheses. Once credible chemical-mechanical models are defined, it may be possible to manipulate fluid chemistry to promote better fracture control in EGS and increase drilling efficiency.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: Issue letter report on chemical controls on the development and sustainability of permeability in induced EGS fractures

STUDIES OF GEOTHERMAL RESERVOIR DYNAMICS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $158K

Cost Share Funding: None

Project Objective: This project applies and enhances mathematical modeling techniques (numerical simulation) to obtain improved characterization and understanding of geothermal reservoirs and reservoir processes. Issues addressed include (1) migration of phase-partitioning tracers in boiling geothermal systems, and (2) mineral dissolution and precipitation effects in geothermal reservoirs during the natural evolution and during production and injection operations, including recovery of valuable minerals from hypersaline brines.

Background / Approach: Advances in reservoir engineering are key to more economical geothermal field exploration, development, and management. Currently available reservoir simulators typically include only rudimentary capabilities for chemical transport and rock-fluid interactions. This limits model calibration to reservoir engineering-type data, such as pressures, temperatures, flow rates, flowing enthalpies, and concentrations of non-reactive solutes. Industry needs more accurate and comprehensive numerical simulation capabilities that can incorporate geochemical and geophysical information, in order to develop more reliable reservoir models, and to optimize field development and management, especially fluid injection for enhanced energy recovery. Comprehensive process models can also aid in exploration and definition of geothermal resources.

Status / Accomplishments: We performed analyses of the migration of man-made or naturally occurring phase-partitioning tracers as a means of characterizing reservoir processes such as boiling of injected fluids. Our studies explained observed tracer breakthrough curves (BTCs) in depleted as well as undepleted regions of The Geysers in terms of boiling of injected water, and fracture-matrix exchange.

The analysis demonstrated a characteristic signature of fracture-matrix interaction in tracer breakthrough curves, which hold a potential for determining the heat transfer area from observed BTCs.

A new fluid property module "EOSN" was developed for TOUGH2 which provides thermo-physical properties of noble gases (solubility and diffusivity) as a function of pressure and temperature, allowing accurate simulation of noble gas behavior in multiphase fractured reservoirs. TOUGH2/EOSN is being used to study the potential of noble gas tracers for characterizing reservoir conditions and processes. A testing program is underway at the completion of which the EOSN module will be made available to the public.

We continued applications of the TOUGHREACT code to study rock-fluid interactions in geothermal systems. Analyses of the natural evolution of hydrothermal systems in volcanic terrains gave substantial agreement with field observations for Japanese and Russian (Kamchatka) geothermal fields. Collaborative efforts with industry (Unocal, EPDC) addressed modeling of scaling processes in geothermal systems with different waters, either naturally occurring or man-made when reinjecting spent brines. First results obtained from this work are encouraging and have suggested ways in which scaling may be avoided through changes in field operating procedures.

Using a newly developed capability for modeling hydro-thermal-mechanically coupled processes, we performed analyses of ground deformation in active hydrothermal systems induced by deep inflows of magmatic fluids.

A very major effort during FY 2002 was directed towards getting the TOUGHREACT code ready for release to the public. This involved an overhaul of all program units and associated thermodynamic databases, development of a comprehensive suite of sample problems to serve as templates for future code applications, extensive code testing and debugging, and writing user documentation. This process was aided by collaborations with industry (ExxonMobile, Unocal, Geothermex, EPDC). A beta-testing version of TOUGHREACT with full documentation is nearing completion and will be released in early FY 2003, with full release of the code to the public expected later in FY 2003.

Upon solicitation by Ingvar Fridleifsson, Director of the Geothermal Training Programme of the United Nations University (UNU), we prepared and taught a course on geothermal reservoir engineering. The lecture notes written for this course are available as a laboratory report.

Reports & Articles Published in FY 2002:

Kiryukhin, A., T. Xu, K. Pruess, J. Apps, and I. Slovtsov, 2002, "Thermal-Hydrodynamic-Chemical (THC) Modeling Based on Geothermal Field Data," submitted to *Geothermics,* August 2002.

O'Sullivan, M. J., K. Pruess, and M. J. Lippmann, 2001, "State of the Art of Geothermal Reservoir Simulation," *Geothermics,* Vol. 30, No. 4, 395–429.

Pruess, K., 2002, "Numerical Simulation of Multiphase Tracer Transport in Fractured Geothermal Reservoirs," *Geothermics,* Vol. 31, 475–499.

Pruess, K., and C. Shan, "Numerical Simulation of Noble Gases as Natural Tracers for Reservoir Processes and Injection Returns in Vapor-Dominated Systems," submitted to 28th Workshop Geothermal Reservoir Engineering, Stanford University, January 2003.

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

Todesco, M., J. Rutqvist, K. Pruess and C. Oldenburg, "Multi-Phase Fluid Circulation and Ground Deformation: A New Perspective on Brady Seismic Activity at the Phlegrean Fields," submitted to 28th Workshop Geothermal Reservoir Engineering, Stanford University, January 2003.

Webb, S. W. and K. Pruess, 2002, "Evaluation of Fick's Law for Trace Gas Diffusion in Porous Media," in press, *Transport in Porous Media*.

Xu, T., E. Sonnenthal, N. Spycher and K. Pruess, 2002, "User's Guide of TOUGHREACT: A Program for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media," Lawrence Berkeley National Laboratory Report.

Presentations Made in FY 2002:

A. V. Kiryukhin, M. D. Lesnykh, T. Ishido, K. Pruess, and A. Polyakov, "Long term Pressure Monitoring in Verkhne-Mutnovsky Two-Phase geothermal Reservoir During Exploitation: Data Analysis and Possible Interpretation Based on Numerical Modeling," *AGU Fall Meeting, San Francisco, CA, December 2001.*

A. Kiryukhin, T. Xu, K. Pruess, and I. Slovtsov, "Modeling of Thermo-Hydrodynamic-Chemical Processes: Some Applications to Active Hydrothermal Systems," presented at *Twenty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28–30, 2002.*

A. Kiryukhin, T. Xu, K. Pruess, J. Apps, N. Spycher, and I. Slovtsov, "Modeling of Thermo-Hydrodynamic-Chemical Processes: Some Applications to Active Hydrothermal Systems," presented at *International Groundwater Symposium, Berkeley, CA, March 25–28, 2002.*

A. Kiryukhin, T. Xu, K. Pruess, J. Apps, and I. Slovtsov, "Thermal-Hydrodynamic-Chemical (THC) Model Calibration Study Based on Geothermal Field Data," presented at *Annual Meeting, Geothermal Resources Council, Reno, NV, September 2002.*

K. Pruess, "Mathematical Modeling of Fluid Flow and Heat Transfer in Geothermal Systems — An Introduction in Five Lectures," course presented at *UNU Geothermal Training Programme, Reykjavik/Iceland, September 2002.* (also, Lawrence Berkeley National Laboratory Report LBNL-51295, Berkeley, CA, August 2002).

T. Xu, K. Pruess, and G. Brimhall, "Modeling Reactive Geochemical Transport in Natural Fractured Rock Systems over Geologic Time," presented at *International Groundwater Symposium, Berkeley, CA, March 25–28, 2002.*

Planned FY 2003 Milestones:

Complete documentation and beta-version of TOUGHREACT	Jan. 03
Public release of TOUGHREACT	Jul. 03
Report on applications of TOUGHREACT to geothermal field problems	Sep. 03
Report on a TOUGH2 module for (saline) water with noble gases	Feb. 03
Report on chemical visibility of hidden geothermal systems	Sep. 03
Organize and conduct the TOUGH Symposium 2003	May 03

OPTIMIZATION AND INTEGRATION OF SEISMIC IMAGING METHODS FOR GEOTHERMAL RESOURCE EXPLORATION AND MONITORING

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $143K

Cost Share Funding: $60K (Unocal Geothermal)

Project Objective: In the past 30 years, technological advances in seismic exploration have increased the impact of seismic surveys on hydrocarbon prospecting. Although 2-D and 3-D seismic methods have proven to be an integral part of modern oil and gas exploration efforts, the heterogeneous nature of geothermal reservoirs makes seismic imaging more difficult. How well exploration methods used in the petroleum industry can be transferred to the geothermal industry is only beginning to emerge. Although geothermal reservoirs are considered difficult targets because of hydrothermal alterations, fracturing/faulting and structural heterogeneity, it is the heterogeneity and fracture properties that control fluid flow in the reservoir and therefore prime target for seismic investigations. The objective of the current project is to apply and extend modern seismic imaging technologies (active and passive) to geothermal reservoirs to image not only the structural and fracture heterogeneity of the subsurface but define the parameters controlling the fluid flow.

Background/Approach: In recent years, microearthquake, 3-D surface seismic and borehole experiments were conducted at several different geothermal sites (The Geysers, Tiwi and the Rye Patch geothermal reservoir, Nevada) to determine the geologic structure and nature of the reservoir. The focus of the 2002 work has been at the Rye Patch reservoir, but we will also briefly discuss the microearthquake results from The Geysers and Tiwi field.

Commercial development of the Rye Patch geothermal project started in the late 1980s and resulted in the construction of a 12 MW power plant and eight geothermal wells, of which seven were either too cold or non-productive. In the successful well, however, significant production at reservoir temperatures in excess of 200°C was encountered. The eight boreholes were drilled within an area of less than one square mile, which indicated that distribution of reservoir fluids is most likely controlled by fractures and faulting with limited areal extent. Therefore, The Industrial Corporation (TIC), as the owner of the project, and Transpacific Geothermal Inc. (TGI), cooperated with the Lawrence Berkeley National Laboratory (LBNL) to evaluate and apply modern seismic-imaging methods for geothermal-reservoir definition under the U.S. Department of Energy's (DOE) Geothermal Program. In 1998, a 3-D surface seismic reflection survey, covering an area of over 3 square miles, was conducted at the Rye Patch reservoir to explore the structural features that may control geothermal production in the area. The results of the seismic surface survey were reported in 1999. As part of the seismic surface survey, an additional surface-to-borehole experiment was conducted, during which a three-component high-temperature geophone was installed in the original VSP well at a depth of 3,900 ft. This geophone recorded all seismic waves generated by the surface sources, creating a second dataset in addition to the seismic-reflection data. The objective of the current project is to determine the subsurface topography of the reservoir using the surface-to-borehole dataset, which was recorded with minimal extra effort during the acquisition of the surface-reflection survey, and show that it can provide additional valuable information, which confirms the results of previous studies, about the reservoir structure at depth.

A total of 1,959 first-arrival travel times were determined out of 2,134 possible traces from the surface-to-borehole dataset. VSP data acquired by LBNL in previous years was also used to constrain the results. Two-dimensional ray tracing was performed to simulate wave propagation from the surface sources to the receiver at depth. The ray tracing was based on a 2-D laterally homogeneous velocity model derived from results of a vertical-seismic-profile (VSP) experiment recorded in the same well (see Figure 1). It is assumed that differences in travel time between the observed and modeled data are caused by structural deviations from a homogeneously layered model as estimated by the VSP profile, and thus are mapped into topographic changes at depth. The mapped changes represent deviations in the interface between the Triassic basement carbonates, and the Tertiary sediments and volcanics above. Mapping the changes in the interface between these major units is an important contribution to imaging the reservoir heterogeneity at depth that may reveal fault structures and possible flow paths for fluids at depth.

Status/ Accomplishments: The seismic imaging of the surface-to-borehole data set at Rye Patch is concluded, based on the currently available velocity information (i.e., one available VSP survey). However, should additional velocity information become available in the future, this project can be easily revisited and the results improved for more spatial accuracy. Current efforts are focusing on modeling the data for fracture effects to determine if those effects can be found in the surface or VSP data acquired.

The project produced a subsurface image of over 3 square miles of the interface between the carbonitic-basement rocks and the overlying sedimentary/volcanic sequence. The result is shown in Figure 2. The estimated elevation changes represent upper bounds of the actual changes, because the reference model is a 2-D velocity model that does not account for localized velocity heterogeneities. The results confirm the regional structure of the Basin and Range province. The general trend of the geologic units reveal a north-south strike and dip to the west, as expected for normal faulting encountered in the extensional regime on the western side of the Humbold Thrust Range. Furthermore, a local disturbance of this general pattern is detected by an elevation of the interface between the carbonate basement and the overlying sedimentary sequence. The structure, which resembles a horst, strikes east-west and appears to be extending throughout the survey area, cross-cutting the westward dipping units along the western boundary of the survey area. Previous studies corroborate the findings of the current work, because the boundaries of the elevated structure co-locate with areas in which the first arrivals of seismic waves undergo a transition from strong to weak amplitudes. A possible explanation can be that of faults bounding the horst to the north and south. Such a fault was traced in the 3-D seismic reflection data and is located along the southern flank of the elevated structure. Furthermore, gravity data in this area indicates a residual gravity high that coincides with the areal extent of the horst in the central section of the Rye Patch reservoir. The synthesis of these results suggests the presence of a local structure resembling a horst, which can be modeled by an up-lift of the interface between the basement and overlying sediments.

The results of the project can be validated by incorporation into reservoir simulations, to determine if the seismic model can explain observed borehole flow patterns. In general, the seismic results can be an important input for reservoir modeling, because they provide subsurface structure over a large scale that is needed for a comprehensive reservoir flow analysis.

In terms of the microearthquake results, processing of the temporary array installed by Unocal Geothermal was completed. There was a good correlation between seismicity and the injection well monitored. The results allowed Unocal to constrain their geologic model of the reservoir as well as confirm the location of the injectate. Figure 3 shows the relation of the earthquakes located with the data from the high-resolution array and improved velocity model in relation to the injection well.

Reports & Articles Published in FY 2002:

Gritto, R., T. M. Daley, E. L. Majer, 2002, “Estimating Subsurface Topography from Surface-to-Borehole Seismic Studies at the Rye Patch Geothermal Reservoir,” *Geothermics*, in review.

Presentations Made in FY 2002:

Gritto, R., T. M. Daley, E. L. Majer, 2002, “Integrated Seismic Studies at the Rye Patch Geothermal Reservoir,” *Geothermal Resources Council Transactions*, Vol. 26, 431–435.

Planned FY 2003 Milestones: Seismic modeling of faults and fractures for a suite of geothermal environments to determine the sensitivity of different scales and methods of measurements for imaging faults and fractures controlling fluid flow. A focus will be for enhanced geothermal systems to determine the characteristics of fractures in geothermal reservoirs in order to determine orientation, geometry, aperture and compliance. The results are envisioned to optimize injection strategies. Both active and passive methods will be considered. The studies will be interfaced with field applications at potential and current EGS study areas.

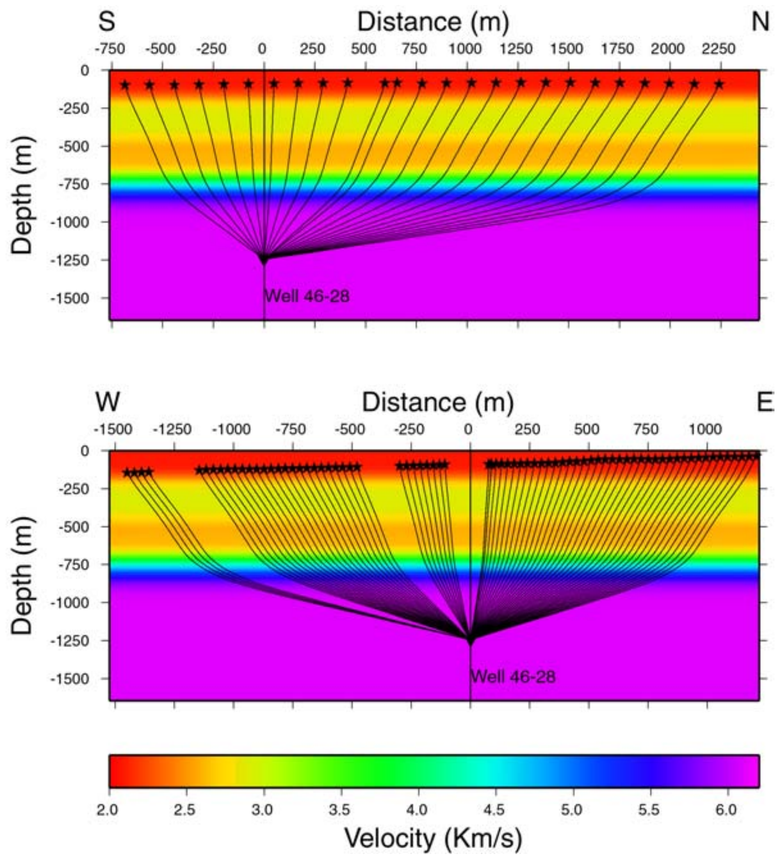

Figure 1. Velocity model and ray paths from two source lines to the down-hole receiver in the borehole. (a) N-S direction; (b) E-W direction.

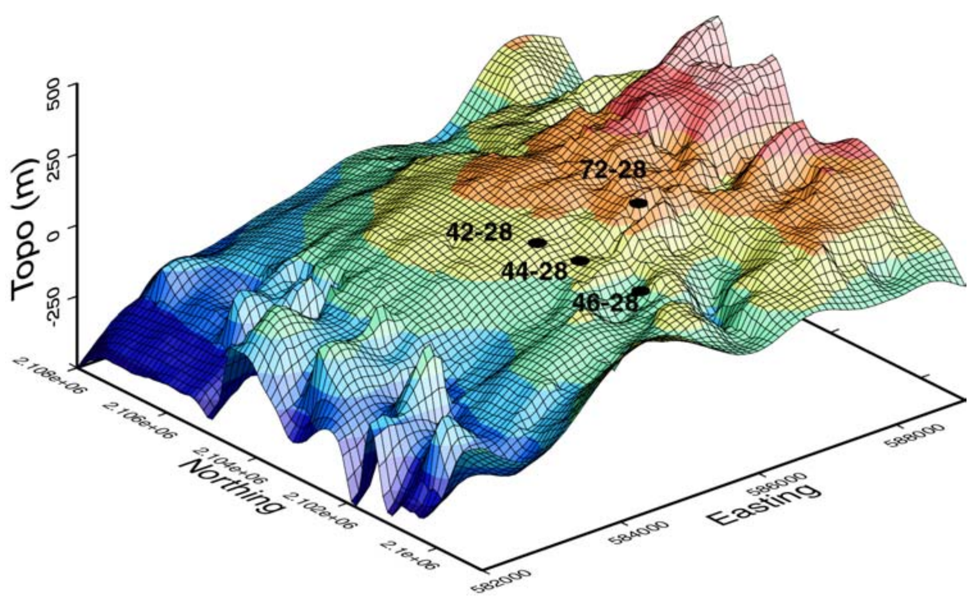

Figure 2. Three-dimensional surface map of topography changes of the interface between carbonate basement and overlying sediments. The topography changes are relative to the interface at 2,300 ft depth. View from south-west. Vertical exaggeration is approximately 5:1.

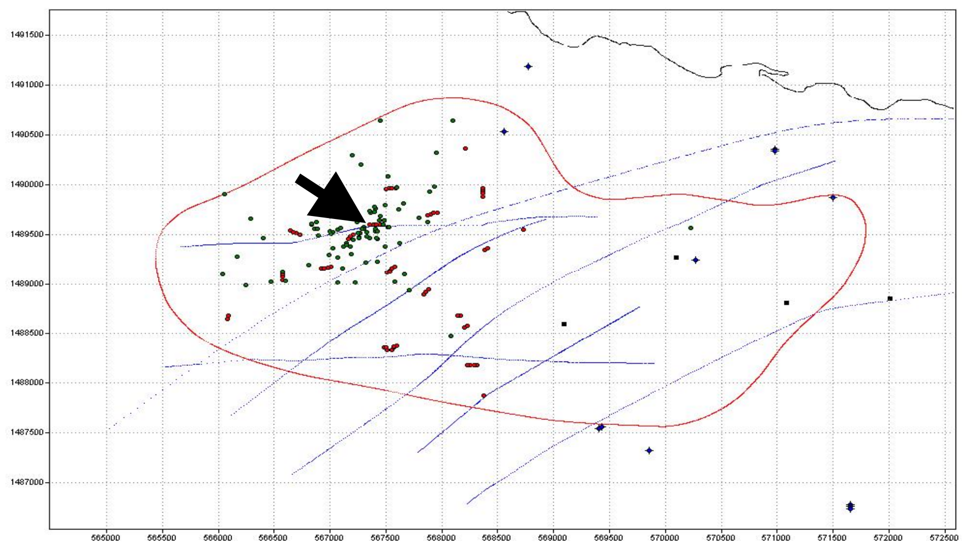

Figure 3. The location of the events during injection at the Tiwi geothermal field, the arrow shows the location of the injection well.

HIGH-TEMPERATURE INSTRUMENTATION AND TOOLS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
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Collaborating Researchers: None

DOE HQ Program Manager: Raymond LaSala
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DOE Funding Allocation: $220K

Cost Share Funding: $50K

Project Objective: The objective of this program is to evaluate and aid the development of tools for possible use in geothermal reservoir testing and modeling. There are four systems under investigation. The objective/task of each tool is listed below.

1. Test new hydrogen-resistive fiber from Fiberguide in actual geothermal well.
2. Assist Thermochem with modification of Sandia-designed liquid sampler.
3. Assist PhotoSonic in building and testing their flow tool.
4. Assess the feasibility of modifying the USGS commercial borehole televiewer from Robertson Geologging.

Each of these programs is working with a small company. With the exception of Robertson Geologging, each company has approached Sandia requesting aid.

Background / Approach: Like any industry depending on deep reservoirs for income, the wells and reservoirs require monitoring. This program addresses high-temperature tools for reservoir monitoring and inspection.

Fiberguide

Optical fiber cable is capable of measuring the complete wellbore temperature profile within seconds. This is an extremely useful function allowing the well owner to monitor any changes in the reservoir temperature at depth.

Fiber testing in FY 2001 found that fibers containing phosphorous were easily damaged by free hydrogen found inside all geothermal wells. Fiberguide produced 9 km of phosphorous-free fiber for testing. Our approach was to construct a fiber system using both conventional fiber and this new fiber from Fiberguide.

The fiber system will be placed within a geothermal well and monitored to see if the new Fiberguide fiber outperforms the conventional fiber over time.

Thermochem

Thermochem was instrumental in developing the existing fluid sampler tool. Paul Hertz of Thermochem has seen the commercial opportunities in this tool and wants to build his own tool. Our approach was to provide Thermochem our tool design and assist them in contracting for manufacturing major components.

PhotoSonic

PhotoSonic has two programs relating to geothermal well logging. They have an existing flow and steam quality tool using optical sensors. They also have an SBIR program to develop a 250°C pressure/ temperature tool. We provided PhotoSonic engineers with our tool design and example software and assisted them in developing their own tool. We also provided them with a much better understanding of geothermal well logging and the impact on tool design.

Robertson Geologging

Until, FY 2002 there was no background on this project. Our approach was to gain an agreement with Robertson Geologging allowing Sandia to understand the technical details of their tool. We followed this up by getting a tool from the USGS to inspect.

Status / Accomplishments: Task 1. Fiberguide provided 50% cost sharing on 9 km of hydrogen tolerant fiber. Following fiber delivery, 3,000 ft of the fiber has been installed into a fiber tube along with 3,000 ft of standard fiber. The two fibers provide for a side-by-side comparison. Caithness at Dixie Valley is working to deploy the test fiber within a test well at their own expense.

Task 2. Sandia has purchased a Dewar for cost sharing with Thermochem while providing them with a working tool and a complete set of drawings. Joe Henfling and Paul Hertz met at a manufacturing facility to discuss some tool modifications and make arrangements for fabrication of parts. Thermochem is now in the process of building their own tool.

Task 3. In assisting PhotoSonic, Sandia has provided them a high-temperature instrumentation system design, complete with software examples. However, contracting with Honeywell has delayed the PhotoSonic tool build by several months. We are working with Honeywell to resolve their issues concerning liability when licensing (even at zero cost) from SNL/DOE.

A back-up plan of licensing through Texas Components is being considered. Texas Components has pre-existing agreements with Honeywell to sell SOI components.

Task 4. A feasibility study has been conducted to investigate the viability of developing a +300°C high temperature borehole televiewer that can be deployed by the USGS to perform fracture imaging at the Coso Geothermal field as part of the Enhanced Geothermal System (EGS) technology demonstration. Completion of the high temperature version of the borehole televiewer is required by late 2003 in order to support USGS field-testing schedules.

The initial focus was to investigate the feasibility of hardening the low-temperature tools from Roberson already owned by the USGS. One of these tools was disassembled and examined in detail at Sandia and a strategy for hardening it for temperature was developed. Quotes were requested from Roberson as well as some of the key component manufacturers (transducer, motor, Dewar, etc.) in order to harden key elements and significantly increase the data transmission capability (i.e., length of cable that could be driven). Some of these quotes were obtained by the end of FY 2002, but not all. We were still in a data collection and data evaluation mode as we entered FY 2003.

We also decided to broaden the search and conduct a market survey to identify and evaluate the technology utilized in other existing low temperature borehole televiewers. An evaluation matrix has been developed to aid our selection process. The template contains categories chosen to permit comparison of the three leading companies that offer borehole televiewers. We are still awaiting cost estimates to complete the assessment and make a choice of which company is best suited to upgrade their borehole televiewer to high temperature.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: The project is not currently part of the draft FY 2003 AOP. If and when the decision is made to pursue development of a high temperature hardened borehole televiewer, the AOP will be modified and FY 2003 milestones will be provided.

TECHNOLOGY FOR INCREASING GEOTHERMAL ENERGY PRODUCTIVITY

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	DE-FG07-99ID133745
Performing Organization:	University of California, San Diego
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DOE Funding Allocation:	$325K
Cost Share Funding:	None

Project Objective: Under our 5-year DOE grant, we carry out several projects each year to meet the following objectives:

- Develop thermodynamic models that describe solid/gas/liquid interactions and heat properties for present-day geothermal energy operations (e.g., prediction of solubilities, phase equilibria, gas breakout, pH).
- Develop new cutting-edge thermodynamic modeling technologies that can successfully treat problems encountered in the exploitation of future high T-P and fluid-limited resources.
- Develop advanced methodologies that reduce the dependence on experimental data.
- Develop user interfaces and software application packages so that our modeling technologies can be easily accessed and used via the Internet.
- Increase the fundamental understanding of the complex chemistry of a wide variety of present-day and future heat sources and energy extraction operations.
- Train students in earth science with expertise in hydrothermal resources.

Background / Approach: Heat beneath the Earth's surface is an enormous but largely untapped source of clean, sustainable energy. To economically expand the use of this valuable resource will require the ability to accurately predict the complex chemistry of reservoir and production processes. Chemical problems, such as major scaling or corrosion of wells and plant equipment, reservoir permeability losses and toxic gas emission, can significantly increase energy production costs and even lead to site abandonment. In future operations that exploit deeper heat sources and low permeability reservoirs, new problems involving very high temperature and pressure rock/water interactions and unknown injection effects will arise. The ability to predict chemical behavior and heat content for wide ranges of conditions would increase the productivity of geothermal energy operations by enabling the assessment of potential resources and the design of optimal operating strategies to avoid adverse chemical effects.

Funded by the DOE Geothermal Program, we develop equation of state (EOS) chemical model technologies that correctly predict resource and process chemistry. Our modeling approach describes the thermodynamics of mixed brine-gas-solid systems via their free energies and allows construction of solubility, phase equilibria and heat models for wide ranges of composition (X), temperature (T) and pressure (P). Below about 300°C and P ≈1 atm, where the main variation of the liquid free energy is due to solute concentration changes, we use our solubility modeling approach, which is based on the Pitzer electrolyte equations, to model solid-liquid-gas equilibria. To treat high T and P resources, we develop EOS that can handle the large changes in density and high solute mole fractions that can be encountered under these conditions. The EOS frameworks and computer technology we develop are capable of handling many complicated chemical reactions, succinctly summarizing large amounts of experimental data and interpolating to desired PTX conditions. Molecular level simulation methods we develop can supply needed thermodynamic information when experimental data are not available. The more advanced theoretical structures we develop minimize the need for both experimental and simulated data. Our EOS models are easily transferable. We develop user interfaces so that our models can be bundled into various application packages (TEQUIL, GEOFLUIDS, GEOHEAT) for quick access on our interactive web site (geotherm.uscd.edu).

Status / Accomplishments: Using our methodology, we have shown that the chemistry of geothermal operations (scaling, breakout, steam fractions, gas emission, phase co-existence, pH, formation temperatures, downhole brine concentrations, heat content, etc.) can be reproduced up to very high brine concentration and temperature (T< 300°C). We have also developed technology to describe the very complex chemical problems (e.g., miscibility, subsurface boiling, 2-phase flow in reservoirs) expected to arise in the future development of higher T-P reservoirs.

Selected Recent FY02 Accomplishments:

TEQUIL, Model for the H-Na-K-Ca-OH-Cl-HSO$_4$-SO$_4$-HCO$_3$-CO$_3$-H$_4$SiO$_4^o$-H$_3$SiO$_4^-$-H$_2$O-CO$_2$(g)-SiO$_2$ System: For present geothermal operations (P ≈1 atm), we have completed parameterization of a comprehensive model that includes solid-liquid equilibria for dominant brine components (Na^+, K^+, Ca^{2+}, Cl^-, and SO_4^{2-}), scale-formers (gypsum, calcite and silica), CO_2 gas reactions, and major acid-base reactions. To illustrate the use of this model, we simulate an example of acid well cleanout. Loss of productivity can result from the buildup of scale in the well bore. It is common to remove calcite ($CaCO_3$) scale by an acid wash (usually with HCl). By calculating the amount of acid needed to remove scale for specific XTP conditions, this model can be used to estimate if the method is cost-effective. For example, calculations (Fig. 1, curve a) show that the addition of 1 mole HCl to a solution with 1 kgm water at 392 F increases calcite solubility by a factor of 1,270. The reaction is assumed to be: $CaCO_3(s) + 2HCl \leftrightarrow Ca^{2+} + H_2O + 2Cl^- + CO_2$. However, when excess amounts of weak acid anions, HCO_3^- or SO_4^-, are present in the brine more HCl is required to dissolve calcite. Figure 1 (curve b) shows that adding 0.1 mole $NaHCO_3$ shifts the calcite solubility curve by the amount of HCO_3^- added making it necessary to add more HCl to achieve the same effect as in curve a. This is a result of the removal of added H^+ via the reaction: $H^+ + HCO_3^- \leftrightarrow H_2O + CO_2$. If 0.1 mole Na_2SO_4 is present (curve c), added H^+ is used up by the replacement reaction: $CaCO_3(s) + 2HCl + SO_4^{2-} \leftrightarrow CaSO_4(s) + 2Cl^- + H_2O + CO_2$. In this case, 2 times (.2 mole HCl) the amount of SO_4^{2-}present in the solution is required to achieve the same slope as in curve a. Curve d, Fig 1, shows that the effect of SO_4^{2-} (.1 mole) and HCO_3^- (.1 mole) is cumulative.

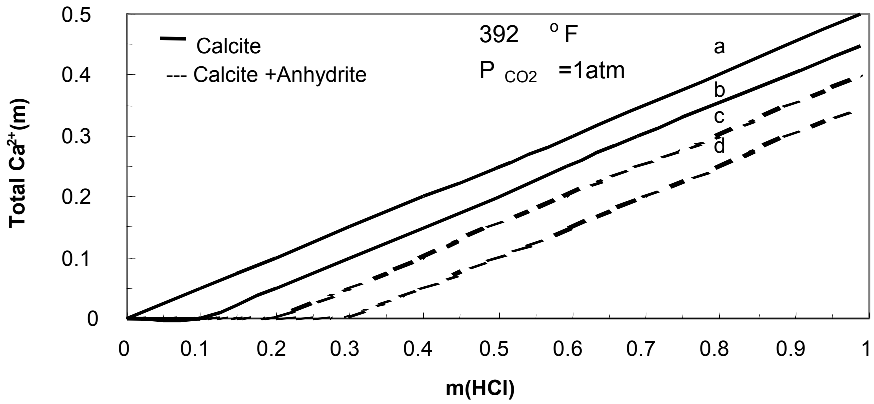

Figure 1.

Calculations also show that for low temperature wells (e.g., petroleum wells) acid wash is not a very effective way to remove calcium sulfate scale because of the small pK1 of bisulphate. For example, at 77°F the solubility of gypsum (the stable calcium sulfate phase at low temperatures) increases only by a factor of 8 with the addition of 1mole HCl to 1kg of solution. However, since pK1 increases with temperature, an acid wash is more effective removing anhydrite scale (the stable phase at high temperatures) in high temperature wells. For example, calculations at 392°F show that anhydrite solubility increases by a factor of 260 with the addition of 1 mole HCl.

TEQUIL, Model of Aluminum Interactions and Solubility: The alteration of reservoir rocks (e.g., $3KAlSiO_3O_8$(K-spar) + $2H^+$ = $KAl_3Si_3O_{10}(OH)_2$(K-mica) + $6SiO_2$(quartz) + $2K^+$) can also be a strong function of the hydrogen ion concentration in solution. We now have a preliminary variable temperature (0°–100°C) model of aluminum interactions and $AlCl_3.6H_2O$ (s) solubility in the H-Na-K-Al-Cl-H_2O system. We will initiate adding sulfate (HSO_4^--SO_4^{2-}) reactions and sulfate solid phases to this model in the next year.

GEOHEAT, Accurate Enthalpy Models for NaCl-H_2O Brines and for H_2O-CH_4-CO_2 Gas Phases: NaCl is by far the largest salt component in most geothermal brines. We have finished programming the model of Pitzer and Peiper (1982, 1984) for the NaCl-H_2O system, and it is ready to add to the GEOHEAT application package. This model was parameterized using measurements of osmotic and activity coefficients, enthalpies and heat capacities from 0° to 300ºC and from saturation pressure to 1,000 bar. A major difficulty we encountered was to make the standard, excess and relative enthalpies consistent for the reference state (273.15 K, 1 bar, liquid state for water) generally accepted by the geothermal community.

The chemical properties of most vapor phases encountered in geothermal applications below 300°C can be described by the behavior of the H_2O-CH_4-CO_2 system because the solubility of brine salt components in a coexisting gas phase is very small under these conditions. Using perturbation theory, we developed a new more accurate EOS for H_2O than in our current EOS for the H_2O-CH_4-CO_2 system now in GEOHEAT. It predicts enthalpies and the latent heat of the liquid-vapor phase changes from 100°C to 1,000° C with errors less than 1%. Water saturation pressure (a function of the latent heat) is predicted with error < 0.5%.

GEOFLUIDS, EOS for the Salt-H_2O-CO_2-CH_4 Systems: The comprehensive NaCl-KCl-$CaCl_2$-$MgCl_2$-H_2O-CO_2-CH_4 system includes many of the equilibria found in high T-P hydrothermal rock/water environments. Using perturbation theory plus additional empirical corrections, we have made substantial progress towards making an accurate high T-P EOS for this system. We have developed EOS for the

KCl-H_2O, $CaCl_2$-H_2O and $MgCl_2$-H_2O salt-water binaries and for mixtures in the NaCl-H_2O-CO_2-CH_4 quaternary that are accurate to high temperature (573–1,300 K) and pressure (1bar - 5 kbar).

GEOFLUIDS, Molecular Simulation of Dipolar Mixtures: EOS for mixed systems must have T, P, X and polar property variation for each species in the mixture. There are few analytical theoretical results that can provide guidance to the development of such an EOS. The one-fluid approach assumes that the mixed system can be described as a single component system made up of an effective species with parameter values that are the mole fraction average of the parameters of the various species in the mixture. This approach would simplify the development of a model for mixed systems. Using Monte Carlo (MC) simulation methods and a Stockmayer potential to describe the interactions between the effective molecules, we implemented the one-fluid approach for the NaCl-H_2O system and tested our results by comparing them with MC results describing the NaCl–H_2O binary system as a true mixture of two kinds of Stockmayer molecules, each with different dipole moments. The results, although not yet sufficiently accurate for modeling geothermal mixtures, are encouraging because they exhibit the right trends. With additional parameters, it seems possible to increase the accuracy of the one-fluid mixture description. We believe that these are the first comprehensive simulations of aqueous polar mixtures.

GEOFLUIDS, Simulation of the Thermodynamic Behavior of Water using the Accurate RWK2 Interaction Potential: Using both traditional molecular dynamics and Gibbs ensemble simulations of water, we found that the RWK2 H_2O-H_2O potential model calculates equilibrium densities, heat of vaporization, saturation pressure, and critical parameters that are in remarkable agreement with experimental vapor liquid equilibrium. Our predictions are also in excellent agreement with water enthalpy and saturation pressure predicted by Haar et al. (1984) (e.g., see Fig. 2). Fig. 2 also shows that saturation pressure predictions, for example, are much closer to experiment than that predicted by other water-water interaction models.

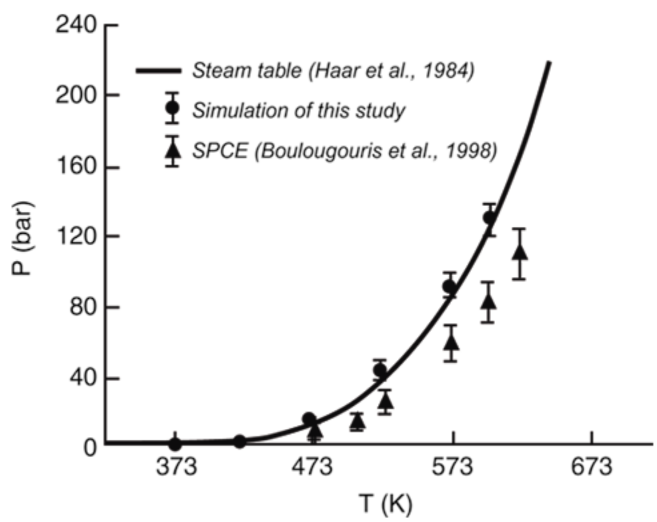

Figure 2.

TECHNOLOGY TRANSFER: Our interactive web site (geotherm.ucsd.edu) averages more than 100 hits for model use per month. In addition, our technology is transferred via presentations at technical meetings, publications and personal communication. We also supervise the research activities of two research scientists developing chemical models for geothermal energy application. Additional service to the scientific community occurs via review of manuscripts and proposals.

Reports & Articles Published in FY 2002:

Zhenhao Duan, Nancy Moller, and John H. Weare, "Equations of State for the NaCl-H_2O-CH_4 System: Phase Equilibria and Volumetric Properties above 573 K," Accepted by *Geochim. Cosmochim. Acta.*

Zhenhao Duan, Nancy Moller, and John H. Weare, "Semiquantitative Liquid/Vapor Phase Equilibrium Predictions for Water Using the Flexible RWK2 Water Potential," Submitted to *J. Phys. Chem B*.

Christomir Christov and Nancy Moller, "A Chemical Equilibrium Model of Solution Behavior and Solubility in the H-Na-K-Cl-OH-HSO_4-SO_4-H_2O System to High Concentration and Temperature," submitted to *Geochim. Cosmochim. Acta.*

Presentations Made in FY 2002:

"Parallel Implementation of Large-Scale Ab Initio Molecular Dynamic Algorithms: Scaling Issues," 1st Computational Chemistry Conference, University of Kentucky, Lexington, Kentucky, October 17, 2001.

"First Principles Prediction of the Structure and Dynamics of Very Nonideal Aqueous Solutions: Ion Solvation and Proton Dynamics," Battelle, Richland, WA, May 21, 2002.

"Parallel Implementation of Ab Initio Simulation Methods," Singapore National University, June 17, 2002.

Planned FY 2003 Milestones:

Liquid Density Brine Models for $0 \leq T < 300°C$: (1) Complete testing of model of the Na-K-Ca-H-HCO_3-CO_3-OH-H_2O-CO_2(g) system. (2) Continue development of model (0°–100°C) of aluminum interactions and solid phase solubility in the H-Na-K-Al-Cl-SO4-H_2O system. (3) Continue parameterization of variable temperature silicate model ($H_4SiO_4^o$-$H_3SiO_4^-$-NaCl-KCl-$CaCl_2$-H_2O).

Equation of State Models for High T, P Conditions: (1) Evaluate mixing parameters for EOS of the $CaCl_2$-$MgCl_2$-H_2O brine system using simulation data. (2) Use molecular dynamics simulation to quantitatively predict vapor-liquid equilibria in binary gas-water and salt-water systems at high T, P conditions. (3) Use simulations and scaling EOS to predict properties of thermodynamic functions, such as enthalpy, in salt- or gas-water systems at high and intermediate temperatures and pressures and in the critical region. (4) Parameterize molecular level potentials for use in steps 2 and 3 using first principle simulation of the properties of Na^+, Ca^{2+}, and Cl^- in water.

New Applications Software: (1) Initiate development of software for silica geothermometer for incorporation into TEQUIL. (2) Initiate development of software for pH-MOD application for incorporation into TEQUIL.

Technology Transfer: (1) Implement computational options (e.g., single phase properties) for GEOFLUIDS on web site. (2) Update model codes on web site; improve navigation and appearance of web site. (3) Begin adding user tools (e.g., silica thermometer, pH Mod software) to TEQUIL on web site.

A THERMOELASTIC HYDRAULIC FRACTURE DESIGN TOOL FOR GEOTHERMAL RESERVOIR DEVELOPMENT

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-99ID13855

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DOE Funding Allocation: $60K

Cost Share Funding: $20K

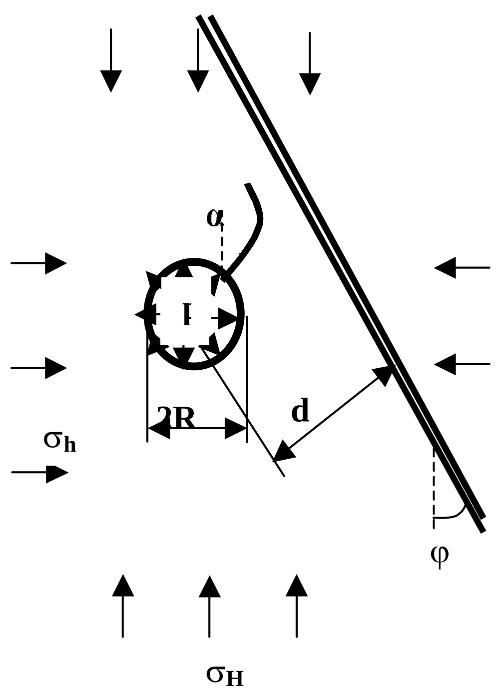
Project Objective: The objective of the project is to develop an advanced two-dimensional, thermo-mechanical model that captures the salient aspects of hydraulically driven fractures in a geothermal environment. This will be accomplished by developing fracture propagation algorithms that consider significant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

Background / Approach: Geothermal energy recovery from hot rocks involves extraction of heat by circulating water through heat exchange areas within the rock mass. Geothermal reservoir rock masses generally consist of igneous and metamorphic rocks that have low matrix permeability. Therefore, cracks and fractures are the major pathways for fluid flow and provide the necessary heat exchange surfaces and play a significant role in extraction of geothermal energy. Thus, knowledge of conditions leading to formation of fracture and fracture networks is of paramount importance. Furthermore, in the absence of natural fractures or adequate connectivity, artificial fractures are created in the reservoir using hydraulic fracturing. Propagation of hydraulic fractures in a geothermal setting is a complex process involving interaction of high pressure fluid with a stressed and hot rock mass, mechanical interaction of induced fractures with existing natural fractures, the spatial and temporal variations of in-situ stress, and rock heterogeneities. As a result it is necessary to develop tools that can be used to study these interactions as an integral part of a comprehensive approach to geothermal reservoir development, particularly for enhanced geothermal systems. We are developing advanced thermo-mechanical models for design of artificial fractures and rock fracture research in geothermal reservoirs. The fracture propagation algorithms consider the 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. The fracture propagation studies include modeling interaction of induced fractures with existing discontinuities such as faults and joints. In addition to the fracture propagation studies, 2D and 3D heat extraction solution algorithms will also be developed and used to estimate the variations of reservoir stresess with cooling. 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.

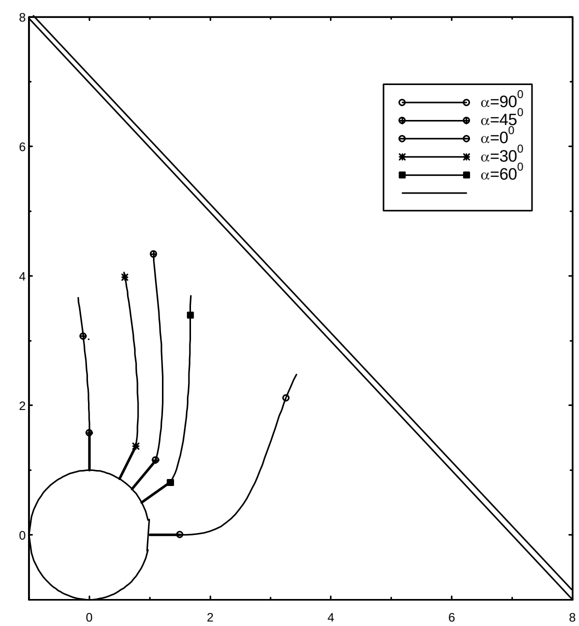
Status / Accomplishments:

(1) Completion of a fully-coupled fictitious stress poro-thermoelastic model for borehole failure and fracture initiation; (2) improvement of the 3D BEM solution for heat extraction, multiple wells and arbitrary-shaped fractures can now be considered; (3) improvement of the user interface for the 3D model; (4) extension of the 2D CVBEM model to allow thermoelastic analysis (5) improvement of the 2D CVBEM to allow fracture behavior analyses near faults and joints by introducing a Mohr-Coulomb joint model; (6) application of the fracture propagation and heat extraction numerical models to practical geothermal problems of interest; and (7) improvement of the 2D fracture propagation code for viewing propagation in real time.

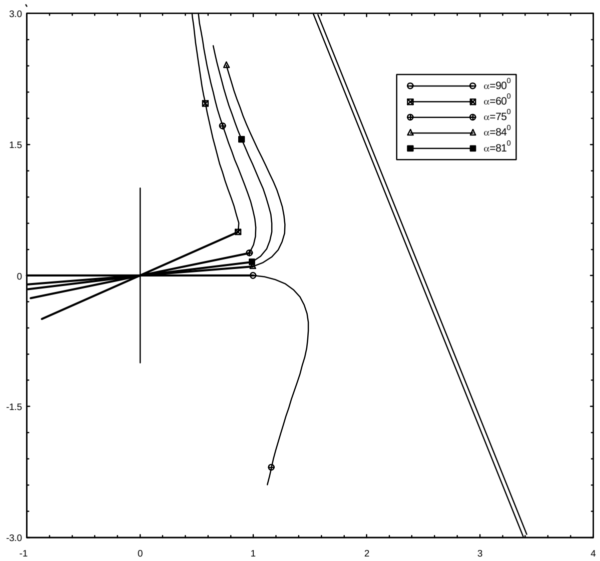
Fracture Propagation Near a Fault or a Joint:



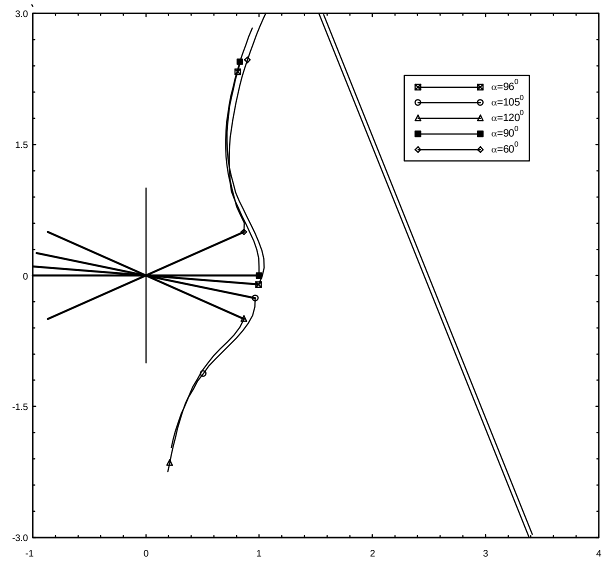
The problem of a hydraulic fracture emanating from a borehole near a fault.



Fracture propagation from a wellbore near a fault Ratio of Max/Min stress=4, fault inclination=45.

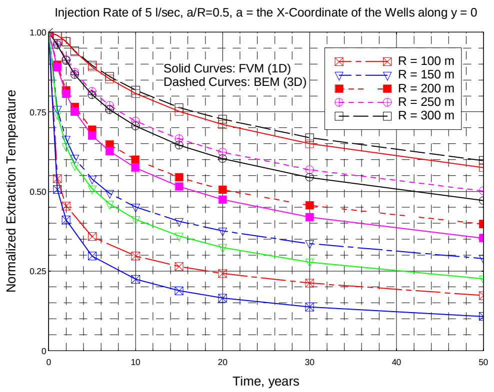


Effect of fault friction (friction angle= 18) on fracture path. Ratio of Max/Min stress=2.

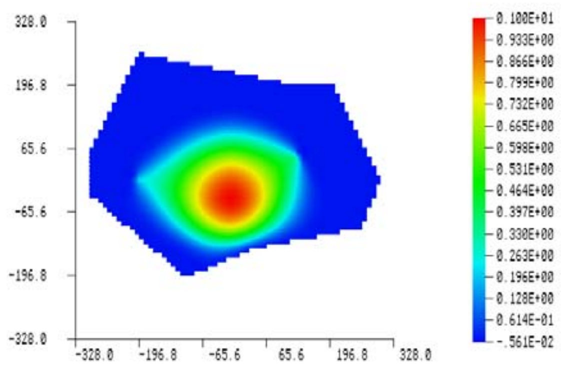


Fracture paths near a fault with a large friction angle= 45. Ratio of Max/Min stress=2.

Three-Dimensional Heat Extraction from a Fracture:

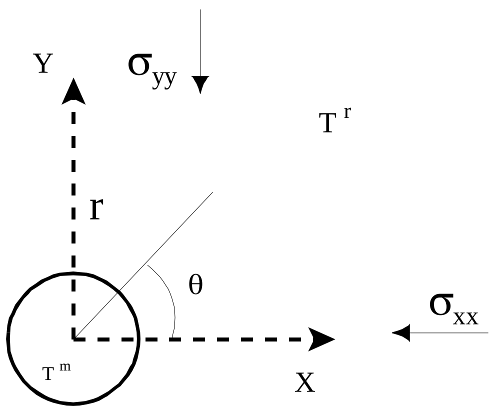


Extraction temperature for various sizes circular with an injection well and two extraction wells.

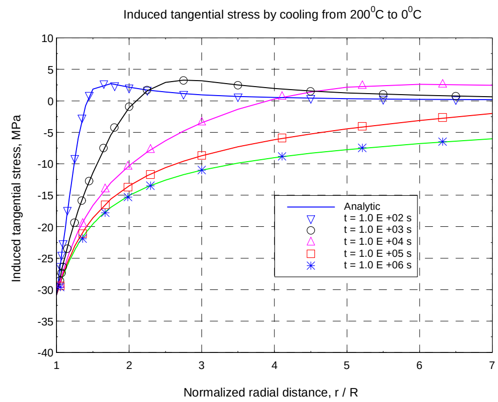


Normalized temperature deficit in an arbitrary-shaped 3D fracture with an injection well and two extraction wells.

Wellbore Failure and Fracture Initiation Caused by Cooling:



Circular borehole in an infinite porous rock.



Distribution of induced tangential stress around the borehole;Note the large tensile stress near the borehole wall.

Reports & Articles Published in FY 2002:

NDRM-01-10, "Extension and improvement of the three-dimensional boundary element solution for heat extraction from a fracture in a geothermal reservoir."

Cheng, A., A. Ghassemi, and A. Tarasovs, 2002, "An Integral equation method for modeling three-dimensional heat extraction from a fracture in hot dry rock," *Int. J. Num. & Anal. Methods in Geomech* (submitted).

Zhang, Q. and A. Ghassemi, "Modeling fracture initiation & propagation using an indirect poro-thermoelastic boundary element method." *GRC Annual Conf. Reno, NV, 2002.*

Presentations Made in FY 2002: "A Three-dimensional solution for heat extraction from a fracture in HDR using the boundary element method," *27th Stanford Geothermal Workshop*.

"Modeling fracture initiation and propagation using an indirect poro-thermoelastic boundary element method," *GRC Annual Conf., Reno, NV.*

CORE ANALYSIS FOR THE DEVELOPMENT AND CONSTRAINT OF PHYSICAL MODELS OF GEOTHERMAL RESERVOIRS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-99ID13761

Performing Organization: New England Research Inc.

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DOE Funding Allocation: $35K

Cost Share Funding: None

Project Objective: The project focuses on the development and constraint of physical models to improve interpretations of geophysical observations in geothermal reservoirs. Detailed studies of core scale properties from a variety of reservoirs are being performed to develop an understanding of the role of mineralogy, pore structure, rock type, degree and type of alteration, and core scale heterogeneity on key physical properties. Models of matrix properties are being developed to improve resource discovery and assessment as well as to improve reservoir engineering practices such as reservoir characterization and the design of enhanced geothermal systems.

Background / Approach: Development of effective exploitation strategies requires the ability to sufficiently characterize geothermal reservoirs. Effective characterization and monitoring of geothermal reservoirs requires a fundamental understanding of the geophysical properties of reservoir rocks and fracture systems. Unfortunately, spatial variability in porosity, fracture density, salinity, saturation, tectonic stress, fluid pressure, and lithology can all potentially produce and/or contribute to geophysical anomalies, causing serious uniqueness problems in interpreting anomalies. The problem is compounded by the fact that geothermal reservoirs are commonly complex, fractured systems with architectures unlike those encountered by the oil and gas industry.

While the extensive and advanced knowledge base of the oil and gas industry is typically applied to geothermal exploration and production workflows, many problems arise due to fundamental differences between geothermal and hydrocarbon reservoirs. To overcome (and/or avoid) these problems, an accurate foundation for the physical understanding of rocks from geothermal reservoirs must be established.

This work is aimed at providing fundamental core measurements and models to improve interpretations of geophysical observations. Laboratory data on core samples is being collected and analyzed to constrain models for geophysical properties which will lay a foundation for interpretation of log and field scale measurements. The work has resulted in the recognition that illite, a common mineral phase in most geothermal reservoirs, plays a controlling role in influencing fundamental geophysical properties.

Status / Accomplishments: This project was initiated in May of 1999 as a 5 year project. The project is nearly 60% complete, but currently slated to be ended prematurely as of June 2003, after expending 64% of the initially committed funds.

Velocities and electrical properties are being measured on core plugs from the Awibengkok Geothermal field in Indonesia and The Geysers Geothermal field in California, providing a suite of cores which are mineralogically similar but texturally quite different.

The measured formation factors, ultrasonic velocities, and dynamic bulk and shear moduli all exhibit normal trends with porosity, however scatter in these relationships is relatively large. The laboratory measurements, evaluated in the context of routine porosity determinations as well as petrographic and modal-mineralogic analysis, have enabled the identification of compositional and textural factors affecting the seismic and electrical characteristics of these rocks which appear to produce much of the observed scatter in the relationships with porosity.

FY 2002 work has concentrated on integrating the laboratory data into a generalized model of seismic and electrical properties of geothermal reservoir matrix through a series of empirical relationships constrained by the data. The resulting model provides a means with which one can study and understand the relative importance of different variables (namely porosity, mineralogy, and texture) on the core scale physical properties. Key findings from this effort include:

- with the exception of the bulk modulus, illite plays an important role in influencing all of the measured properties, both with regards to intrinsic variation, and with respect to processes related to saturation (rock/water interaction).
- joint interpretation of velocity and electrical resistivity can provide constraint on illite content and porosity, two of the most fundamental reservoir matrix parameters needed for reservoir engineering.
- a single linear dependence on illite content is sufficient to describe the rock/water interaction on the dynamic shear modulus of the matrix at both Awibengkok and the Geysers. Understanding and quantification of this phenomenon is critical to proper interpretation of field data.
- the role of porosity in affecting the saturation dependence on the dynamic bulk modulus is well described by low frequency Biot-Gassmann theory.
- scatter in the bulk modulus with respect to the first order porosity trend appears to be influenced by two yet to be identified mineralogical/textural variables.
- the same variables controlling scatter in dynamic bulk modulus also control intrinsic variation in Vp/Vs ratio, a key saturation indicator used for exploration and reservoir monitoring. Key samples which should provide end-member values of these variables have been identified.

One potential application of these relationships is for improved log analysis, such as characterization of porosity and illite concentration from resistivity and velocity logs. Figure 1 illustrates saturated V_p and formation factor contours based on the empirical relationships of each property. This graph illustrates some important interrelationships between these two commonly logged properties. At low porosities, formation factor is found to be relatively insensitive to illite content. For saturated matrix, if F is known, porosity can be inferred directly from F and velocities can be used to infer illite content. High porosity materials have different systematics owing to the fact that porosity effect on F decreases at higher porosities while the illite effect retains its strength. In this case, resistivity becomes a poor predictor of porosity, but in combination with velocities, could again be used to constrain both porosity and illite. Also of significance at moderate porosities, F and V_p contours are relatively parallel, indicative of a regime where porosity and illite cannot be distinguished even using a joint interpretation approach. The Awibengkok reservoir contains a number of units in this regime.

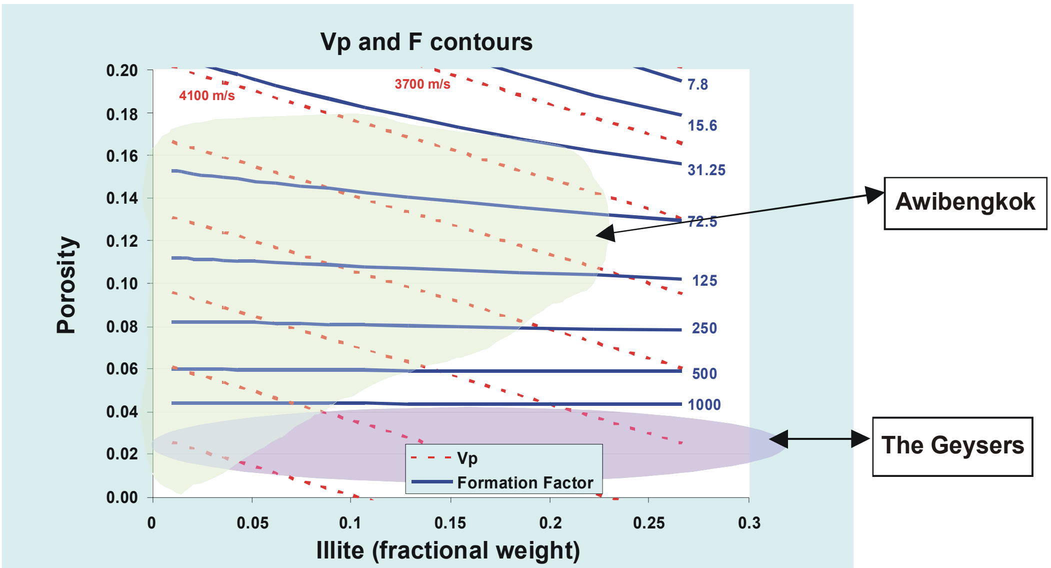

Figure 1: Contours of saturated V_p and F. A zone of parallel contours highlighted in green indicates a region where porosity variations cannot be distinguished from illite variations. Below this zone (i.e., low porosity) F is the best indicator of porosity and V_p can be used to constrain illite. Purple shading indicates typical Geysers matrix values, while green shading indicates typical Awibengkok matrix values

Another noteworthy finding, which will serve as the focus of remaining work, involves evidence of textural/mineralogical controls on Vp/Vs ratio. It has long been observed that the dynamic bulk modulus of reservoir cores exhibit considerable scatter with respect to a first order linear trend with porosity. The cause of this scatter has not been identified, but it is of great interest because it leads to scatter in the Vp/Vs ratio, a seismic property commonly used to infer saturation in a reservoir. Recent analysis based on the developed empirical relationships has found that the residual in the bulk modulus with respect to the first order porosity trend, when plotted versus Vp/Vs, results in a separation of samples into logical groups based on lithology and reservoir (see Figure 2). This segregation provides an important clue that intrinsic Vp/Vs variation is controlled in part by textural/and or mineralogical variables linked to lithology. Two types of variation are apparent in the data, one being intra-group variations and the other being inter-group, the latter of which appears to lead to systematics between cores from Awibengkok and The Geysers. A broader look at mineralogy and texture variations is certainly warranted. Establishing controls on dynamic bulk modulus and Vp/Vs will greatly improve our ability to model and interpret seismic and sonic log data from geothermal reservoirs.

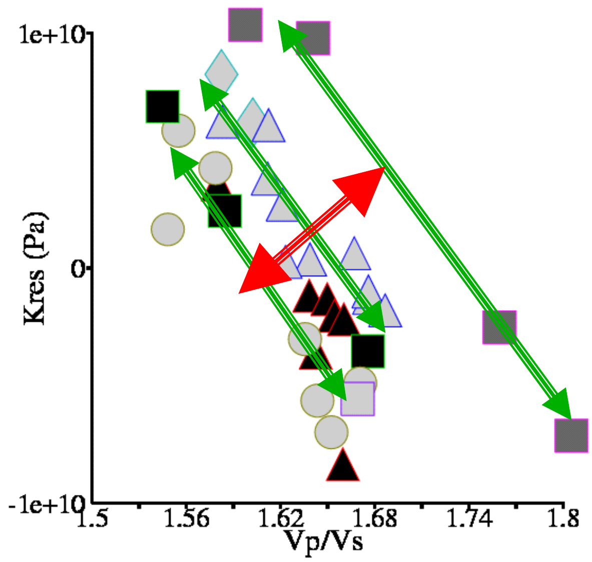

Figure 2: Cross plot of the residual in the bulk modulus (with respect to the predicted modulus based on a simple linear function of porosity) versus the Vp/Vs ratio for core plugs from the Awibengkok geothermal field and The Geysers. This plot indicates that Vp/Vs variation is linked to scatter in the dynamic bulk modulus, the causes of which are not well understood. Different symbols indicate different lithologies. Both intragroup (green arrows) and intergroup (cross cutting red arrow) variations are noted, providing clues to possible mineralogical and textural controls.

Reports & Articles Published in FY 2002: In addition to DOE reports and publications, a paper was presented in an oral session at the GRC annual meeting. A paper introducing that work was published in the proceedings. A poster covering heterogeneity in electrical properties was also presented at the meeting, without publication in the proceedings. An award for best paper in the Geophysical Measurements session was received for the oral presentation and paper.

Presentations Made in FY 2002:

Poster Presentation: GRC Annual meeting
Oral Presentation: GRC Annual meeting

Planned FY 2003 Milestones: The project is currently scheduled to be completed by June 2003.

GAS ANALYSIS OF GEOTHERMAL FLUID INCLUSIONS: A NEW TECHNOLOGY FOR GEOTHERMAL EXPLORATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-F007-00ID13953

Performing Organization: New Mexico Tech
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DOE Funding Allocation: $181K

Cost Share Funding: $9K

Project Objective: To 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. The knowledge gained by this program can be applied to geothermal exploration, which may expand geothermal production. Knowledge of the gas contents in reservoir fluids can be applied to fluid inclusion gas analysis of drill chip cuttings in a similar fashion as used in the petroleum industry. Thus the results of this project may lower exploration costs both in the initial phase and lower drill hole completion costs. Commercial costs for fluid inclusion analysis done at 20 ft intervals on chip samples for 10,000 ft oil wells is about $6,000, and the turn around time is a few weeks.

Background / Approach:

1. Update the New Mexico Tech fluid inclusion gas analysis facility. A dual quadrapole gas analysis system will increase the quality of gas analyses, and improvement in software and vacuum systems will increase research capabilities.
2. Add to the merger database of magmatic gases by measuring gases in magmatic glass inclusions.
3. Analyze the volatiles in Karaha-Telaga Bodas, Indonesia fluid inclusions studied by Joe Moore. The Karaha-Telaga Bodas is a steam field less than 5,000 years old and its study is yielding new insights on how such geothermal systems develop.

4. Develop a technology base for the analysis of fluid inclusion organic compounds. There are almost no known quantitative data on organic compounds in geothermal systems, although their presence has been long known (for example, Kerosene Creek at the Waiotapu geothermal system in New Zealand).
5. Develop methods of applying geothermal gas analysis to geothermal exploration using knowledge gained during the project

Status / Accomplishments: Sub-objectives 1-4 above were completed and reported on (Blamey, Nigel J. F. 2001; Norman 2001; Norman 2001; Blamey and Norman, 2002; Lutz et al., 2002; Norman et al., 2002b; Norman 2002, Norman et al., 2002d, and Moore et al., 2002). These papers show how geothermal gas compositions may indicate fluid source and fluid process. Gas compositions can readily differentiate reservoir fluids from shallow ground waters, steam heated water, and basin groundwater. A paper at the 2003 Stanford Meeting will present an application of our work in understanding geothermal organic species to the Karaha-Telagas Bodas geothermal system. Organic species are sensitive to boiling processes and entrants of steam-heated water into geothermal systems. Objective 5 was reported on in Norman, et al., 2002a; Norman, 2002; Kurilovitch and Norman, 2002 and Canales and Norman, 2002. Work the on the application of gas analysis to geothermal exploration is on going. At present, a Masters student is using soil gas analysis to locate structures and upflow zones at the Lightning Dock geothermal system, NM, in cooperation with Lightning Dock Geothermal. The methodology used is reported in Norman, 2002, and Canales and Norman, 2002.

Application of fluid inclusion analysis to drill chip cuttings is being tested on the Coso geothermal system in cooperation with Coso Operating Company, LTD. Funding is by a California Energy Commission grant titled: *Fluid Inclusion Stratigraphy: A New, Inexpensive Method for Geothermal Reservoir Assessment*

Reports & Articles Published in FY 2002:

Blamey, Nigel J. F., and David I. Norman, 2002, “New Interpretations of Geothermal Fluid Inclusion Volatiles: Ar/He and N2/Ar Ratios — A Better Indicator of Magmatic Volatiles, and Equilibrium Gas Geothermometry,” *Proceedings, Twenty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California,* 188–197.

Lutz, Susan J., Joseph N. Moore, Nigel J. F. Blamey, David I. Norman, 2002 “Fluid-Inclusion Gas Chemistry of the Dixie Valley (NV) Geothermal System,” *Proceedings, Twenty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California.* 206–216.

Norman, D. I., Nigel Blamey, Lynne Kurilovitch, 2002a, “New Applications of Geothermal Gas Analysis to Exploration,” *Geothermal Resources Council Transactions: v. 26*, 335–341

Norman, D. I., Nigel Blamey, Joseph N. Moore, 2002b, “Interpreting Geothermal Processes and Fluid Sources from Fluid Inclusion Organic Compounds and CO_2/N_2 Ratios,” *Proceedings, Twenty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California,* 266–274.

Norman, D. I., “Gas Analysis Of Geothermal Fluid Inclusions: A New Technology for Geothermal Exploration,” 2002, Final Report DOE Geothermal for Grant DE-F007-00ID13953.

Moore, J. N., D. I. Norman, and R. G. Allis, 2002c, “Geochemical Evolution of the Vapor-dominated Regime at Karaha-Telaga Bodas, Indonesia: Insights from Fluid Inclusion Gas Compositions,” (in press), *Proceedings of the 24th New Zealand Geothermal Workshop, November 2002.*

Norman, David I., L. Kurilovitch, and N. Blamey, 2002d, "Analyses of Ar-He-N_2 Ratios in Magmatic and Geothermal Fluid Inclusions," *Canadian Mineralogist* (submitted).

Kurilovitch, L., and David I. Norman, (2002) "Analysis of Fluid Inclusions in Drill Core Chips: Implications for Exploration," *Canadian Mineralogist* (submitted).

Presentations Made in FY 2002:

N. Blamey and David I. Norman, 2002, "New Interpretations of Geothermal Fluid Inclusion Volatiles: Ar/He and N2/Ar Ratios — A Better Indicator of Magmatic Volatiles, and Equilibrium Gas Geothermometry," *Proceedings, Twenty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California*.

D. Canales and D. I. Norman, 2002, "Determining Buried Structures by Soil Gas Analysis," Lightningdock Geothermal System, New Mexico, *Geothermal Resources Council Annual meeting, August, 2002*.

J. N. Moore, D. I. Norman, and R. G. Allis, 2002, "Geochemical Evolution of the Vapor-dominated Regime at Karaha-Telaga Bodas, Indonesia: Insights from Fluid Inclusion Gas Compositions," (in press), Presented at the *24th New Zealand Geothermal Workshop, Auckland, November, 2002*.

D. I. Norman, Nigel Blamey, 2002, "New Applications of Geothermal Gas Analysis to Exploration," *Geothermal Resources Council Annual meeting, August 2002*.

D. I. Norman, Nigel Blamey, Joseph N. Moore, 2002, "Interpreting Geothermal Processes and Fluid Sources from Fluid Inclusion Organic Compounds and CO_2/N_2 Ratios," *Proceedings, Twenty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 2002*.

David I. Norman, L. Kurilovitch, and N. Blamey, 2002, "Analyses of Ar-He-N_2 Ratios in Magmatic and Geothermal Fluid Inclusions," *9th Biannual Meeting of PACROFI, Newfoundland, July, 2002*.

L. Kurilovitch and David I. Norman, 2002, "Analysis of Fluid Inclusions in Drill Core Chips: Implications for Exploration," *9th Biannual Meeting of PACROFI, Newfoundland, July, 2002.*

Planned FY 2003 Milestones: Grant finished July 2002.

GEOTHERMAL RESOURCE ANALYSIS AND STRUCTURE OF BASIN AND RANGE SYSTEMS, ESPECIALLY DIXIE VALLEY GEOTHERMAL FIELD, NV

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-00ID13886

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DOE Funding Allocation: $142K

Cost Share Funding: In Kind-Caithness

Project Objective: There are main two objectives to this research. The first is to develop a detailed geologic model of Basin and Range geothermal systems (using Dixie Valley, NV as an example) to materially aid in the development of other geothermal systems throughout the province. The second objective is to continue development and publication of a regional geothermal gradient/heat flow database for exploration use by the geothermal industry in the development of new resources.

Background / Approach: Recent information has been made public dealing with the Dixie Valley geothermal system that indicates a greater potential for geothermal systems in the Basin and Range in terms of their reservoir size temperature than has been anticipated based on historical results and suggests. This new information suggests new directions in exploration and evaluation. In this project the approach is to use this new information in a new, in depth, look at Basin and Range geothermal resources. The scale will gradually broaden as the project progresses with the first years' studies focused on Dixie Valley.

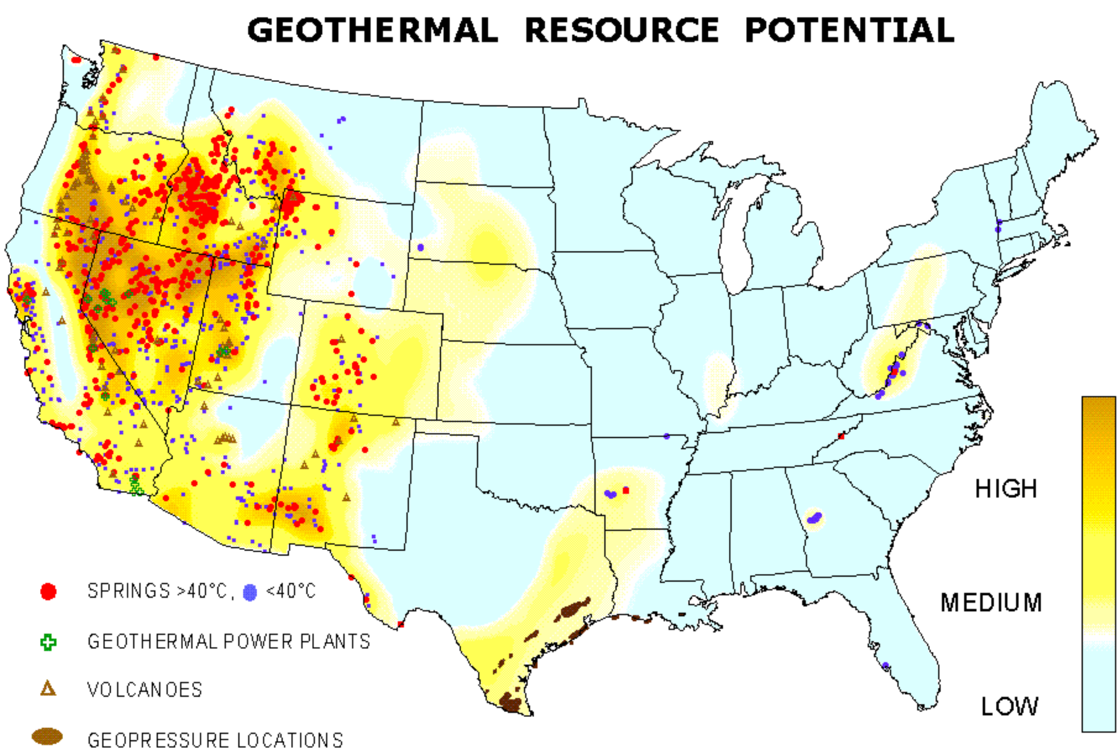
In a previous project an extensive database of thermal gradient wells (over 5,000) for the western U.S. was compiled and put into the public domain on our website. We will continue to add additional wells to the database and to add additional data to the existing wells sites in the catalogue, such as thermal conductivity and heat flow, for those sites that do not have such basic data at the present time. The data base will be used in subsequent resource evaluation using some of the results from the detailed Dixie Valley studies described in the first paragraph

Status / Accomplishments: In FY 2002 a number of tasks were accomplished. We gave papers at the DOE/NBM Dixie Valley Workshop and at the Geothermal Resources Council Annual Meeting on the thermal regime in Dixie Valley to introduce the results to the the geothermal community. We presented two posters at the GRC meeting giving the results of the regional geophysical studies in order to communicate to industry the new results, the types of data available, and some of the important resource implications.

In the Dixe Valley area we completed integration of the gravity survey, seismic sections, and older regional magnetic surveys. We wrote a paper on a natural state model of the system and submitted it to the journal *Geothermics*.

We accumulated a total of over 5,000 points in the regional thermal well data base. We continued to update the Web Page (www.smu.edu/geothermal) to make it more user friendly and to simplify access to the data by interested users. For many wells we determined lithology, thermal conductivity and calculated heat flow for those sites which did not already have that information. We used the added heat flow values in the regional geothermal data base to determine heat loss for as many systems as possible. We compiled ancillary data sets that will be used with the regionalization of the results from the Dixie Valley specific studies (regional gravity, earthquake locations, and locations of young faults). This data base has been extensively used by exploration companies in the evaluation of areas for leasing and further examination.

We developed a new geothermal resource map published by NREL (see below). This map was used as the geothermal component of the *Renewable Energy Atlas of the West, A Guide to the Region's Resource Potential* published by Land and Water Fund of the Rockies and sponsored by the Hewlett Energy Series.



2002 Geothermal Resource Map (NREL)

We published 3 papers in the GRC Bulletin applying the results from Dixie Valley to other areas in Nevada outlined by the regional data compilation. Finally, we completed initial compilation of the databases for the new Geothermal Map of North America.

Reports & Articles Published in FY 2002:

Blackwell, D. D., M. Leidig, and R. P. Smith, 2002, "Regional Geophysics of the Dixie Valley Area: Example of a Large Basin and Range Geothermal Resource," *Geothermal Resources Council Trans*., 26*,* 519–522.

Blackwell, D. D., M. Leidig, R. P. Smith, S. Johnson, and K. W. Wisian, 2002, "Exploration and Development Techniques for Basin and Range Geothermal Systems: Examples From Dixie Valley, Nevada," *Geothermal Resources Council Trans*., 26, 513–518.

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

Richards, M., and D. D. Blackwell, 2002, "The Forgotten Ones: Geothermal roads less traveled in Nevada," *Geothermal Resources Council Bulletin*, 31(2), 69–75.

Richards, M., and D. D. Blackwell, 2002, "The Nevada Story—turning a loss into a gain," *Geothermal Resources Council Bulletin*, 31(3), 107–110.

Richards, M., and D. D. Blackwell, 2002, "A Difficult Search, Why Basin and Range Systems are Hard to Find," *Geothermal Resources Council Bulletin*, 31(4), 143–146.

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

Wisian, K. W., and D. D. Blackwell, 2002, "Numerical modeling of Basin and Range geothermal systems," submitted to *Geothermics*, June 2002, received from review, accepted for publication pending recommended revisions, December, 2002.

Presentations Made in FY 2002:

D. D. Blackwell, "Regional Geophysics of the Dixie Valley Area," Reno, NV, June 2002.

D. D. Blackwell, "Exploration and Development Techniques for Basin and Range Geothermal Systems: Examples From Dixie Valley, Nevada."

D. D. Blackwell, "Regional Geophysics of the Dixie Valley Area: Example of a Large Basin and Range Geothermal Resource," poster presentation, *Geothermal Resources Council Annual Meeting, 2002*.

D. D. Blackwell, "Exploration and Development Techniques for Basin and Range Geothermal Systems: Examples From Dixie Valley, Nevada," Oral presentation, *Geothermal Resources Council Annual Meeting, 2002.*

Planned FY 2003 Milestones: The planned milestones for FY 2003 are completion of a final report and publication of the revised Geothermal Map of North America.

LABORATORY MEASUREMENTS OF PROPERTIES FOR STEAM/WATER FLOW IN GEOTHERMAL ROCK

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-99ID13763

Performing Organization: Stanford Geothermal Program
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DOE Funding Allocation: 250K

Cost Share Funding: None

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

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

The Stanford Geothermal Program uses both theoretical and experimental approaches to conduct this 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) Relative Permeability of Geothermal RockTask.

The preliminary nitrogen-water experiments conducted on The Geysers geothermal core were not all successful. However, data from this experimental study gave insights into behavior of fractures and fluid flow through these fractures that will be helpful in the next steps of the research. Using the apparatus shown in Figure 1, basic geothermal rock properties such as irreducible saturations and porosity were determined.

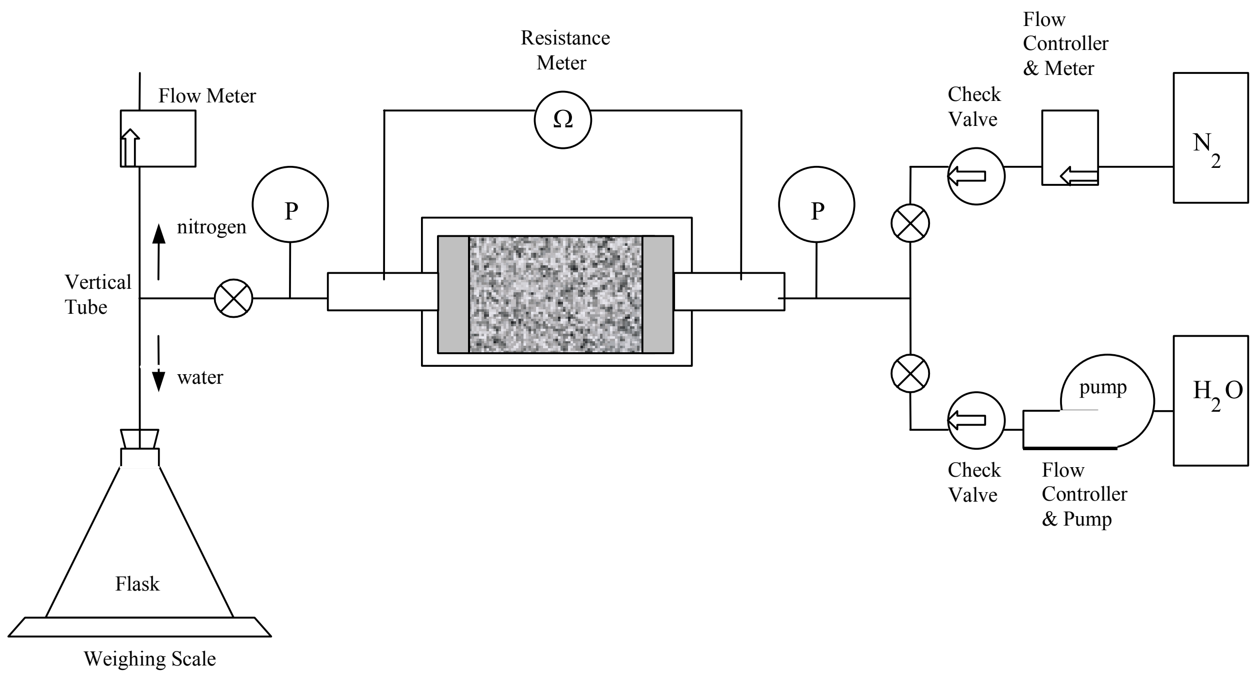

Figure 1: Apparatus for nitrogen-water relative permeability experiment.

1. The irreducible water saturation of The Geysers geothermal rock is approximately 15%. The irreducible gas saturation obtained is around 20%, but may actually be lower. Porosity of the core is 4.3%.

2. The resistivity method provides acceptable estimates of average water saturation in the core. The error is within ±5% compared to the values obtained by weighing the core.

3. At the endpoint saturations, the water relative permeabilities are much higher than the nitrogen gas relative permeabilities. This can be attributed to higher friction during water flows at irreducible gas saturation compared to nitrogen gas flows at irreducible water saturation. At irreducible water saturation, water will occupy small spaces in the fracture surface and reduce the surface roughness. Smoother surfaces have lower friction factors. The decrease in void volume due to the presence of water within the fractures may not be as significant as the reduction in surface roughness.
4. Flow experiments in fractures are very much linked to the rock mechanics of the fractures. Fracture aperture, fracture roughness, and fracture propagation/initiation are affected by the number of loading cycles and the net stresses applied. Eliminating these changes to the core during an

experiment will be the ideal case. Less than ideal situations will require quantification of these changes and incorporating the changes into the flow calculations.

(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 how 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 (see Fig. 2). 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.

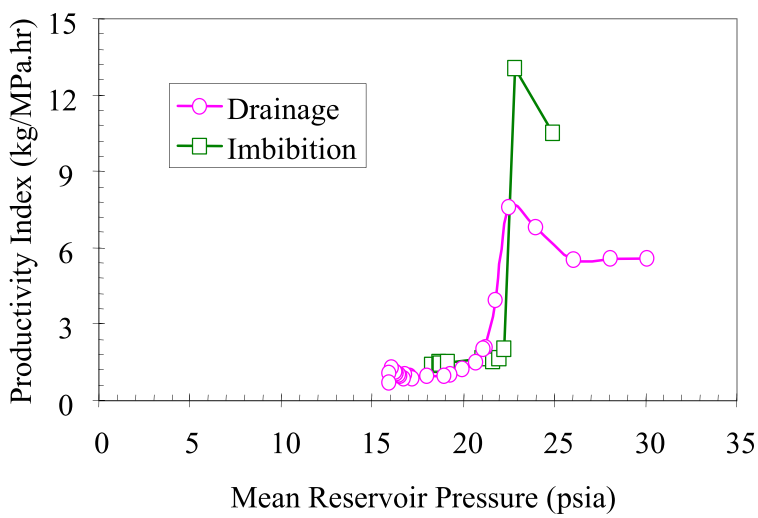

Figure 2: Effect of reservoir pressure on the productivity index.

(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 (see Fig. 3).

Figure 3: Examples of gas-water flow 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, as shown in Fig. 4. 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. Steam-water experiments were initiated in FY 2002 to compare boiling with nonboiling flow (such as the nitrogen-water results). Preliminary measurements suggest that steam-water flow in the same fracture apparatus follows a very different behavior as the two phases interfere much less (Figure 5).

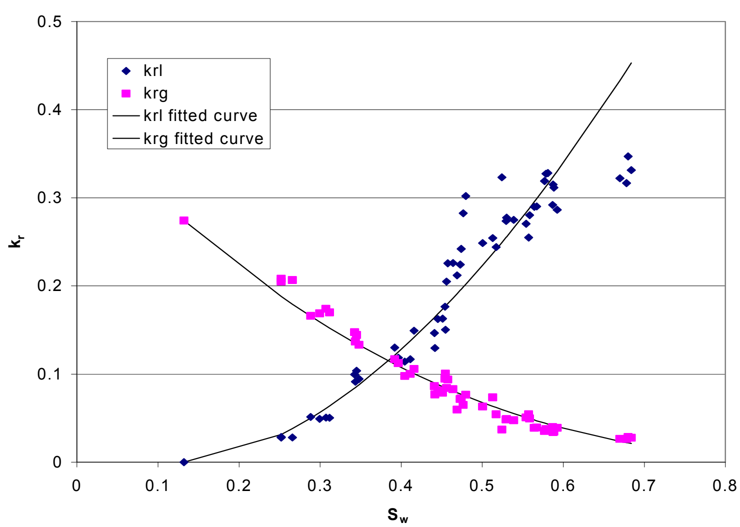

Figure 4: Drainage relative permeability curves for nitrogen-water flow in a rough-walled fracture.

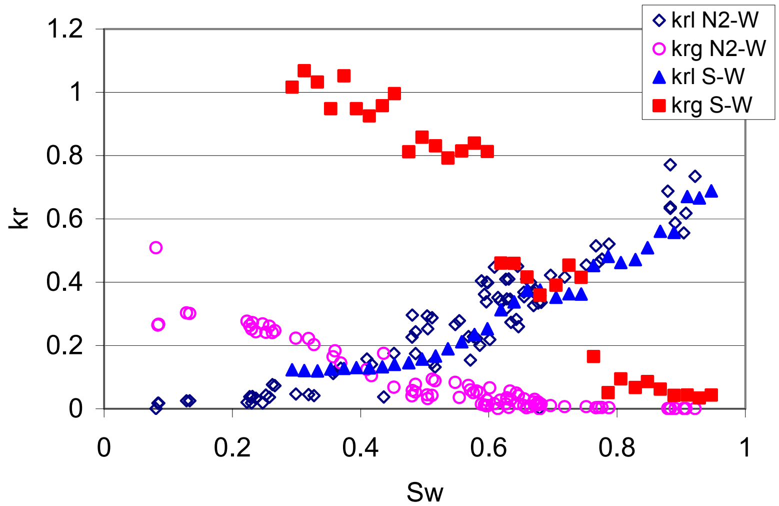

Figure 5: Comparison of relative permeability curves between steam- and nitrogen-water cases in the smooth wall fracture.

Reports & Articles Published in FY 2002:

Chen, C. Y., G. P. Diomampo, K. Li, and R. N. Horne, "Steam-Water Relative Permeability in Fractures," *Geothermal Resources Council Transactions* 26 (2002).

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

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

Li, K., H. Nassori, and R. N. Horne, (2001), "Experimental Study of Water Injection into Geothermal Reservoirs," *Proceedings of the GRC 2001 annual meeting,* August 26–29, 2001, San Diego, USA; *Geothermal Resources Council Transactions 25*.

Li, K., and R. N. Horne, "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 R. N. Horne, "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 R. N. Horne, "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 R. N. Horne, (2002), "A Capillary Pressure Model for Geothermal Reservoirs," *Geothermal Resources Council Transactions,* 26.

Li, K., and R. N. Horne, "An Experimental and Theoretical Study of Steam-Water Capillary Pressure," *SPEREE* (December 2001), 477–482.

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

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

Sullera, M. M., and R. N. Horne, (2001), “Inferring Injection Returns form Chloride Monitoring Data,” *Geothermics*, 30, 591–616.

Presentations Made in FY 2002:

C. Y. Chen, G. P. Diomampo, K. Li, and R. N. Horne, “Steam-Water Relative Permeability in Fractures,” *Geothermal Resources Council Annual Meeting,* Reno, NV (2002).

K. Li, H. Nassori, and R. N. Horne, “Experimental Study of Water Injection into Geothermal Reservoirs,” *Geothermal Resources Council Annual Meeting,* August 26–29, 2001, San Diego, CA.

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

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

K. Li, and R. N. Horne, “A Capillary Pressure Model for Geothermal Reservoirs,” *Geothermal Resources Council Annual Meeting,* Reno, NV (2002).

Planned FY 2003 Milestones:

Completion of steam/water relative permeability experiments in fractures.

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

WESTERN U.S. GEOTHERMAL SYSTEMS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-00ID13891

Performing Organization: Energy & Geoscience Institute
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Stuart Johnson, Senior Geologist, Caithness Corporation, Reno, NV
Will Osborn, Resource Manager, CalEnergy Corporation, Calipatria, California;
Dennis Kaspereit, Senior Geoscientist, CalEnergy Corporation, Calipatria, California;
Melinda Wright, Geochemist, CalEnergy Corporation, Calipatria, California;
Mitch Stark, Senior Geoscientist, Calpine Corporation, Middletown, California;
Joseph N. Moore, Geologist/Geochemist, Energy & Geoscience Institute, University of Utah, Salt Lake City, Utah;
Gregory D. Nash, Geologist/Geographer, Energy & Geoscience Institute, University of Utah, Salt Lake City, Utah

DOE HQ Program Manager: Allan Jelacic
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DOE Funding Allocation: $300K

Cost Share Funding: No direct cost share, but the companies referenced above have generously provided formerly proprietary samples and resource data worth literally tens of millions of dollars.

Project Objectives:

1. Refine and develop new geological, geophysical, and numerical models for western U.S. moderate- to high-temperature hydrothermal systems, including those certain to be found, but presently cryptic, in association with young andesitic volcanoes along the eastern flank of the Cascade Range, and those totally concealed beneath valley-fill sediments of the Great Basin

2. Assist domestic geothermal companies in the application of these models for risk-reduced and more cost-effective exploration and development.

3. Maintain and augment the world-class EGI Geothermal Sample Laboratory as a national repository and study center for geothermal cores, cuttings, and information, and as a research resource for the entire geothermal community.

Background / Approach: The western U.S., in particular the Great Basin, Cascade Range, and California Coast Range, is one of the world's richest moderate- and high-temperature geothermal provinces. Geothermal energy currently accounts for about 2,600 MW of installed electrical-energy generating capacity, yet the region's immense resource potential is far from fully realized. These facts, and the nation's growing and troubling dependence on imported petroleum, underpin the Department of Energy's stated aim for geothermal energy to supply 10% of the western states' electric-power needs by the year 2020. Achieving this ambitious goal will clearly depend in large part upon gaining a much clearer understanding of (1) important systems, selected as exemplary, in the region already under production; (2) details of the special local and regional geologic settings that foster the inception of these systems.

In close collaboration with longtime geothermal-industry partners (referenced above), we have undertaken to obtain significantly greater insight into the intricate and interlinked geological, geochemical, and hydrologic controls on the inception, evolution, and three-dimensional configurations of the two distinct types of of moderate- to high-temperature systems prevalent in the western U.S. – (1) those demonstrably heated by shallow, cooling igneous intrusions (for example, at CalEnergy's Salton Sea field, California); and (2) those ostensibly heated entirely in response to circulation along deeply-penetrating faults and fractures in regions of thinned crust and consequent, elevated heat flux (for example, Caithness Corporation's Dixie Valley field, Nevada).

What makes this approach particularly favorable now is the geothermal companies' increasing recognition of the value of DOE-sponsored and highly focused research and development. Fiscal realities have driven the companies to ever-leaner and more efficient operations, with smaller scientific staffs and a greater array of responsibilities for individual scientists. These scientists are eminently qualified to conduct high-level geothermal research on their own, but they simply do not have enough time to do so and still do justice to their other duties.

Still, the companies' value focused, long-term research projects of the sort discussed at greater length below in this summary. As a result, they are increasingly making available, for industry-DOE partnerships, their unique site-specific expertise as well as vast, priceless, and formerly unavailable collections of borehole samples and resource data. These samples and data make possible highly refined observations and interpretations that will not only advance fundamental scientific knowledge of hydrothermal systems, but will also materially assist the companies to reduce risks and costs in the exploration for, and development or enhancement of systems already under production.

Status / Accomplishments:

1. Discovered a major new and hitherto unsuspected structural component of the Dixie Valley geothermal system, long studied as a fine example of "deep-circulation" systems throughout the Basin and Range province. Detailed geologic studies of intermediate-depth injection wells in the so-called Senator thermal area of the field revealed the subsurface presence of an enormous (at least several cubic kilometers) and relatively intact gravity-slide block hydrologically connected to deep production wells located further out in the Valley. Such slide blocks, known elsewhere in the province, become highly fractured and expanded as they collapse catastrophically into an

adjacent valley from an oversteepened range front. They have not been recognized heretofore in the Dixie Valley geothermal field (though the resource has been scientifically scrutinized for decades) but are likely critical components of the field's thermohydrologic regime. The discovery will allow the field operator, Caithness Operating Company, to produce more realistic reservoir models, thereby improving field performance, longevity, and profitability.

2. Also at Dixie Valley, discovered that thick (up to 250 m) intercepts of "quartzite" in the injection wells are actually silicified Quaternary alluvium. This alteration is clear evidence of an earlier and more energetic phase of the Dixie Valley geothermal system. It also has important implications for reservoir and geophysical modeling, since silicification of the alluvium in effect produces a new, dense, and brittle rock. The silicified alluvium would be indistinguishable geophysically from other types of basement rock in and around the geothermal field. It would also theoretically be susceptible to fracturing, therefore itself becoming a potential geothermal-reservoir rock.

3. Determined through radiocarbon dating of pollens and other organic materials that some siliceous sinter deposits in the Dixie Valley field may be as young as a few decades, perhaps deposited as a result of catastrophic breakage of the Dixie Valley range front fault as late as 1954. These phenomena record seismic permeability renewal in extensional tectonic regimes.

4. At the Salton Sea geothermal field, showed that heat sources for this huge resource, rather than being gabbroic as previously envisioned, are much more likely to be sizable granitic plutons produced by crustal melting of the thick Salton trough siliciclastic sedimentary sequence. The top of one such pluton is almost certainly situated no more than one kilometer beneath the bottom of the hottest well completed to date in the field – 389 degrees Celsius at a depth of only 2 km. There is further evidence that these granitic bodies and smaller diabase intrusions were emplaced into an already-existing hydrothermal system. Interaction of the plutons with thermal waters inevitably would rejuvenate the system, and would create significant additional fracture permeability through magmatically-induced, natural hydrothermal rock rupture.

5. Working with a large and previously proprietary subsurface database accumulated in the past 15 years, calculated a new ultimate resource potential for the Salton Sea geothermal field. The estimate is based on production data and the extent of a 72 square km shallow thermal anomaly within which all successful wells have been drilled here to date. The new estimate is 2,330 MW for at least 30 years. This amount of energy could supply the household needs of a quarter of California's present population.

Reports & Articles Published in FY 2002:

Hulen, J. B., D. Kaspereit, D. L. Norton, W. Osborn, and F. S. Pulka, "Refined conceptual modeling and a new resource estimate for the Salton Sea geothermal field," *California: Geothermal Resources Council, Transaction*, 2002, 10 p. – Also won the award for best poster presentation at the Annual GRC Meeting in Reno, NV, September 2002.

Johnson, S. D., and J. B. Hulen, "Subsurface stratigraphy, structure, and alteration in the Senator thermal area, northern Dixie Valley geothermal field, Nevada – Initial results from injection well DV 38-32 and a new structural scenario for the Stillwater escarpment," *Geothermal Resources Council, Transactions,* 2002, v. 27, 10 p. – Won the best paper award for the session on the Great Basin at the Annual GRC Meeting in Reno, NV, September 2002.

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,” Stanford University, 27th Workshop on Geothermal Reservoir Engineering, Proceedings, 2002, 14 p.

Presentations Made in FY 2002:

J. B. Hulen and S. J. Johnson, “Presentation on the Dixie Valley gravity-slide scenario,” at the Dixie Valley Workshop hosted by the Desert Research Institute, Reno, Nevada, June 2002 – Hulen also chaired the discussion group at the Workshop devoted to resource characterization.

S. J. Lutz, “Presentation on alteration in the Dixie Valley geothermal system,” 2002, presented at the Dixie Valley Workshop mentioned above.

Made two formal presentations on progress toward a new conceptual model of the Salton Sea geothermal field to the CalEnergy Resource Group, Calipatria, California.

Made a formal presentation on a new model for the 3D geologic setting of the Aidlin sector of The Geysers geothermal field, California – to the scientific staff of Calpine Corporation, August 2002.

Planned FY 2003 Milestones:

1. The Salton Sea field, California – We are working closely with geologists, geochemists, and reservoir engineers to produce an updated and refined conceptual geologic model of this resource. The work is especially timely, since CalEnergy is proceeding with plans to develop an additional 185 MW of electrical-generation capacity in their “Unit 6” in the southwestern part of the field. The expansion will bring the total capacity here to 520 MW. With access to virtually the entire CalEnergy Salton Sea database, we have already discovered a number of hitherto unsuspected major reservoir controls. Our continuing work here will help enable CalEnergy to develop and expand the existing field and, when made available to the entire geothermal community, will allow more cost-effective and successful exploration throughout the Salton trough. Pending availability of funds, we will be working closely on this project with Denis Norton, a specialist in numerical modeling of hydrothermal systems, who has proposed to the DOE to model such systems throughout the broader Salton trough.

   Complete 3-D geologic and conceptual model of the southwestern Salton Sea geothermal field. This part of the field hosts the impressive well Vonderahe-1, which supports a capacity in excess of 45 MW by itself. There is good potential for completion of similar wells in CalEnergy’s Unit 6 expansion area. Present this model in a paper to be submitted to a peer-reviewed journal such as the Journal of Volcanology and Geothermal Research

2. The Dixie Valley field, Nevada – Our work on this important “deep-circulation” Basin and Range system during FY 2002 led to a number of important discoveries, including a gigantic buried gravity-slide block and up to 250 meters of intensely silicified alluvium previously identified as Jurassic quartzite. The first discovery has added to the model an entirely new type of geothermal reservoir control – intensely fractured slide-block debris. The second discovery may be important for the remote detection of subjacent, high-quality, high-temperature reservoir rock, and for pinpointing, geophysically, major fluid-transmitting conduits in the shallow subsurface.

   Complete 3-D geologic model of the Senator thermal area in the northern Dixie Valley geothermal field. This will entail detailed geologic logging of at least three production wells and seven shallow thermal-gradient boreholes in the region. It will also encompass detailed lithologic, alteration, and mineralization mapping of the Stillwater escarpment above the Senator area. Present this model at the Geothermal Resources Council Annual Meeting, and publish it in the *GRC Transactions*, 2003.

3. The Aidlin "high-temperature" steam reservoir in The Geysers, California. There are large tracts of essentially undrilled but highly prospective steam-reservoir rock not only within the Aidlin area itself, but to the west and northwest. Drilling success in this region, which presumably could supply as much as 100 MW of new electrical-energy generating capacity at the The Geysers, will be enhanced considerably by improving knowledge of the geological and geochemical framework for the Aidlin reservoir and wells in the Ottoboni Ridge area nearby. Calpine Corporation has granted us essentially unlimited access to drillhole and reservoir data for both regions. We will be working closely with Kit Bloomfield and Mike Shook of INEEL to produce an integrated conceptual geologic and reservoir model for this resource.

   Geologically log in detail well OF27A-2 and possibly one additional deep well just east of the Aidlin reservoir. Log two additional deep wells, including one of those recently completed in the southern part of this region, possibly within the Mercuryville fault zone. Working with Kit Bloomfield and Mike Shook, refine the existing and in-progress 3-D geologic and conceptual model of Aidlin, and predict the geologic setting and reservoir characteristics of the undrilled region between Aidlin and Ottoboni Ridge, about two miles to the east.

TRACING GEOTHERMAL FLUIDS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-00ID13893

Performing Organization: Energy & Geoscience Institute at the University of Utah (EGI)

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DOE HQ Program Manager: Allan Jelacic
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DOE Funding Allocation: 220K

Cost Share Funding: None

Project Objective: The overall goal of this project is to provide tools for reservoir management that will increase the electrical power output from geothermal energy. In detail, the objective is to develop chemical tracers that will track both steam and liquid water and increase the understanding of underground flow through fractures.

Tracer research is an ongoing project. The objectives in previous years were to develop the first successful chemical tracers for liquid- or vapor-phase geothermal systems, to develop techniques for their use and interpretation, and to perform tracer tests in conjunction with industry. These objectives, which are all designed to aid resource management through re-injection of spent geothermal fluid, were all met.

Background / Approach: The purpose of geothermal tracers is to evaluate the injection pathways and recovery in geothermal reservoirs. Since injectate recovery is directly related to energy production, the technology supports increased power production from geothermal fields. We have developed tracers that will track either steam or liquid injectate as it flows through the reservoir, but tracers that will partition equally between these phases (two-phase tracers) are to date problematic. Two-phase tracers are needed in vapor-dominated systems to trace the liquid path of the injectate after it boils. In liquid-dominated systems the reservoir flow paths change after the reservoir boiling gets significant. Alcohol tracers have been developed that will partition satisfactorily, but they are neither stable nor detectable enough for all geothermal applications. The primary purpose of the current research is to find more stable two-phase tracers and to improve the detection limit of the alcohol tracers.

Past experience has shown that a successful geothermal two-phase tracer must be nontoxic, soluble in water, liquid at room temperature, contain the elements carbon, fluorine, and oxygen, be thermally stable at geothermal temperatures, and be electrically neutral under boiling conditions. The literature has been searched for compounds that meet these specifications. One hundred candidates were found by searching the chemical literature. Most of these candidates will have drawbacks, primarily in solubility or thermal stability. At the present time fluorinated alcohols appear to be the most likely to succeed. Of these, the literature indicates that mono and difluoroethanols are quite toxic, but four of the fluoropropanols and seven of the fluorobutanols and fluoropentanols are only irritants in the pure form, and are fairly soluble. Four fluorohexanols and fluoroheptanols are suitable, although limited in solubility, and five longer-chain fluoroalcohols are nontoxic but immiscible. It is possible that the immiscible compounds will work as tracers. The results of the INEEL perfluorocarbon EOS studies that are in progress may help with that decision. Cost of the compounds has not been considered yet, just solubility, detection limits, and toxicity. We have chosen three compounds to begin our lab tests. These are 3,3,3-trifluoro-1-propanol, 4,4,4- trifluorobutanol, and 1,1,1-trifluoro-2-propanol. Our work over the last year has consisted of testing these compounds for their thermal stability and determining their detection limits.

Status / Accomplishments:

Thermal Stability

Experiments conducted this year defined the stability of the fluorinated alcohols in water at geothermal temperatures. Two of the compounds, 1,1,1-trifluoro-isopropanol and 4,4,4-trifluoro-n-butanol, were shown to be significantly more stable than their hydrocarbon analogues and the hydrofluorocarbon vapor-phase tracer R-134a (Figure 1). The third compound, 3,3,3-trifluoro-n-propanol, proved to be similar in stability to both n-propanol and R-134a. This level of stability makes the fluorinated alcohols usable, but not spectacular, as geothermal tracers. For example, they are more stable than fluorescein (Adams and Davis, 1991) or R-134a (Adams and Kilbourn, 2000), and could be used at The Geysers or in a moderate-temperature liquid-dominated system. However, they are less stable than the naphthalene sulfonates (Rose et al., 2001) and could not be used in the multi-year tracer tests conducted with these polyaromatic sulfonates.

Estimation of Detection Limits

Minimum detection limits of the fluorinated alcohols were estimated in a study conducted with Thermochem, Inc, a company that is a standard supplier of chemical methods for the geothermal industry. This study was conducted to provide an indication of the detection limits that might be expected using conventional methods. The results are listed in Table 1 based on direct injection volumes of 1 μL and purge volumes of 5 ml.

The FID exhibits fairly high sensitivity for the fluorinated alcohol compound tested, with detection limits below 200 ppb. However, the lack of selectivity may limit the application of this detector to actual geothermal fluid samples, which often contain a wide range of light hydrocarbons in ppb to ppm concentrations.

The detection limit using the electron capture detector (ELCD) by purge and trap could probably be extended into the 50 to 100 ppb range, assuming the contaminant can be eliminated, and larger sample volumes are purged. The signal to noise ratio of the ELCD will make it difficult to extend the detection limit any lower than this. The purge and trap method also yields a very low recovery for the fluorinated alcohol compounds due to their low volatility.

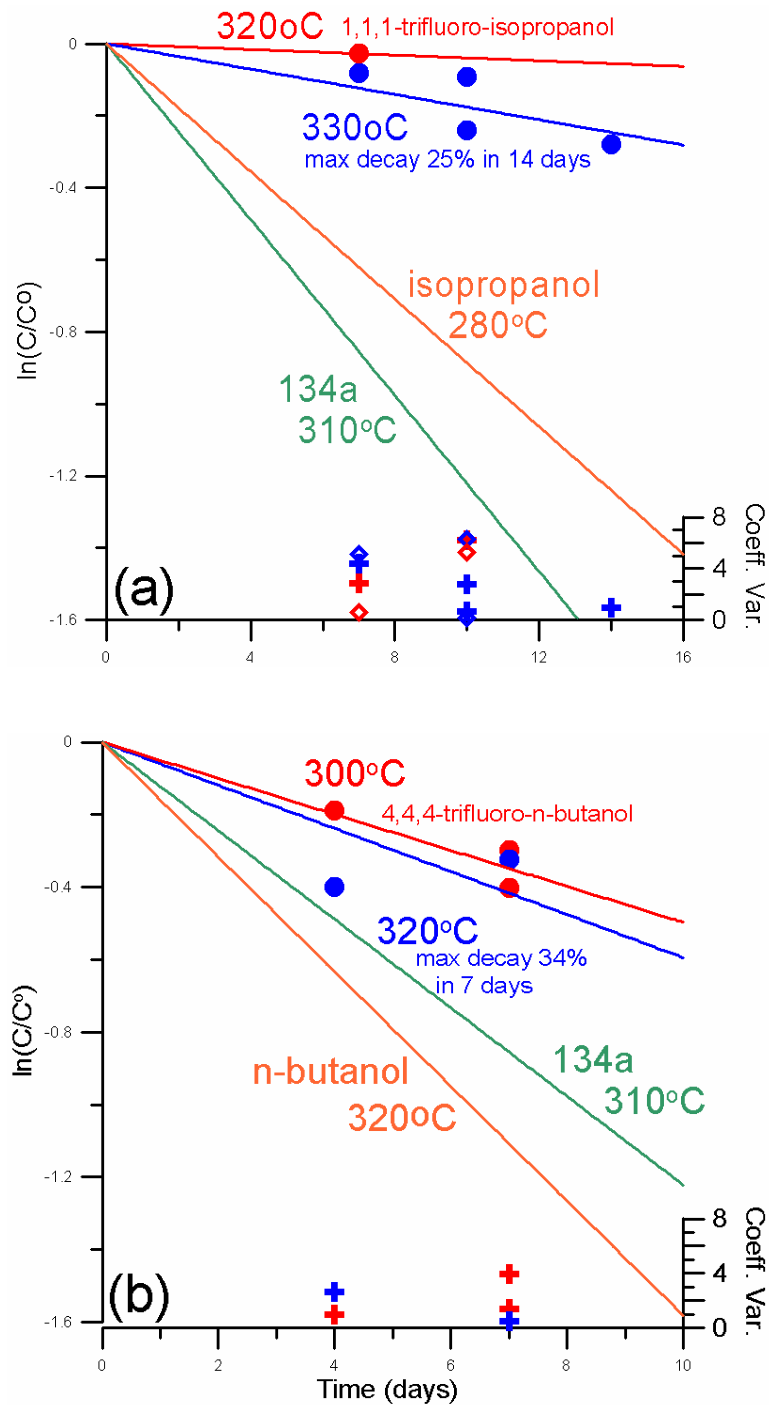

Figure 1. (a) Thermal stability of 1,1,1-trifluoro-isopropanol at 320° and 330°C. (b) Thermal stability of 4,4,4-trifluoro-n-butanol at 320° and 330°C. The stability of the hydrocarbon alcohol analogue and the hydrofluorocarbon vapor-phase tracer R-134a are shown for comparison. The coefficient of variation (stardard deviation/average) of the sample preparation (diamonds) and analyses (crosses) of the fluorinated alcohols are shown at the bottom of each chart.

A more efficient sample concentration technique will be necessary in order to reduce the detection limit to low ppb levels for any of these detectors. Solid phase extraction (SPE) techniques may be possible for these compounds. This technique concentrates polar organic compounds in water and extracts them with a suitable organic solvent. Since the ELCD does not respond to non-halogenated organics, SPE may be an applicable pre-concentration method for this detector.

Technology Transfer: A special issue of *Geothermics* devoted to the topic of geothermal tracers was guest edited by Adams and Nash under this contract.

Reports & Articles Published in FY 2002:

Adams, M. C., J. J. Beall, S. L. Enedy, P. N. Hirtz, P. Kilbourn, B. A. Koenig, R. Kunzman, and J. L. B. Smith, "Hydrofluorocarbons as geothermal vapor-phase tracers," 2001, *Geothermics,* 30, 747–775.

Beall, J. J., M. C. Adams, and J. L. B. Smith, 2001, "Geysers reservoir dry out and partial resaturation evidenced by twenty-five years of tracer tests," *Transactions, Geothermal Resources Council 25*.

Bloomfield, K. K., J. N. Moore, M. C. Adams, and T. L. Sperry, 2001, "Tracer test design and sensitivity studies of the Cove Fort geothermal resource tracer test," *Transactions, Geothermal Resource Council 25*.

Nash, G. D., and M. C. Adams, 2001, "Cost effective use of GIS for tracer test data mapping and visualization," *Transactions, Geothermal Resources Council 25*.

Presentations Made in FY 2002: Geysers reservoir dry out and partial resaturation evidenced by twenty-five years of tracer tests (Geothermal Resources Council, by J. J. Beall), Tracer test design and sensitivity studies of the Cove Fort geothermal resource tracer test (Geothermal Resources Council, by K. K. Bloomefield), and Cost effective use of GIS for tracer test data mapping and visualization. *Transactions* (Geothermal Resources Council, by G. D. Nash).

Planned FY 2003 Milestones:

(1) Publish R-23 kinetic studies

(2) Commence studies of R-245fa (when available in U.S.)

(3) Develop better analytic techniques for two-phase tracers.

IMPROVED TECHNOLOGIES FOR GEOTHERMAL RESOURCE EVALUATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	DE-FG07-00ID13891
Performing Organization:	Energy & Geoscience Institute, University of Utah
Principal Investigator:	Gregory D. Nash
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Collaborating Researchers:	Elizabeth Dudley-Murphy, Jeffery B. Hulen, Joseph N. Moore, Michael C. Adams
DOE HQ Program Manager:	Jay Nathwani
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E-mail:	jay.nathwani@go.doe.gov

DOE Funding Allocation:	$208K
Cost Share Funding:	None

Project Objective: To test new remote sensing data and emerging processing techniques, coupled with the advanced use of geographic information systems for data integration and interpretation, to determine their usefulness in geothermal exploration and system characterization. An emphasis is placed upon cost/benefit analysis and technology transfer. These objectives directly address DOE Geothermal Energy Program goals to (1) supply the electrical power or heat energy needs of 7 million homes and businesses in the United States by 2010 and (2) double the number of States with geothermal electric power facilities to eight by 2006. In order to meet these goals more resources must be found and developed. Remote sensing is a noninvasive, environmentally friendly, technology that can be used to find hidden geothermal resources though the identification and mapping of often subtle surficial features, such as hydrothermal convection and structurally related vegetation and soil mineralogy anomalies, and other geologic phenomena. These can be invaluable in exploration efforts and in gaining a better understanding of known resources in order to increase production. Additionally, the techniques found useful in this study can be applied in new areas. The tools and methodologies developed in this project can also be used to aid the expansion of geothermal energy to states not currently generating geothermal power.

Background / Approach: Remote sensing and geographic information system technologies are being used in an integrated study to map surficial features that may be indicative of, or give clues to, the location of blind geothermal systems and to better characterize known systems. Remote sensing data, at different spatial and spectral resolutions, are being used in tectonic, structural geology, and mineralogy studies. Additionally, these data are being tested for nontraditional exploration methods, such as mapping soil and vegetation anomalies that can result near and on geologic structures penetrating hydrothermal convection systems. GIS and the Internet are being used to integrate data and research results, and to distribute them to industry and other interested parties in a technology transfer program. Cost-benefit analysis and research results amenability for technology transfer to industry is a priority.

Status / Accomplishments: To date, three phases of this project have been completed and the results published or papers written for submittal. These include

1. mapping hydrothermal system and structurally related soil mineralogy anomalies in the production area in Dixie Valley, Nevada using AVIRIS hyperspectral data;
2. detecting vegetal-spectral anomalies related to geologic structure over the Cove Fort-Sulphurdale, Utah thermal anomaly; and
3. initiating a web-based GIS system for technology and data transfer.

All three of these phases were successful. The Dixie Valley hyperspectral study led to the discovery of a major soil calcium carbonate and a minor soil kaolinite anomaly. The close spatial proximity of these anomalies to a piedmont fault leaves little doubt that they are related to this structure and the geothermal system. Fieldwork revealed a relatively extensive $CaCO_3$ crust that is similar to those found in close proximity to many hot springs through the Basin and Range. However, there is currently no hot spring in the area of the anomaly suggesting that the source of the $CaCO_3$ may be buried deposits formed in the past when hot springs were present. The presence of kaolinite further suggests that hydrothermal circulation within the buried piedmont fault may have produced alteration products that have now been incorporated into the soil. The methods used in this study may be useful in detecting other similar anomalies in the Basin and Range and elsewhere.

The Cove Fort-Sulphurdale study revealed that vegetation anomalies can be detected using high resolution spectral data and provided evidence that in the study area the anomalies are related to major faults, in particular the range-front fault system that is located immediately west of the production wells. The spatial distribution of anomalous vegetation, near and along this fault system, supports geophysical evidence suggesting the presence of west-stepping synthetic faults that may extend for some distance to the north and south of the production area. This study further suggests that hand-held spectrometers can be used in a cost-effective manner in local geothermal exploration efforts in semiarid areas such as the Basin and Range.

As for the web-based GIS, this has been put online. Users can access a map of geothermal areas and find documents and data by clicking on a location. The infrastructure is completed, however the addition of data and documents will be ongoing.

At this time the project is moving into three new phases including:

- thermal anomaly detection and mapping using NASA ASTER derived thermal infrared (TIR) data (Dixie Valley, Nevada, and Salton Sea, California);
- geologic mapping using HyMap high spatial resolution hyperspectral data over a new exploration target – Dixie Meadows, Nevada;
- characterization of tectonic extension through time for Dixie Valley, Nevada, using geomorphometric techniques on high spatial resolution panchromatic satellite images, digital elevation models, and field measurements.

Dixie Valley Hyperspectral Study — A cooperative planning effort among EGI (Greg Nash), LLNL, and Caithness Energy personnel resulted in hyperspectral data acquisition over a new exploration area in Dixie Valley, Nevada on September 11, 2002. This new data covers the Dixie Meadows area, which was identified by Caithness Energy as a high priority exploration target. The data processing and analysis will be a cooperative effort between EGI and LLNL. Structural, lithological, and mineralogical interpretations will be done. This effort will provide primary geologic information that will be integral in decision making for future drilling. The hypserspectral data analysis study will be augmented with the analysis of ASTER TIR data, which will be tested for use in mapping shallow thermal anomalies.

Salton Sea Thermal (TIR) Study — In a recent meeting between EGI and CalEnergy personnel, the importance of mapping and monitoring shallow thermal anomalies was discussed and determined to be a priority. Therefore, we will test new ASTER TIR derived kinetic temperature data (1) to determine if shallow thermal anomalies can be detected and (2) if the detection effort is successful, to monitor the spatial extent of the anomalies through time. A known shallow thermal anomaly near CalEnergy Unit 1 will be used as a test case.

Dixie Valley Tectonic Geomorphology Study — A meeting of DOE, Caithness personnel, and Dixie Valley geothermal researchers in Reno, Nevada in June 2002, led to the concurrence that the quantification of extension rates is a priority research topic in Dixie Valley and other areas of the Basin and Range. Therefore, work will begin this year using geomorphometric techniques, supported by remote sensing data, digital elevation models, raster GIS analysis, and fieldwork, to develop a methodological approach leading to the quantification of localized uplift, which is directly related to extension. It is expected that the methods developed in this study will be applicable over the entire Basin and Range area.

The results of these three new phases will be applicable to other areas with the extension characterization being particularly suited to Basin and Range exploration, where structurally controlled deeply circulating systems are directly related to tectonic extension and where producing systems appear to be largely controlled by local extension rates.

Reports & Articles Published in FY 2002:

Nash, G. D., and G. Johnson, "Soil Mineralogy Anomaly Detection in Dixie Valley, Nevada Using Hyperspectral Data," 2002, *Proceedings: Twenty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28–30, 2001, SGP-TR-171*.

Nash, G. D., C. Kesler, and M. C. Adams, 2002, "Geographic Information Systems: Tools for Geothermal Exploration; Tracers Data Analysis; and Enhanced Data Distribution, Visualization, and Management," *Geothermal Resources Council Transactions*, vol. 26.

Nash, G. D., J. N. Moore, and T. Sperry, in press, "Vegetal-Spectral Anomaly Detection at the Cove Fort-Sulphurdale Thermal Anomaly, Utah, U.S.A., "Implications for Use in Geothermal Exploration," *Geothermics,* vol. 32, no. 2, (accepted for publication in 2002 – to be published in the March–April 2003 journal).

Presentations Made in FY 2002:

Soil Mineralogy Anomaly Detection in Dixie Valley, Nevada, Using Hyperspectral Data, Twenty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University.

Dixie Valley Remote Sensing Research Overview: 1996–2002, Dixie Valley Workshop, Desert Research Institute, Reno, Nevada.

Geographic Information Systems: Tools for Geothermal Exploration; Tracers Data Analysis; and Enhanced Data Distribution, Visualization, and Management, Geothermal Resources Council conference.

Planned FY 2003 Milestones:

A paper will be presented on this project at the GRC conference in 2003 or to a peer reviewed journal regarding the hyperspectral data study at Dixie Valley;

A paper describing the results of the kinetic temperature study will be presented at the 2003 GRC conference; and

A paper will be presented on the tectonic geomorphology study at the 2003 GRC conference.

IMPROVING EXPLORATION MODELS OF ANDESITE-HOSTED GEOTHERMAL SYSTEMS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FGO7-001ID13891

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Susan Lutz (EGI)
Jess McCulloch (Coso Operating Co., LLC)
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James Stimac (Unocal)

DOE HQ Program Manager: Robert Creed
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DOE Funding Allocation: $297K

Cost Share Funding: Industry has provided samples and data collected at a cost of more than $100K

Project Objective: Most of the world's productive geothermal systems are associated with young volcanism around the "Pacific Ring of Fire." Within the U.S., active volcanoes occur within the high Cascades of the Pacific Northwest. The purpose of this study is to develop a better understanding of the characteristics, behavior, and geometry of these systems. Improved conceptual models will reduce the cost of exploration and development by minimizing the number of wells needed and improving drilling targets.

Background / Approach: The basic premise behind this investigation is that there are common geologic factors that favor the formation and growth of geothermal systems in volcanic environments. The recognition of these factors is a critical step in developing better conceptual models. In this investigation, broad based geoscientific studies of several volcanic-hosted geothermal systems are being conducted. The investigations will specifically consider their origins, geometries, permeability and chemical structure, and time-temperature histories. Unocal and the Karaha Bodas Co., LLC (an affiliate of Caithness Energy) have made well data, core and cuttings samples, and the results of geophysical studies available for study from Bulalo, Philippines, Awibengkok, Indonesia, and Karaha-Telaga Bodas, Indonesia. The material from Karaha-Telaga Bodas is particularly important because it represents the most extensive suite of geologic, geophysical, geochemical, and well data that has ever been made available to DOE on andesite-hosted geothermal systems.

Status / Accomplishments: Significant progress has been made on each of the geothermal systems under study. At Karaha-Telaga Bodas, our investigations are providing fundamental information on the behavior and evolution of andesite-hosted systems in general and vapor-dominated systems in particular. Downhole measurements, chemical analyses, more than 4 km of core, cuttings, and electrical images from 4 deep wells and the results of MT and gravity surveys have been provided for study. The results to some of the key questions being addressed are summarized in the following paragraphs.

1. What are the essential features of volcanic-hosted vapor-dominated systems? Figure 1 shows a refined conceptual model developed by us from downhole temperature, pressure and chemical data. An extensive vapor-dominated regime and an underlying liquid-dominated resource are present. Vapor-dominated conditions extend laterally for at least 10 km and to depths below sea level. The deep liquid resource is characterized by fluids with salinities of 1-2 weight percent, temperatures of at least 350°C and pressures at least 30 bars less than the predicted hydrostatic pressure in the adjacent valleys. These dilute waters represent meteoric recharge from adjacent lowlands. The system is being heated by young intrusions, which come closest to the surface beneath Telaga Bodas, a shallow acid lake.

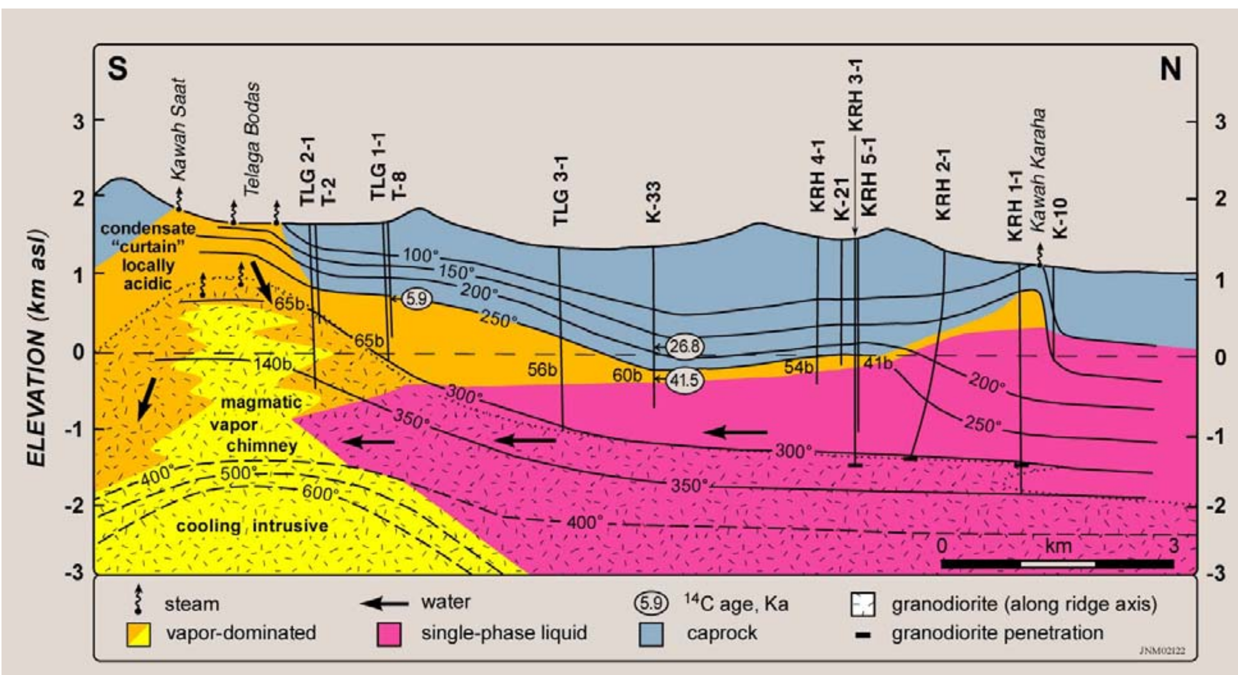

Fig. 1. Model of the Karaha-Telaga Bodas geothermal system. Modified from Allis et al. (2000).

2. How do volcanic-hosted vapor-dominated systems form? ^{14}C dating of organic matter at Karaha-Telaga Bodas indicates these systems may develop very rapidly. An age of 5910 +/- 76 years BP has been obtained on lakebeds from core hole T-8 (Fig. 1). Petrographic studies indicate the overlying volcanic rocks contain actinolite and epidote related to an early liquid-dominated system and later chalcedony and quartz produced during the transition to the modern vapor-dominated regime. Fluid inclusions trapped in quartz document temperatures in excess of 250°C during this transitional event. At these temperatures, catastrophic depressurization and boiling is required to deposit chalcedony. The most likely cause of depressurization was the formation of the volcano's crater, Kawah Galunggung, ~4200 years ago (Bronto 1989). Thus the high temperature liquid-dominated system developed above the lakebeds and boiled off within a period of less than 2000 years. From these observations, we conclude that extensive vapor-dominated systems will develop within volcanic structures following large-scale sector collapse. Such a system is likely below Mt. St. Helens.

3. Does the formation of vapor-dominated conditions leave distinctive petrologic and geochemical signatures? At Karaha-Telaga Bodas, the boiling off of the early liquids resulted in the deposition of chalcedony, fluid inclusions with variable but high salinities (e.g., 5 to 24 weight percent $NaCl-CaCl_2$), fluid inclusions containing more than several mole percent gas and complex chemical precipitates on rock surfaces. We have found chalcedony that was deposited at high temperatures at Darajat, Indonesia, which is also vapor-dominated, and at Bulalo, Philippines. Permeabilities at Bulalo, however, appear to have been too high to allow a vapor-dominated regime to develop.

4. What factors influence permeabilities within the field? We are integrating mineralogic and structural observations from the high temperature core holes (>250–320°C) to establish the permeability history of the geothermal system. These observations show that during the early liquid-dominated stage, the uppermost andesite flows were only weakly fractured due to the insulating effect of the intervening altered pyroclastics, which absorbed the deformation. Shear and tensile fractures were filled with carbonates at shallow depths and by quartz, epidote and actinolite at depths and temperatures over 1 km and 300°C. The system underwent numerous local cycles of overpressuring, which are marked by subhorizontal tensile fractures and implosion breccias.

During decompression of the liquid, chalcedony and quartz were deposited in fractures having the largest apertures and steepest dips. The orientations of these fractures indicate that the escaping over-pressured fluids used the shortest possible paths to the surface. As the vapor zone, expanded downward, pore pressures decreased and the fracture system within the vapor-dominated reservoir progressively collapsed, leaving only residual permeability, with apertures supported by asperities. Complete collapse of the fractures has occurred where normal stresses acting on the fracture walls exceeded the compressive strength of the wall rock

As the pressures declined, steam condensate formed at the top of the system and percolated downward. Clay minerals, anhydrite and calcite were deposited. The progressive sealing of the fractures resulted in the downward migration of the cap rock. Chemical changes recorded by fluid inclusions in these minerals have been numerically simulated. The simulations demonstrate the importance of specifically considering the behavior of SO_4 in the interpretation of fluid inclusion salinities.

A variety of fracture types are found in the cap rock but only tensile fractures and normal faults occur in the reservoir. This indicates a change in fracture dynamics from $\sigma_1 \geq \sigma_2 >> \sigma_3$ in the cap rock to a stress field with $\sigma_1 >> \sigma_2 \geq \sigma_3$ in the reservoir. This stress change results in wider fracture apertures and increases the likelihood of more dilatant fractures in the deeper, reservoir, rocks. This change is caused by the faster increase of the vertical stress (σ_1) with increasing overburden compared to the horizontal stresses σ_2 and

σ_3. Principal stress orientations (trend/plunge) determined from tensile fractures represented in the EMI data are: σ_1 = 0/90; σ_2 = 188/0; and σ_3 = 98/0. Integrated production and fracture data indicate that the “appropriate” oriented fractures have strikes of about 8^o and dips over 50^o.

Bronto, S., 1989, Volcanic Geology of Galunggung, West Java, Indonesia: Unpublished Ph.D. thesis, Univ. of Canterbury, 490 p.

Reports & Articles Published in FY 2002:

Barker, B. J., T. L. Sperry, J. N. Moore, and H. P. Ross, 2002, “Progress of recent exploration at Cove Fort-Sulphurdale, Utah,” *27th Workshop on Geothermal Reservoir Engineering, Stanford University.*

Christensen, C., M. Nemčok, J. McCulloch, and J. Moore, 2002, “Characteristics of productive zones in Karaha-Telaga Bodas geothermal system,” *Transactions, Geothermal Resources Council*, 623–626.

Lutz, S. J., J. N. Moore, N. Blamey, and D. I. Norman, 2002, “Fluid inclusion gas chemistry of the Dixie Valley (NV) geothermal system,” *27th Workshop on Geothermal Reservoir Engineering, Stanford University*, 206–216.

Moore, J. N., R. Allis, J. L. Renner, D. Mildenhall, and J. McCulloch, 2002, “Petrologic evidence for boiling to dryness in the Karaha-Telaga Bodas geothermal system, Indonesia,” *27th Workshop on Geothermal Reservoir Engineering, Stanford University*, 223–232.

Moore, J. N., B. Christensen, P. R. L. Browne, and S. J. Lutz, 2002, “The mineralogic consequences and behavior of descending acid-sulfate waters: an example from the Karaha-Telaga Bodas geothermal system, Indonesia,” *27th Workshop on Geothermal Reservoir Engineering, Stanford University*, 257-265.

Nemčok, M., J. Moore, R. Allis, and J. McCulloch, 2002 “Fracture development within the Karaha-Telaga Bodas geothermal field, Indonesia,” *Transactions, Geothermal Resources Council*, 815-818.

Norman, D. I., N. Blamey, and J. N. Moore, 2002, “Interpreting geothermal processes and fluid sources from fluid inclusion organic compounds and CO_2/N_2 ratios,” *27th Workshop on Geothermal Reservoir* Engineering, Stanford University, 266–274.

Powell, T., J. Moore, and B. Bill Cumming, 2002, “Conceptual models of Karaha-Telaga Bodas and The Geysers,” *Transactions, Geothermal Resources Council*, 369–373.

Tripp, A., J. Moore, G. Usher, and J. McCulloch, 2002, “Gravity modeling of the Karaha-Telaga Bodas geothermal system, Indonesia,” *27th Workshop on Geothermal Reservoir Engineering, Stanford University*, 444–452.

Presentations Made in FY 2002: Pan American Conference on Fluid Inclusion Research (Evolution of a volcanic hosted vapor-dominated geothermal system associated with Galunggung Volcano, Indonesia by Joseph Moore, Richard Allis, Bruce Christenson and Jess McCulloch; July 2002)

Planned FY 2003 Milestones: Papers will be presented at geothermal conferences on: (1) the origin and evolution of the geothermal fluids at Karaha Telaga Bodas, based on an evaluation of fluid inclusion gas compositions; and (2) the rheology of the Karaha-Telaga Bodas reservoir rocks.

ENHANCED DATA ACQUISITION AND INVERSION FOR ELECTRICAL RESISTIVITY STRUCTURE IN GEOTHERMAL EXPLORATION AND RESERVOIR ASSESSMENT

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-00ID13957

Performing Organization: University of Utah/Energy & Geoscience Institute

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DOE Funding Allocation: $238K

Cost Share Funding: No formal cost-share; $40K from SAIC for 3-D CSAMT development support

Project Objective: Development of refined electrical models and EM modeling algorithms for the geothermal environment, improving the quality and quantity of electrical geophysical data, and incorporating independent geological data in cooperative interpretations.

Background / Approach: Electrical resistivity is a primary physical property of the earth that can be strongly affected by geothermal processes. Since an increased fluid content due to fracturing, and the development of more conductive alteration minerals (clays, etc.), can give rise to an electrical resistivity contrast, electromagnetic (EM) methods of probing have been investigated and applied for many years. The reliable mapping of electrical resistivity should increase chances of discovering blind geothermal resources, in defining the extent of geothermal reservoirs, in imaging controlling structures for geothermal systems, and in locating and characterizing permeable fracture zones (DOE/OWGT Strategic Plan, 1998).

Status / Accomplishments: <u>Interpretation in Andesitic Systems:</u> Wannamaker and student have produced the first detailed electrical image from dense MT data of the magmatic chimney above a high-sulphur andesitic geothermal system, Karaha-Telaga Bodas, Indonesia, using the a-priori inversion approach discussed below (Figure 1). Enrichments in chloride, fluoride, and sulfur in acid lake water and the presence of tourmaline, fluorite, and native sulfur at depth are related to the flux of magmatic gases. The magmatic chimney is believed to be the near-vertical conductive structure (<10 ohm-m) inside a slightly more resistive region of propyllitic alteration and densification in the center of the section. The low resistivities are interpreted to represent advanced argillic alteration assemblages formed by interactions between magmatic sulfur dioxide and the surrounding geothermal waters. The profile suggests that the gases migrate upwards through a vapor-dominated magmatic chimney overlying a cooling intrusion. We submitted an abstract to the Fall 2003 AGU meeting on this topic, with Wannamaker's student Raharjo presenting.

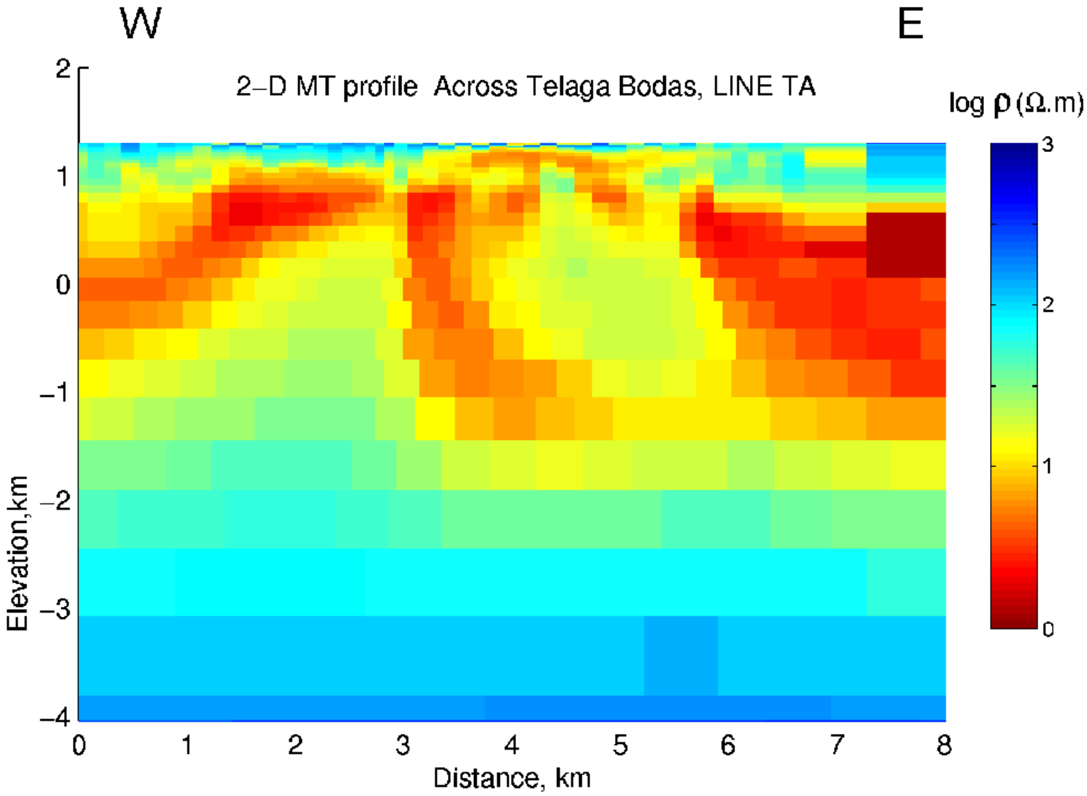

Figure 1. Two-dimensional MT inversion section across the Telaga Bodas geothermal prospect, Java, Indonesia. Section is based on TM mode responses at 47 sites in an E-W profile.

Algorithm development: Wannamaker completed a prototype algorithm for joint MT/DC-IP inversion of dense array profile data. This is the type of data being collected across the Dixie Valley thermal area, NV, under independent support from the DOE/OWGT/Univ. Prog. As discussed early on by T. R. Madden, EM data are a first-order function of conductivity-dimension product while DC data are a first-order function of resistivity-dimension product. In other words, MT is attuned to conductive structures primarily while the DC results improve resolution of resistive structures. Included here is a brief set of figures exemplifying the images produced by the joint inversion code (see Figure 2). These are for a 5 ohm-m prism in a 100 ohm-m half-space with depth to top of 440 m and depth to bottom of 950 m. It is 6 bipoles wide. Resistivity images are on the left, PFE on the right. MT data range from 10 kHz to 0.1 Hz. Gaussian MT errors are +/- 2% app.res., 0.5 deg phase, 1.5% galvanic app.res. and 1% IP. Following the forward (fwd) model images, there are the res-IP pairs due to various combinations of the galvanic data with MT subsets. The tmi inversion is perhaps the most compact representation of the body but the qa is good also. Including TE data helps with intrinsic body resistivity (qep), although we always have to be concerned about how 2-D this quantity behaves in nature. The IP image contrast is not high, in part muted by the color scheme, and peaks around 9% whereas the body is 25%.

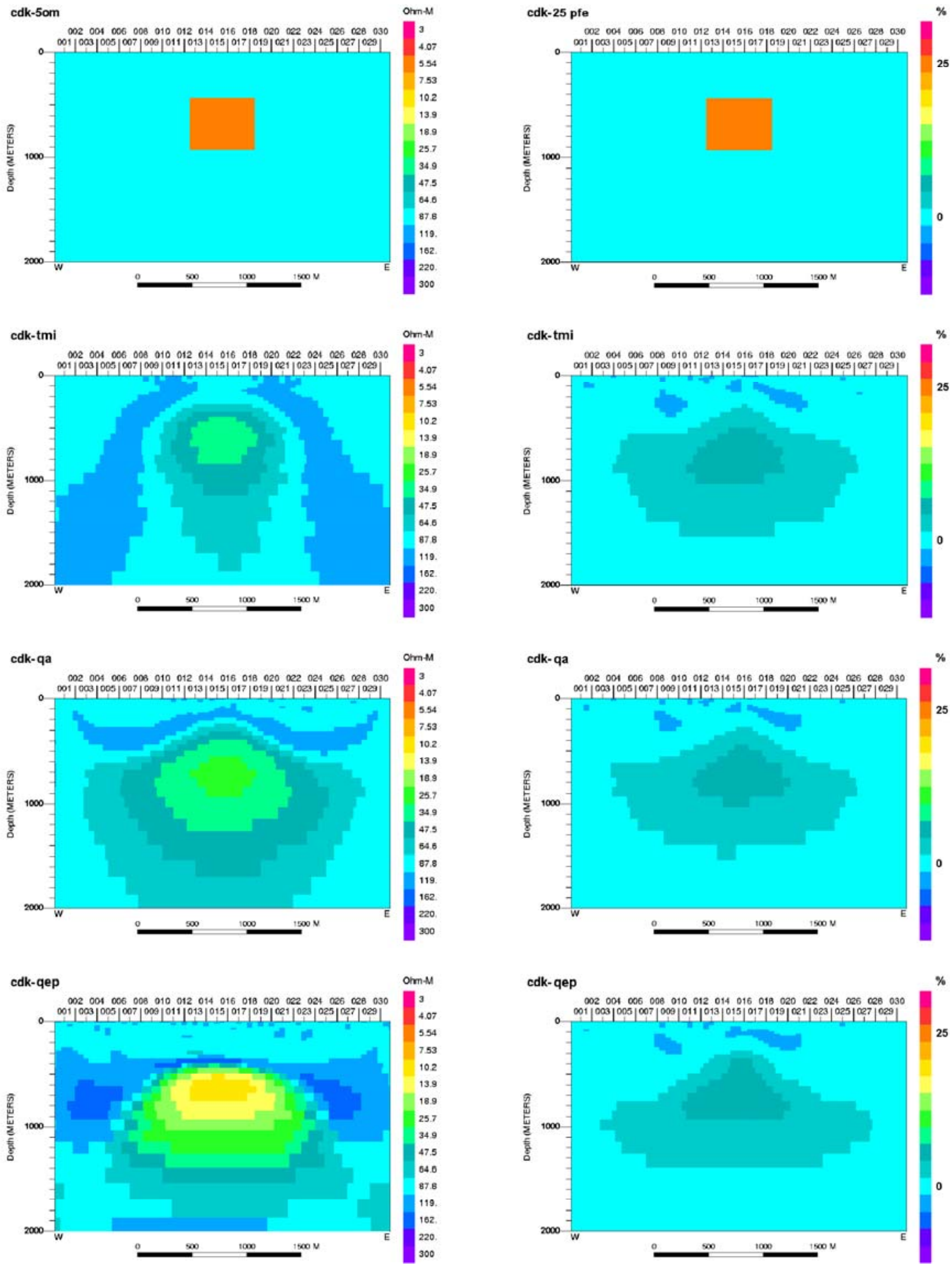

Figure 2. Example MT/DC inversion sections over conductive/polarizable prism in a half-space. Image pairs include TM inversion of the MT data (tmi), followed by IP inversion of the PFE data referenced to the TM res. section. Next is the pair of images from sole galvanic inversion for both the resistivity and PFE sections (qa). The final pair is from joint inversion of DC app.res. and TE mode phase for the resistivity section, and inversion of the PFE referenced to that res. section (qep).

Magnetotelluric Instrumentation (J. Stodt): This year, the MT system was advanced in three primary areas. First, system testing exposed an intermittent operational error in the internal high-speed serial IO communications protocol we developed for communications between the system interface card and the individual channel cards. The problem was traced to a bus contention between memory devices due to improper control of the chips by the FPGA firmware and corrected. Second, file IO between the MT receiver and an external (laptop) PC was defined. The user interface to the MT receiver will reside on a portable PC, and file exchanges via standard FTP over a LAN interface will be used to deliver control and setup information to the MT receiver, and to upload MT data files from the receiver to the PC for processing and data archive. Third, the MT receiver's interface card design was advanced substantially. With regard to VHDL firmware, timing control to discipline a precision VCXO to the GPS 1PPS pulse was adapted from our successful standalone prototype to its final implementation on the interface card. A calibration waveform generator has been implemented with appropriate signal routing. A port IO communications interface between the MT receiver's controller and the micro-controller on the system interface card has been implemented.

Reports & Articles Published in FY 2002:

Wannamaker, P. E., G. R. Jiracek, J. A. Stodt, T. G. Caldwell, A. D. Porter, V. M. Gonzalez, and J. D. McKnight, 2002, "Fluid generation and movement beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric (MT) data," *J. Geophys. Res.,* 107(B6), ETG 6, 1–22.

Wannamaker, P. E., and W. M. Doerner, 2002, "Crustal structure of the Ruby Mountains and southern Carlin trend region, northeastern Nevada, from magnetotelluric data," *Ore Geology Reviews*, 21, 185–210.

Zhdanov, M. S., and P. E. Wannamaker, eds., 2002, "Three-dimensional electromagnetics," *Proceedings, Second International Symposium, Methods in Geochemistry and Geophysics, Vol. 35, Elsevier, Amsterdam,* 385 pg.

Presentations Made in FY 2002:

P. E. Wannamaker, S. K. Park, J. R. Booker, G. D. Egbert, G. R. Jiracek, and A. D. Chave, "National Instrument Facility for Electromagnetic Studies of the Continents (EMSOC)," 2002, *Eos Trans.* AGU, 83(47), Fall Meeting, Suppl., Abstract U11A-0008, subm.

I. Raharjo, P. Wannamaker, J. N. Moore, R. Allis, and D. Chapman, "Magmatic Chimney Beneath Telaga Bodas Revealed by Magnetotellurics Profiling: A Case Study at the Karaha Bodas Geothermal System, Indonesia," 2002, *Eos Trans.* AGU, 83(47), Fall Meeting, Suppl., Abstract V61B-1371, subm.

W. M. Doerner, P. E. Wannamaker, T. L. Sodergren, J. A. Stodt, D. P. Hasterok, and M. J. Unsworth, "Resistivity Architecture and Physical State of the Great Basin: Separate and Joint Roles of Fluids and Graphite," 2002, *Eos Trans*. AGU, 83(47), Fall Meeting, Suppl., Abstract GP52A-04, subm.

Planned FY 2003 Milestones: The 2-D inversion approach will be extended to the 3-D finite difference algorithm which we have been developing. It will be applied to existing MT data from the Karaha-Bodas andesitic system and to upcoming results from the DOE enhanced geothermal systems project. We will continue to move forward to complete the system interface card design so that boards can be fabricated. Once this is done, final integration of the system interface and channel cards via internal control software can be performed.

FIELD STUDIES OF GEOTHERMAL RESERVOIRS RIO GRANDE RIFT, NEW MEXICO

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-98ID13653

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Collaborating Researchers: N/A

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DOE Funding Allocation: $300K

Cost Share Funding: None

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.

Background / Approach: 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 study 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 ages, Pleistocene to Holocene, and are believed to be intermediate-to-high temperature systems at depth. The Jemez Pueblo system is part of the outflow plume of the Valles high temperature geothermal system.

This project investigates several concepts that are new to the geothermal community who are familiar with the Rio Grande rift. Higher temperature Rio Grande rift systems are bedrock-hosted and occur in structurally-high terraine 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 penetration of up to several km's across 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 survy 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.

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 likely to soon be used for a geothermal direct-use by the Jemez Pueblo.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: Project Completed.

CHARACTERIZATION OF FRACTURE PATTERNS IN THE GEYSERS AND COSO GEOTHERMAL RESERVOIRS BY SHEAR-WAVE SPLITTING

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: Award # DE-FG07-00ID13956

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Collaborating Researchers: M. Elkibbi, M. Yang (UNC), V. Pereyra (Weidlinger Assoc.)

DOE HQ Program Manager: Jay Nathwani
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DOE Funding Allocation: $467K
$110K subcontract to Weidlinger Assoc. Inc

Cost Share Funding: None

Project Objective: Shear-wave splitting data is used to determine the geometry and physics of subsurface fracture networks at The Geysers and Coso geothermal reservoirs. The project aims at developing a computer-based methodology to produce 3D maps of crack geometry, crack distribution, and crack density in fractured reservoirs. These are crucial in determining directions of underground fluid flow as well as areas of increased permeability, essential in locating production targets. For data obtained from the Coso field, we are also capable of tracking temporal changes in the general behavior of crack systems.

The raw data for the project consists of seismographic recordings of microearthquakes (MEQ) detected over many years by arrays of sensors at both The Geysers and Coso. With the experience acquired in the processing and interpretation of these data in FY 2000 and 2001, we have, during FY 2002, continued with the development of a software package for the exploration of fractured reservoirs which consists of the following platform independent, fully interactive, Matlab-GUI based modules:

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

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

The analysis of split shear waves is thus a valuable technique to detect and map the main orientation and fracturing intensity in the subsurface. When fully developed, this approach has the potential of becoming a desirable technical and industrial resource to advance the exploration of fracture-controlled geothermal, hydrocarbon, and water reservoirs. For the last few years we have studied and processed shear-wave splitting data in two seismically active, fracture-controlled environments, From the analysis and processing of over 60,000 local micro-earthquakes, we have to date collected what is arguably the world's most complete set of high resolution, high quality shear-wave splitting observations.

Status / Accomplishments: The data processing stage for both The Geysers and Coso is complete and results in terms of fast S-wave polarizations and time delays have been included in previous reports (e.g., March report 2002). The forward modeling package to simulate various crack geometries (Fig. 1) has also been implemented on time. The final addition of the third module (or inverse modeling package) permitted us to proceed with interactive inversion for crack patterns on a station-by-station basis. We are now working on supplementing the code with a fully automated inversion program provided by Weidlinger Associates, discretizing the medium into transversely isotropic (TI) blocks. A summarized description of the interactive 3D crack-mapping software follows:

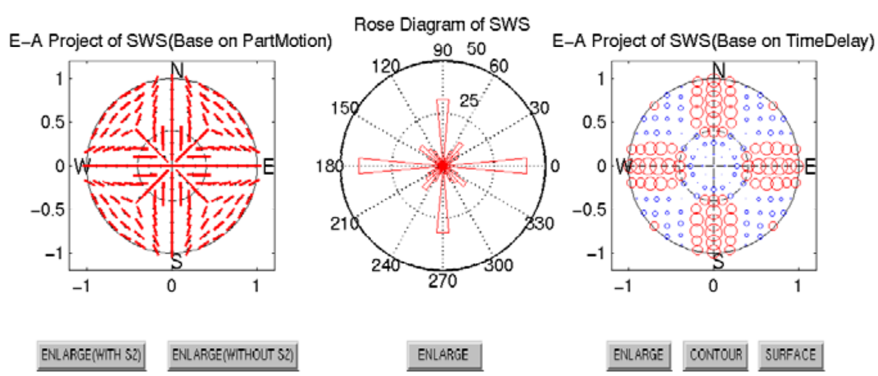


Figure 1. Forward synthetic modeling (module two). Using fully automated and interactive GUI's, one can reproduce theoretical polarizations, rose diagrams, and time delays for particular crack models. The leftmost diagram shows the theoretical polarizations of the fast split shear-wave in an equal area projection depicting the entire lower hemisphere beneath the station. The interior circle is the shear-wave window. The middle figure is a rose diagram of fast S-wave polarizations. The righmost diagram is an equal-area projection showing circles whose diameter is proportional to the predicted time delay at that point.

Blue and red circles represent below and above average delays respectively. All three diagrams can be enlarged, separated individually, and saved as files. At any time the user can interactively change the crack parameters and display controls. This model is for two othogonal vertical crack systems of equal crack densities of 0.05. The first fracture set is oriented NS while the second fracture set strikes EW. Both sets have a crack aspect ratio of 0.01.

(1) Module one

In brief, the data processing package allows for rapid and precise measurement of fast S-wave polarizations and time delays through the windowing and display of seismic waveforms and the corresponding power spectra. The user can plot the ground particle motion in 2D and 3D diagrams, rotate the components to determine the polarization ϕ and the time delay δt, and automatically store them for later use in the modeling and inversion procedures. The analysis process is greatly facilitated by fully interactive GUIs (graphic user interface).

(2) Module two

The forward modeling package has been significantly upgraded and extensively tested. In addition to generating synthetic seismograms, synthetic particle motions, and synthetic polarization/time delay equal-area plots for waves in transversely isotropic material, the user is now able to model shear-wave splitting effects in media with two fracture systems. This notably increases the modeling capacity of the program allowing for more complex conditions, which may be consistent with the actual tectonic/geological setting. There are no restrictions imposed on the relationship between the two fracture sets. The user can choose among any pairs of crack strikes, dips, aspect ratios, and densities. Models involving dipping cracks have been included in a previous report. We now show in Figure 1 an example of forward modeling entailing two crack sets.

(3) Module three

The inverse modeling package (Figs 2a-c) allows comparison of observed fast S-wave polarization and time delay distributions with theoretical values corresponding to a particular crack model. A new option for wave modeling in inhomogeneous media with depth-varying velocity has been added to the code.

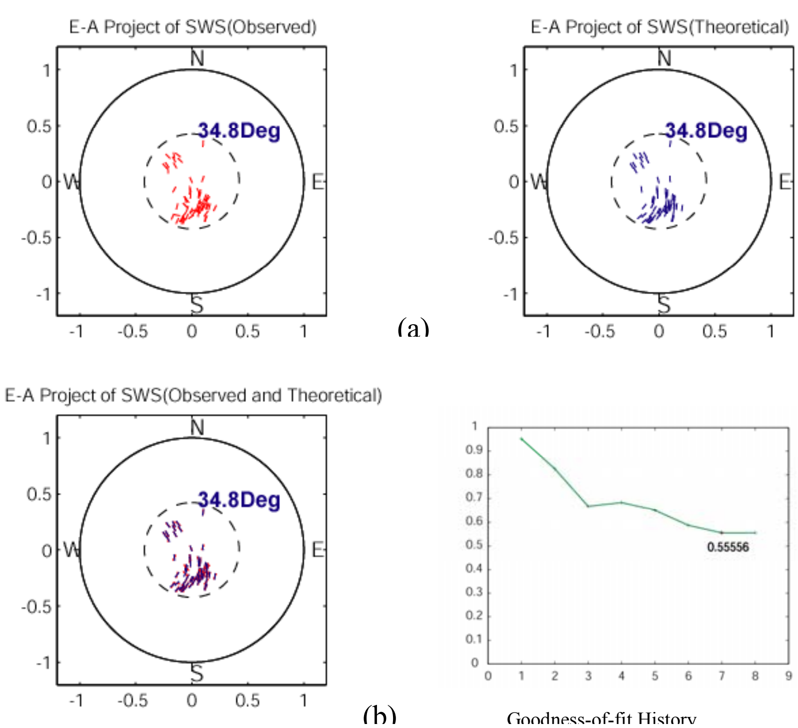
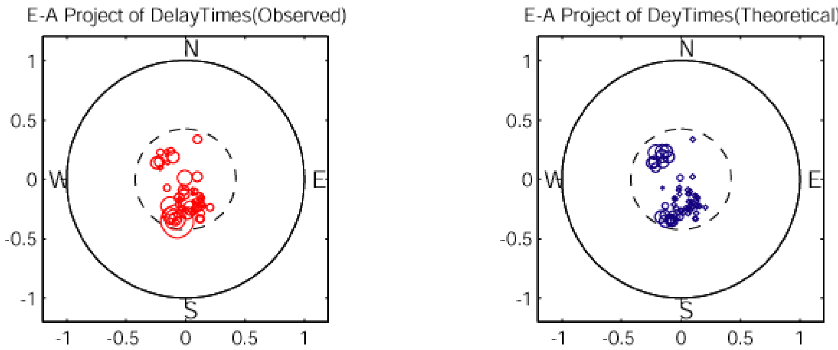


Figure 2. Module three.
(a) Example of polarization inversion using a two-crack set model (station S2 in NW Geysers). By trial-and-error, the user chooses a first crack model and refines it by tracking changes in the graph of polarization misfit history (b).
In this case, the best crack model obtained corresponds to a system of two cracks of equal densities. The first crack set is vertical and strikes N37W while the second crack set strikes N45E and is steeply dipping at 70° to the NW. Both fracture sets characteristics are compatible with The Geysers regional/local tectonic setting. The top diagrams are equal-area plots of observed (left) and predicted (right) polarizations. The lower left diagram shows the superposition of both. Interactive sliders are used to change the parameters of the crack model (strike, dip, density, and aspect ratio) as the trial and error process advances. (shear wave window is 34.8 degrees)
For station S2, a good fit between patterns of observed and theoretical polari-zation angles could not be achieved with a single (dipping) crack system. Hence, introducing an additional fracture set to our model increases modeling flexibility and power as it clearly enhances the quality of the inversion results.

The user needs to find the best fracture model simulating observed distributions of recorded ϕ and δt pairs. The first attempt uses trial-and-error but trials are guided by the history of goodness of fit (Fig. 2b), which indicates whether the search is converging to a better (minimum misfit) solution. The code allows for easy switching back and forth between the ϕ and the δt fitting procedures, which often provides models with best ϕ and δt fits. An example of the inversion process is illustrated in figures 2a-c.



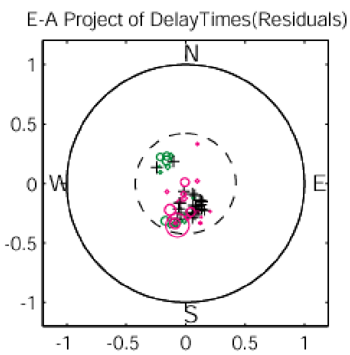


Figure 2 (c). Example of time delay inversion using the two-crack model from Fig. 2(a). The user chooses the crack density value (0.066 in this case), for which the misfit index is minimum while guided by the graph of time delay misfit history (displayed in Fig 2b). The top diagrams are equal-area plots of observed (left) and predicted (right) time delays. The lower left diagram shows the difference between observed and predicted delays. Green and purple circles indicate that observed time delays are respectively smaller and greater than syn-thetic delays. If the difference is less than ±2.1ms (the sampling interval), a cross is used.

Reports & Articles Published in FY 2002:

Vlahovic, G., M. Elkibbi, 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 University.*

Vlahovic, G., M. Elkibbi, and J. A. Rial, 2003, “Shear Wave Splitting and Reservoir Crack Characterization: Coso Geothermal Field,” *Journal of Volcanology and Geothermal Research*, 120, 123-140 (in press).

Elkibbi, M., D. Erten, and J. A. Rial, 2002, “Detection of 3D Fracture Patterns and Crack Densities at the Geysers Geothermal Field, CA, using Shear-Wave Splitting,” (ready to submit to *Geophysics*).

Elkibbi, M., M. Yang, and J. A. Rial, 2002, “Inverse modeling of 3D Crack Attributes and Crack Densities at The Geysers, CA,” (to be submitted to *Geophysics*).

Presentations in FY 2002:

M. Elkibbi, “Fracture Characterization at The Geysers, CA based on Shear-wave Splitting Results,” 2002, Invited Talk, Princeton University, Princeton, NJ.

M. Elkibbi, D. Erten, and J. A. Rial, "Depiction of Subsurface Cracks at The Geysers, CA, using Shear-wave Splitting," 2002, *AGU Spring meeting 28-31 May 2002*, Washington, D.C.

G. Vlahovic, M. Yang, and J. A. Rial, "Fracture Characterization Using Shear-Wave Splitting: Results From a High Density Temporary Array in the Coso Geothermal Field," 2002, *AGU Spring meeting 28-31 May 2002*, Washington, D.C.

Planned FY 2003 Milestones: The first version of the complete full-inversion/optimization code provided by our corporate partners (Weidlinger Associates, CA) is currently under testing and evaluation. When integrated to our three-module software, this code adds accuracy and robustness to the trial and error inversion procedure described above.

A complete 3D fracture map consisting of modeled subsurface crack systems will be developed for The Geysers and Coso geothermal fields. The fracture characteristics obtained will be compared with the regional and local tectonic setting in order to ensure their geological credibility.

A GEOCHEMICAL AND MICROANALYTICAL STUDY OF SILICA SCALE DEPOSITION IN GEOTHERMAL BRINES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-00ID13954

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DOE Funding Allocation: $107K

Cost Share Funding: None

Project Objective: This project seeks to determine the mechanisms and to quantify the kinetics of colloidal silica aggregation from geothermal brines so that geothermal industries can control or prevent the precipitation of silica scale within pipes, well-heads, and in the field following re-injection. Our results will be communicated to industry via published papers and through our long-term collaboration with the Geothermal and Power Operations division of Unocal, and our reaction analyses will provide rate equations that can be incorporated into computer models used by Unocal and others to predict the conditions under which silica scaling will occur in new geothermal fields.

Background / Approach: Researchers have proposed a number of hypotheses to account for the very rapid coagulation of silica colloids in aqueous fluids with increasing ionic strength. Hypotheses have included: (1) a lowered activity of the water component in brines due to electrolyte hydration (Marshall and Warakomski 1980); (2) a decrease in the "shielding" of the silica surface by water molecules in response to surface dehydration at neutral to high pH (Matijevic 1973); (3) an increase in the effective zpc of silica due to the incorporation of metal cations in the surfaces of silica colloids (Yokoyama et al. 1993); and (4) interparticle coagulation based on the inner-sphere bonding of sorbed metal cations (Yates et al. 1998). We are performing experiments that will allow us to test these hypotheses. Specifically, we are examining individual steps in the reaction sequence by which monomeric silica transforms to amorphous opal. By separating this reaction pathway into discrete events, we will be able to monitor with high specificity the interactions between aqueous silica with dissolved metal ions of interest. Once the nature of these sub-reactions is established, geothermal industries will be able to inhibit the formation of scale by targeting those factors that induce coagulation with precision.

Status / Accomplishments: We have completed four and currently are working on two 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 1,000 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) was continued (Task 3). The experiments were designed around four primary variables that exhibit controlling influences on the solubility of silica. These variables were pH, concentration of silica, ionic strength, and time. Changes in monosilicic acid, nanocolloidal silica (<0.1 µm effective diameter), and silica precipitate concentrations were monitored in batch reactions. The experiments were conducted with initial silica concentrations of 4.1, 12.3, and 20.5 mmolal and with ionic strengths of 0.015 and 0.24 molal. The dissappearence of monomeric silica, as well as the development of nanocolloidal silica and silica gel was monitored during these experiments. These studies have provided kinetic information on the transformation of dissolved silica to gel, and they serve as a baseline for inhibition studies.

Inhibition studies involving sulfite were also continued during this fiscal year (Task 7). In these experiments sodium sulfite (0.61 mmolal sulfite) is added to solutions with the same solution compositions as our baseline studies. These studies provide a quantitative measure of the efficiency of sulfite as an inhibitor as a function of pH and silica concentration.

The kinetic modeling of the results from the long-term silica stability experiments was conducted and the results were presented at the Twelfth Annual V. M. Goldschmidt Conference, in Davos, Switzerland (see reference below). The goal of the modeling effort is to develop a concentration- and pH-dependent kinetic model that can be used to predict the formation of silica colloids and precipitates. Previous experiments have shown that in solutions supersaturated with respect to amorphous silica, monomeric silica first condenses to nanoscale colloids with particle sizes of ~3 nm. This population persists metastably until the nanocolloids coalesce and precipitate as silica gel. Our analysis of the reaction kinetics that govern the initial stages of transformation from monosilicic acid to nanocolloids reveals that the rate of decrease of dissolved monomeric silica with time, *R*, has a fourth-order rate dependence: $R = k [SiO_2]^4$. Here, *k* ($mmolal^{-1}$ sec^{-1}), the rate constant, varies with pH according to $log\ k = x \cdot pH + k_o$ (or $k = k_o[H^+]^x$), and k_o is the rate constant at pH 0. The sulfite inhibitor experimental data was also kinetically modeled and a pH dependent equation was developed. An example of a fourth-order fit is shown in Figure 1 for the data with high ionic strength (0.24 molal), high initial silica concentration (20.6 mM), and 0.61 mmolal sulfite.

Our kinetic analysis already has been incorporated into the geochemical computer algorithms used by scientists at Unocal to predict the occurrence of silica scale in their fields.

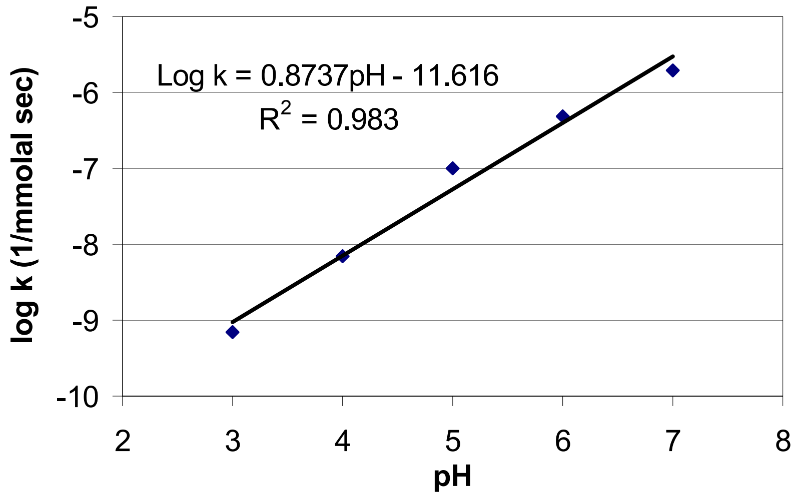

Figure 1. The log of the fourth-order rate constant (k) versus pH for the transformation of monosilicic acid to nanocolloids in solutions with initial SiO_2 concentrations of 20.8 mmolal and an ionic strength of 0.24 molal.

In addition, we also are embarking on an examination of the interaction of organic compounds with monomeric and colloidal silica (Task 8). More than 25 organic inhibitors are available commercially, but the efficiency of these compounds is very poorly established. Manufacturers typically do not publicize the chemical compositions or structures of their products, so that the inhibiting functionalities are not known. Moreover, D. Gallup at Unocal has tested over 20 organic inhibitors and found that only 1 (Geogard SX) is effective at high temperatures. We have begun to investigate the interactions of organic compounds with silica using molecular dynamical simulation methods with the program Cerius[2]. Specifically, we have explored the nature of the silica complexes formed with simple alcohol-rich molecules using MD approaches in collaboration with J. Kubicki (Penn State). This work has revealed that silica will form stable complexes with polyols in which Si is 5- or 6-coordinated, rather than 4-coordinated, in agreement with recent NMR studies by Kinrade and colleagues. Biological systems may employ simple polyols for the transport of silica in order to maintain silica in its monomeric state at concentrations that exceed the solubility of amorphous silica. These polyols may therefore prove to be effective inhibitors for silica scale. A paper describing this work has been accepted for publication pending minor revisions in *Geochimica et Cosmochimica Acta*.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002:

G. A. Icopini, S. L. Brantley, and P. J. Heaney, "Kinetics of silica nanocolloid formation from supersaturated solutions," 2002, Abstracts: Twelfth Annual V. M. Goldschmidt Conference, *Geochimica et Cosmochimica Acta*, 66 (15A): A351 Suppl. 1.

J. D. Kubicki and P. J. Heaney, "Structures of Si-carbohydrate aqueous complexes: Comparison of NMR spectra and molecular orbital results," 2002, *Eos,* 83, F243.

Planned FY 2003 Milestones: We have completed a sizable fraction of our proposed experimental work, and our milestones for 2003 are intended to promote technology transfer of our results. Our goals are:

(1) To meet with and offer an oral presentation to the members of the Geothermal and Power Operations division at Unocal in order to communicate our results to their staff. *(Completed Dec. 9, 2002)*

(2) To complete the revisions and return our manuscript on the molecular orbital modeling of aqueous organosilicon complexes for publication in *Geochimica et Cosmochimica Acta*.

(3) To submit a manuscript describing the kinetics of silica oligomerization as a function of pH, ionic strength, and silica concentration to *Geochimica et Cosmochimica Acta*.

(4) To submit a manuscript describing the effects of the Unocal sulfite inhibitor on the kinetics of silica precipitation as a function of pH, ionic strength, and silica concentration to *Geothermics*.

(5) To employ a high-resolution particle size analyzer (purchased using internal Penn State funds) to monitor the evolution of silica monomer and colloid populations as a function of time and solution chemistry.

(6) To initiate our experimental studies of the effects of organic inhibitors on the coagulation of silica in the geothermal brine solutions specified by Unocal.

EXPANDING GEOTHERMAL RESOURCE UTILIZATION IN NEVADA THROUGH DIRECTED RESEARCH AND PUBLIC OUTREACH

Reporting Period: FY 2002 (March 20, 2002 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-02ID14311

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DOE Funding Allocation: $936K

Cost Share Funding: None

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

Background / Approach: The Great Basin Center for Geothermal Energy was established at the University of Nevada, Reno in May 2000 to promote research on and utilization of geothermal resources in the Great Basin of the Western United States. The Center received funding through this grant to promote increased geothermal development in the Great Basin. Most of this funding is used to fund peer-reviewed research to improve exploration for and assessment of geothermal resources. The Center awarded seven research grants that were competitively selected with the assistance of external reviewers, and research on these projects was initiated in FY 2002.

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

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

2. Targeting potential geothermal resources in the Great Basin from regional relationships between geodetic strain and geological structures $86,917 (Geoff Blewitt).

3. Testing unique surface identifiers for geothermal site characterization from remote sensing imagery, $63,733 (Wendy Calvin, Mark Coolbaugh).

4. Structural and geophysical analysis and characterization of the Desert Peak-Brady Geothermal Field: Implications for understanding linkages between northeast-trending structures and geothermal anomalies $95,811 (James Faulds, Larry Garside).

5. Assembly of a crustal seismic velocity and density database for the western Great Basin, $144,584 (John Louie).

6. Geochemical sampling of thermal and nonthermal waters in Nevada: Evaluation of geothermal resources for electrical power generation and direct-use applications, $117,359 (Lisa Shevenell, Larry Garside).

7. Regional assessment of exploration potential for geothermal systems in Nevada using a Geographic Information System (GIS) - $146,026 (James Taranik, Mark Coolbaugh, Gary Raines, Lisa Shevenell, Tim Minor, Don Sawatzky, Richard Bedell)

Work is proceeding on each of these, and preliminary results were presented for each at the annual GRC meeting in September 2002. Accomplishments on these research projects are summarized here.

- The extensional strain project has achieved the stated goal of producing and publishing (at the GRC 2002 conference) updated maps of various types of strain in the Great Basin, concluding that, on the regional scale, the extensional component of strain normal to favorably-oriented quaternary faults does well to predict the spatial trends of current geothermal power production and high well temperatures, particularly along the Humboldt lineament and in the Walker Lane; conversely, the maps therefore suggest a much lower geothermal potential toward the east-central to south-east regions of Nevada where strain rates are extremely small (Blewitt).

- Thermal infrared imagery from the SEBASS airborne scanner and the ASTER satellite scanner were used to map alteration minerals associated with geothermal activity at Steamboat Springs, Nevada and map structures along a 4-km-long thermal anomaly at Brady's Hot Springs, Nevada; these results were published in *Remote Sensing of the Environment*, a talk was given at the Denver annual GSA meeting, and a talk will be given at the annual meeting of Geological Remote Sensing Group in London in December (Calvin) .

- In the Desert Peak subproject, the major accomplishments to date include: (1) compilation of existing isothermal, well, and geologic data into a GIS data base; (2) completion of a new detailed gravity survey (323 stations covering 200 km^2); (3) construction of a new Bouguer gravity map of the northern Hot Springs Mountains; and (4) enhanced understanding of the subsurface geologic framework of the Hot Springs Mountains, including depth to basement and geometry of faults (Faulds, Garside).

- A regional geophysical database supporting the exploration for new, hidden geothermal fields has been initiated with a resolution of 8 km, and supplemented by a successful deep seismic sounding experiment in May 2002 that provided the first evidence of a deep crustal root to the Sierra Nevada (Louie).

- Over 50 hot spring waters were sampled and analyzed in collaboration w/Arehart, the results of which will be used in FY 2003 to evaluate the geothermal potential those areas. Major and trace element analyses are nearly complete (Shevenell, Garside).

- Maps of the GPS-derived strain-rate, depth to groundwater, heat flux, and deep geothermal gradient were added to an existing geothermal GIS (of Nevada and the Great Basin) and used to predict geothermal potential in areas where geothermal activity at the surface may be suppressed because of groundwater characteristics (Taranik, Coolbaugh).

Outreach activities include database and web page development, which are continually in progress, and workshops. Workshops that have been conducted as part of the GPW activities in FY 2002 include the following:

1. *Geothermal Opportunities in Nevada* involved representatives from Nevada's geothermal industry, academia, and state and federal government agencies, and was organized by the Center and held on January 11, 2002. Over 200 people attended the highly successful workshop that identified barriers to geothermal development. Presentations from the meeting can be found at http://www.unr.edu/geothermal/.

2. Another workshop was held January 17, 2002, at UNR to discuss and initiate Center collaboration with researchers from Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory.

3. A third workshop was held on April 18 and 19 at the Desert Research Institute in Reno, titled *Introduction to Geothermal Energy;* it was cosponsored with the Geothermal Resources Council (GRC) and the U.S. Department of Energy (DOE) GPW Program.

4. A fourth workshop, cosponsored by DOE, was held in Reno June 12–14, 2002 to highlight *DOE Sponsored Research at the Dixie Valley Geothermal Area*. Following formal presentations, working groups were assembled and a document was produced summarizing the results of research at the site. Presentations and the summary document are at: http://www.unr.edu/geothermal/meetingsandpresentations/meetings_dixie.html

Reports & Articles Published in FY 2002:

Arehart, G., M. Coolbaugh, and S. R. Poulson, 2002, "Geochemical Characterization of Geothermal Systems in the Great Basin: Implications for Exploration, Exploitation and Environmental Issues," *Transactions,* Geothermal Resources Council 26, 479–482.

Blewitt, G., M. Coolbaugh, W. Holt, C. Kreemer, J. Davis, and R. Bennett, 2002, "Targeting of Potential Geothermal Resources in the Great Basin from Regional Relationships between Geodetic Strain and Geological Structures," *Transactions,* Geothermal Resources Council 26, 523–526.

Calvin, W., M. Coolbaugh, and R. G. Vaughan, 2002, "Geothermal Site Characterization Using Multi-and Hyperspectral Imagery," *Transactions,* Geothermal Resources Council 26, 483–484.

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

Coolbaugh, M., J. Taranik, G. Raines, L. Shevenell, D. Sawatzky T. Minor, and R. Bedell, 2002, "A Geothermal GIS for Nevada: Defining Regional Controls and Favorable Exploration Terrains for Extensional Geothermal Systems," *Transactions,* Geothermal Resources Council 26, 485–490. (Won GRC session best paper award)

Faulds, J., L. Garside, G. Johnson, J. Muehlberg, and G. Oppliger, 2002, "Geologic Setting and Preliminary Analysis of the Desert Peak-Brady Geothermal Field, Western Nevada," *Transactions,* Geothermal Resources Council 26, 491–494.

Garside, L., L. Shevenell, J. Snow, and R. Hess, 2002, "Status of Nevada Geothermal Resource Development, Spring 2002," *Transactions,* Geothermal Resources Council 26, 527–532.

Louie, J. N., 2002. "Assembly of a crustal seismic velocity database for the western Great Basin," *Transactions*, Geothermal Resources Council 26, 495–500.

Skalbeck, J. D., R. Karlin, L. Shevenell, and M. Widmer, 2002, "Geothermal reservoir volume estimation from gravity and aeromagnetic modeling of the Steamboat Hills geothermal area, Reno, Nevada," *Transactions,* Geothermal Resources Council 26, 443–448.

Shevenell, L., and J. Taranik, 2002, "Overview of Activities of the Great Basin Center for Geothermal Energy," *Transactions,* Geothermal Resources Council 26, 507–510.

Shevenell, L., L. Garside, G. Arehart, M. van Soest, and B. M. Kennedy, 2002, "Geochemical Sampling of Thermal and Nonthermal Waters in Nevada to Evaluate the Potential for Resource Utilization," *Transactions* Geothermal Resources Council 26, 501–506.

Shevenell, L., and J. V. Taranik, 2002, "Summary of Activities of the Great Basin Center for Geothermal Energy," Bulletin, Geothermal Resources Council 31(5), 179–182.

Shevenell, L., P. Kasameyer, C. Bruton, J. L. Renner, and B. M. Kennedy, 2002, "Executive Summary of the Workshop on DOE Sponsored Research at Dixie Valley, Nevada (June 12–14, 2002)," published on CD and at: http://www.unr.edu/geothermal/meetingsandpresentations/intro_summarydv.pdf

Vaughan, R. G., W. M. Calvin, and J. V. Taranik, 2002, "SEBASS hyperspectral thermal infrared data: surface emissivity measurement and mineral mapping: Remote Sensing of the Environment," *in press*.

Presentations Made in FY 2002: Presentations at the *Geothermal Opportunities in Nevada*, January 11, 2002, meeting:

Arehart, G., "Geochemical Techniques for Exploration and Assessment."

Coolbaugh, M., "Regional Controls on the Distribution of Geothermal Systems in Nevada."

Shevenell, L., "Updated Database and Assessment of Nevada Geothermal Resources."

Garside, L., "Geology of Geothermal Energy," presented at the *Nevada Indian Commission's Renewable Energy Summit for Nevada Tribes*, September 10, and *Introduction to Geothermal Energy,* April 18–19, 2002.

Garside, L., "History of Nevada Geothermal Resources Research," presented at a regional GPW meeting on September 26, 2002.

Presentations at the *Annual Geothermal Resources Council Meeting,* Reno, NV, September 23-5:

Arehart, G., "Geochemical Characterization of Geothermal Systems in the Great Basin: Implications for Exploration, Exploitation and Environmental Issues."

Blewitt, G., "Targeting of Potential Geothermal Resources in the Great Basin from Regional Relationships between Geodetic Strain and Geological Structures," (poster only).

Calvin, W., "Geothermal Site Characterization Using Multi- and Hyperspectral Imagery."

Coolbaugh, M., "Geothermal GIS for Nevada: Defining Regional Controls and Favorable Exploration Terrains for Extensional Geothermal Systems."

Oppliger, G., "Geologic Setting and Preliminary Analysis of the Desert Peak-Brady Geothermal Field, Western Nevada."

Garside, L., "Status of Nevada Geothermal Resource Development," Spring 2002.

Louie, J. N., "Assembly of a crustal seismic velocity database for the western Great Basin," (oral and poster).

Shevenell, L., "Overview of Activities of the Great Basin Center for Geothermal Energy."

Planned FY 2003 Milestones:

- Solicit, review and select additional research projects for funding in FY 2003 (Shevenell).
- Organize a workshop(s) in cooperation with DOE, based on DOE priorities (Shevenell, Taranik).
- Evaluate recently collected as well as historically available water chemistry data to determine unique characteristics of magmatic versus non-magmatic systems (Arehart).
- Construct and refine updated map using extensional strain analysis results showing favorable geothermal targets (Blewitt, Coolbaugh).
- Finalize analysis of hyperspectral data and synthesize SWIR/TIR data at Steamboat Hills (Calvin).
- Construct a new geologic map and gravity survey in GIS format of the Desert Peak, Hot Springs Mountains geothermal area, and construct a 3-D subsurface model in digital format (Faulds, Garside).

- Collect industry feedback on web interface to seismic database, and make final changes to web database, delivering a copy of the database on CD/DVD to DOE (Louie).
- Complete sampling and analysis of the first phase of hot springs selected for evaluation; calculate and evaluate geothermometers (Shevenell, Garside).
- Prepare predictive maps of geothermal potential in using multiple GIS layers (Taranik, Coolbaugh).
- Technical papers and reports will continue to be prepared as part of all of the subprojects.

GEOCHEMICAL SAMPLING OF THERMAL AND NONTHERMAL WATERS IN NEVADA: EVALUATION OF GEOTHERMAL RESOURCES FOR ELECTRICAL POWER GENERATION AND DIRECT-USE APPLICATIONS

Reporting Period: FY 2002 (March 20, 2002 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-02ID14311

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

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DOE Funding Allocation: $117K

Cost Share Funding: None

Project Objective: The objective of this project is to obtain geochemical data from springs (and some wells) for which data are not publicly available, or for which the analyses are incomplete or poor. With these data, geothermometers will be calculated and a preliminary assessment of the geothermal potential of the sampled areas will be conducted using the new geochemical data. The objectives of this applied research is to increase the amount of energy produced with geothermal resources in the Great Basin by evaluating existing, new and developing scientific methods to improve exploration and assessment of these resources.

Background / Approach: There are more than 350 known geothermal systems in Nevada; at least 30% of these do not have modern, complete water analyses, and many of these have analyses from one spring in a group of springs, but it is not known from which spring in the group that the sample was taken or if it was the highest temperature spring in that group. Additional data are available from a previously digitized database containing all springs and wells on 7.5 ft quadrangles. From these digitized site locations, there are ≈1,000 springs for which a location is known, but for which there are no available temperature (or chemical) measurements. Although many of these sites are within known geothermal areas and are located near springs for which temperature and/or geochemical data are available, many of these sites are not so located and require evaluation before the geothermal potential of the area can be assessed. A sampling team was assembled and collaboration with researchers at Lawrence Berkeley National

Laboratory (Thijs van Soest, B. Mack Kennedy) was initiated. Fluid sampling for geochemical analysis was initiated and will continue into FY 2003. Analyses of the samples collected thus far are becoming available.

Status / Accomplishments:

- Initiated and participated in a meeting with LBL geochemists/researchers to discuss collaborations on sampling thermal springs in Nevada, April 17, 2002. Proceeded with joint project sampling hot springs in Nevada.

- In collaboration with Greg Arehart (UNR) and Thijs van Soest (LBNL) several areas were selected as high priority for geochemical sampling due to no, or incomplete geochemical data being available for the hot springs in an area.

- Preliminary results were presented for each at the annual GRC meeting in September 2002. Accomplishments on these research projects are summarized here.

- Over 50 hot spring waters in 18 areas in northern Nevada were sampled and analyzed. Temperatures of over 100 springs were measured. Approximately 80% of the analytical work for stable isotopes has been completed Major and trace element analyses are nearly complete.

- Of the sites visited thus far, all of which were noted on topographic maps or other references to be hot, one was completely dry, and three were not thermal. Hence, future geothermal maps will be edited to remove reference to these sites as hot or warm.

- Gas samples from selected spring sites were collected for noble gas analyses by our collaborator Thijs van Soest, who accompanied us on several sampling trips. Preliminary results from all sites sampled thus far indicate low (0.2–0.6) He ratios for several sites across Nevada, exclusive of Steamboat Springs.

- A geochemical database for Nevada geothermal systems is being assembled that includes geochemistry, state and site maps, photos, and text summaries of what is known to date at Nevada's geothermal resource areas.

- All activities are being coordinated with USGS assessment efforts through project lead Colin Williams.

- A field sheet and photo database is being constructed such that all field data will be captured.

- One student (Ben Delwiche) was trained in field sampling of geothermal fluids.

Reports & Articles Published in FY 2002:

Garside, L., L. Shevenell, J. Snow, and R. Hess, 2002, "Status of Nevada Geothermal Resource Development," Spring 2002, *Transactions,* Geothermal Resources Council 26: 527–532.

Skalbeck, J.D., R. Karlin, L. Shevenell, and M. Widmer, M. 2002. Geothermal reservoir volume estimation from gravity and aeromagnetic modeling of the Steamboat Hills geothermal area, Reno, Nevada, *Transactions*, Geothermal Resources Council 26: 443–448.

Shevenell, L., L. Garside, G. Arehart, M. van Soest, and B.M. Kennedy. 2002. Geochemical Sampling of Thermal and Nonthermal Waters in Nevada to Evaluate the Potential for Resource Utilization, *Transactions*, Geothermal Resources Council 26: 501–506.

Presentations Made in FY 2002:

Garside, L., Status of Nevada Geothermal Resource Development, Spring 2002," presented at the *Annual Geothermal Resources Council Meeting*, Reno, NV, September 23–25.

Shevenell, L., "Updated Database and Assessment of Nevada Geothermal Resources," presented at the *Geothermal Opportunities in Nevada,* January 11, 2002*,* meeting.

Shevenell, L., "Geochemical Sampling of Thermal and Nonthermal Waters in Nevada to Evaluate the Potential for Resource Utilization," presented at the *Annual Geothermal Resources Council Meeting,* Reno, NV, September 23–25.

Planned FY 2003 Milestones: We will continue sampling springs and conducting chemical analyses of hot and cold waters sampled. Evaluation of data will commence in the next Fiscal year. Data will be added to a digital database being constructed by Center personnel, in part, under separate funding. Potential problems meeting deliverables may ensue due to the delay in obtaining chemical analyses of the waters as a result of difficulties in maintaining the ICP-MS. However, major element data are available currently for some of the waters, and geothermometer calculations can commence on those in the next quarter.

We plan to accomplish the following in the next fiscal year:

- Complete sampling and analysis of the first phase of hot springs selected for evaluation.
- Calculate and evaluate geothermometers.
- Rank sampled sites for their geothermal potential.
- Prepare predictive maps of geothermal potential in using multiple GIS layers in collaboration with other Center personnel (Taranik, Coolbaugh). Add new geochemical data to these maps.
- Technical papers and reports will continue to be prepared.

REGIONAL ASSESSMENT OF EXPLORATION POTENTIAL FOR GEOTHERMAL SYSTEMS IN THE GREAT BASIN USING A GEOGRAPHIC INFORMATION SYSTEM (GIS)

Reporting Period: FY 2002 (March 20, 2002 to December 31, 2002)

DOE Grant / Contract #: DE-FG07-02ID14311

Performing Organization: University of Nevada, Reno
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DOE Funding Allocation: $146K

Cost Share Funding: None

Project Objective: This research develops a geographic information system (GIS) of geothermal systems of the Great Basin. Included in this GIS will be co-registered geological, geochemical, hydrological and geophysical maps useful in defining geothermal potential. These databases will be assembled in collaboration with other PI's working on Center projects. The objectives of the research are to: (1) better define regional relationships between geothermal activity and geologic, geochemical, and geophysical features, (2) produce regional maps of geothermal energy potential, and (3) post the database and maps on the web to make it available to other researchers and the public.

Background / Approach: The research expands on an initial geothermal GIS constructed for a Ph.D. dissertation at the University of Nevada, Reno by the first collaborator, and takes advantage of a preliminary database constructed by Mark Mihalasky of the USGS. Relevant data from all available sources are being used, and collaborators include the Nevada Bureau of Mines and Geology (NBMG), the United States Geological Survey (USGS), and the Desert Research Institute (DRI). Significant contributions have been made from other organizations including Southern Methodist University and the GeoHeat Center.

The geothermal database is being compiled using ArcView GIS 3.x software and is being analyzed statistically using the spatial analytical methods of weights-of-evidence, logistic regression, and fuzzy logic. Predictive maps of geothermal potential, together with the geothermal database, will be posted on the web site of the Great Basin Center for Geothermal Energy, which is being constructed as part of task (1) of the parent DOE grant "Expanding Geothermal Resource Utilization in Nevada through Directed Research and Public Outreach".

Status: The following data acquisitions and analyses have been made:

- The locations, temperatures, and chemistries of geothermal systems in the Great Basin have been added to the database (data were received from numerous sources including the Nevada Bureau of Mines and Geology, the GeoHeat center, and state maps of geothermal potential).

- Using available water geochemistry data, geothermometer-based estimates of reservoir temperatures have been made for the geothermal systems in the database.

- An updated and improved model of depth to the water table in Nevada has been created by the Desert Research Institute.

- Regional maps of crustal inter-seismic strain rate for Nevada, provided by the Blewitt et. al., research project, have been integrated into the model for the state of Nevada.

- A Great Basin database of geologic age dates compiled by the USGS has been added.

- Maps of Quaternary volcanic activity have been added for the states of Nevada and Utah.

- A digital catalog of earthquake activity for the state of Nevada has been incorporated, and a moment release map based on seismic activity has been provided by Center research project led by John Louie.

- Digital maps of heat flux and temperature gradients covering the entire Great Basin have been provided by Southern Methodist University.

- Quaternary faults from Nevada and Utah have been added to the database.

- Digital geologic maps at various scales covering the Great Basin have been included.

- Mineralization and alteration maps of most of the Great Basin, interpreted from Landsat satellite imagery, have been provided by the USGS.

- Regional gravity and magnetic geophysics have been added to the database.

- Water geochemistry data from the USGS National Water Information System have been synthesized and added to the database.

- Spatial analyses have been conducted on the above data using weights-of-evidence, logistic regression, and fuzzy logic methods.

- Preliminary predictive maps of geothermal potential have been generated for the state of Nevada.

Accomplishments: Major accomplishments during the year are listed below.

1) Prediction of Geothermal Favorability in "Concealed" Terrains: Some geothermal systems in the Great Basin may remain undiscovered because they don't have surface expressions such as hot springs or fumaroles to attract attention. Statistical analysis conducted as a part of this study helped demonstrate that the current inventory of geothermal systems is biased towards areas where groundwater levels are shallow. Maps of regional geothermal potential were created that are independent of groundwater phenomena by using geologic and geophysical evidence unaffected by water table depth or aquifers. These maps can be used to assess geothermal potential in areas where groundwater tables and aquifers are deep.

2) Quantification of Link between Geothermal Activity, Quaternary Faulting, and Rates of Crustal Extension: With the help of a companion Center research project led by Geoff Blewitt (GPS-Strain study), spatial analysis was used to demonstrate that young faults with high rates of extension are more likely to host geothermal resources than faults with low rates of extension. Because crustal extension in much of Nevada is currently oriented northwesterly, northeast-striking faults will tend to have higher rates of normal extension than northwest-striking faults. This explains why northeast-striking faults in Nevada correlate more strongly with high-temperature geothermal resources (≥160°C) than northwest-striking young faults. Strain rate maps derived from GPS station measurements provide valuable information to help define regional geothermal potential.

3) Correlations between geothermal activity and Quaternary silicic and mafic volcanism: A very strong correlation between magmatic-type geothermal systems and Quaternary silicic volcanism was demonstrated statistically. The only Quaternary silicic volcanic centers without known high-temperature geothermal resources in the Great Basin occur in south-central and southeastern Idaho, where laterally flowing groundwaters in young basalt flows could be concealing underlying geothermal activity. This suggests that southern Idaho has a strong potential for hosting high-temperature geothermal systems hidden beneath volcanic-hosted groundwater aquifers.

Extensional-type geothermal systems in Nevada were found to correlate with vents of Quaternary basalt, even though extensional-type systems are not believed to have magmatic heat sources. The basalts may be indicative of high rates of crustal extension. High rates of extension could permit circulating meteoric fluids to penetrate to greater depths in the crust, and be heated to relatively high temperatures.

Reports & Articles Published in FY 2002:

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

Coolbaugh, M., J. Taranik, G. Raines, L. Shevenell, D. Sawatzky T. Minor, and R. Bedell, 2002, "A Geothermal GIS for Nevada: Defining Regional Controls and Favorable Exploration Terrains for Extensional Geothermal Systems," *Transactions,* Geothermal Resources Council 26: 485–490. (Won GRC session best paper award).

Presentations Made in FY 2002:

Coolbaugh, M., at the *Geothermal Opportunities in Nevada*, January 11, 2002, meeting; titled "Regional Controls on the Distribution of Geothermal Systems in Nevada;" a PowerPoint® file with added text is posted http://www.unr.edu/geothermal/meetingsandpresentations/geooppsnv1_11_02.html

Coolbaugh, M., at the *Annual Geothermal Resources Council Meeting,* Reno, NV, September 23–25; titled "A Geothermal GIS for Nevada: Defining Regional Controls and Favorable Exploration Terrains for Extensional Geothermal Systems;" a PowerPoint® file with added explanatory text is posted at the web site http://www.unr.edu/geothermal/meetingsandpresentations/meetings_grc.html

In addition, a presentation by M. Coolbaugh is scheduled January 17, 2003 for the *January meeting of the Geological Society of Nevada in Reno*; and is titled "Regional Geologic Controls, Geochemical Characteristics, and Thermal Infrared Signatures of Geothermal Systems of the Great Basin." An abstract has been published in the January 2003 newsletter of the Geological Society of Nevada (see above).

Planned FY 2003 Milestones:

- Continue expansion of the geothermal GIS to cover the entire Great Basin by acquiring additional evidence outside the state of Nevada.

- Integrate seismic models of crustal thickness and other parameters from the John Louie research project.

- Integrate a refined model of extensional strain analysis (provided by the Blewitt research project) into the geothermal GIS.

- Complete a spatial analysis of interrelationships between evidence layers and geothermal systems in the Great Basin.

- Post the geothermal GIS and predictive maps of geothermal potential on the web site of the Great Basin Center for Geothermal Energy.

TESTING UNIQUE SURFACE IDENTIFIERS FOR GEOTHERMAL SITE CHARACTERIZATION FROM REMOTE SENSING IMAGERY

Reporting Period: FY 2002 (March 20, 2002 to December 31, 2002)

DOE Grant / Contract #: DE-FG07-02ID14311

Performing Organization: University of Nevada, Reno
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DOE Funding Allocation: $64K

Cost Share Funding: None

Project Objective: The objective of this research is to establish mineral or thermal anomaly markers that could lead to identification of new geothermal resources or expansion of existing sites. Minerals associated with fumarole deposits or mineral variation occurring due to closed hydrothermal systems are particularly targetted along with day/night temperature variations as indicators of hot spot potential. This work seeks to define surface identifiers of geothermal sources through analysis of remote sensing imagery to characterize mineral, vegetation, and thermal properties at a known source region (Steamboat Hills) and compare the results to similar properties at an area with geothermal exploration potential (near Bradys Hot springs, Nevada).

Background / Approach: Thermal infrared imagery has been used previously to locate hot springs above geothermal resources, but its usefulness in exploration has been limited because the thermal anomalies were detected only in the immediate vicinity of known hot springs or fumaroles. Hyperspectral imagery in the visible and near-infrared has long been used to map surface mineralogy and alteration deposits. Recent significant advances in the availability and quality of both short-wave and thermal infrared imagery demand a reassessment of their role in geothermal exploration. This work builds on our demonstrated success using both TIMS and ASTER data that show increases in the number of remotely detected thermal anomalies by an order of magnitude. This initial study was performed in the Steamboat Springs region. Preliminary work with ASTER data suggests the potential for obtaining similar results over the Brady Hot Springs region. At 90m/pixel, this space-borne data can easily identify a thermal anomaly ~3+ km in length. The work will acquire higher resolution airborne imagery to map mineralogy and other features at known vents and fumaroles in the region and provide a regional scale assessment of other thermal anomalies at the site.

Status / Accomplishments: An analysis of ASTER data over Brady's Hot Springs was completed as part of a lab project for a graduate-level course in thermal remote sensing. After corrections for albedo, topographic slope, and thermal inertia, improved anomaly definition was obtained, and the thermal anomaly was detectable over a minimum distance of 4 km. These anomalies were verified in the field with temperature thermocouples and by using GPS units to produce a detailed map of fumaroles and warm ground. The GPS-generated maps confirmed indications from the thermal imagery that multiple faults with multiple strikes were responsible for the surface thermal features. The thermal imagery and fumarole maps have been given to Ormat, who will use the information to help locate secondary structures at depth. A PowerPoint® talk discussing these results was given at the annual meeting of the Geologic Remote Sensing Group (affiliated with the British Geological Society) in London on December 6, 2002.

Mineral mapping with SEBASS data has been completed and the results were presented at the GRC meeting in Reno and at the Fall Meeting of the American Geophysical Union in San Francisco. The SEBASS imagery has proved capable of mapping several hot-spring-related minerals including opal (sinter) and clay minerals. Old and young sinters have been distinguished based on the strength of their absorption features.

Airborne hyperspectral short wave IR data were acquired at the Brady site on July 2 by SpecTIR Corporation, and SpecTIR is currently refining atmospheric and radiometric calibrations for this most recent set of acquisitions. Calvin discussed collaboration at Dixie Valley with Bill Pickles of LLNL. Flights with the HyVista corporation (HYMAP) sensor occurred over the Dixie Valley site, and Bill has agreed to share the data. We requested flight lines for AHI, but we are presently uncertain when or if these acquisitions will occur. Incoming MS candidate Chris Kratt is available to work on these projects and he began work in mid-August.

Reports & Articles Published in FY 2002:

Calvin, W., M. Coolbaugh, and R. G. Vaughan, 2002, "Geothermal Site Characterization Using Multi- and Hyperspectral Imagery," *Transactions,* Geothermal Resources Council 26: 483–484.

Calvin, W., M. Coolbaugh, and R. G. Vaughan, 2002, "Thermal infrared remote sensing for geothermal site characterization: GSA Abstracts with Programs," Denver, CO. Annual Meeting, Oct. 27–30, 2002, v. 34, n. 6, p. 551.

Coolbaugh, M., Kratt, C., Fallacaro, A., Mahoney, S., Muehlberg, J., Calvin, W., and Taranik, J., 2002, "Enhancement of geothermal anomalies using ASTER thermal infrared images at Brady's Hot Springs, Nevada, USA," 2002, annual meeting of the Geological Remote Sensing Group, London, England, Dec. 5–7, PowerPoint® with added text published on CD.

Vaughan, R. G., W. Calvin, and S. J. Hook, 2002, "Thermal infrared surface mineral mapping at Steamboat Springs, Nevada: comparisons of airborne and field spectral measurements," *EOS Transactions Supplemental*, v. 83, n. 47, p. F285.

Vaughan, R. G., W. M. Calvin, and J. V. Taranik, *in press*, SEBASS hyperspectral thermal infrared data: surface emissivity measurement and mineral mapping: Remote Sensing of the Environment.

Presentations Made in FY 2002:

Calvin, W., at the *Annual GSA Meeting*, Denver, CO., Oct. 30; titled: "Thermal infrared remote sensing for geothermal site characterization,"GSA Abstracts with Programs; Denver, CO. Annual Meeting, Oct. 27–30, 2002, v. 34, n. 6, p. 551.

Calvin, W., at the *Annual Geothermal Resources Council Meeting,* Reno, NV, September 23–5; titled "Geothermal Site Characterization Using Multi- and Hyperspectral Imagery," a PowerPoint® file is posted at the web site http://www.unr.edu/geothermal/meetingsandpresentations/meetings_grc.html

Coolbaugh, M., at the *Annual Meeting of the Geologic Remote Sensing Group*, London, UK, Dec. 6, titled: Enhancement of geothermal anomalies using ASTER thermal infrared images at Brady's Hot Springs, Nevada, USA. PowerPoint® talk with added text published on CD.

Vaughan, G., at the *Annual Fall Meeting of the American Geophysical Union*, San Francisco, Dec. 6–10, titled "Thermal infrared surface mineral mapping at Steamboat Springs, Nevada: comparisons of airborne and field spectral measurements," published in *Eos Transactions* (see above).

In addition, a presentation by M. Coolbaugh is scheduled January 17, 2003 for the *January meeting of the Geological Society of Nevada in Reno*; and is titled "Regional Geologic Controls, Geochemical Characteristics, and Thermal Infrared Signatures of Geothermal Systems of the Great Basin." An abstract has been published in the January 2003 newsletter of the Geological Society of Nevada (see above).

Planned FY 2003 Milestones:

- SpecTIR airborne hyperspectral imagery from Brady's Hot Springs will be computer-enhanced and compared to surface mineral assemblages mapped on the ground with GPS instruments.

- SEBASS imagery at Steamboat will be synthesized with AVIRIS, TIMS, and MASTER data to identify strengths of each system in mapping various mineral assemblages and thermal anomalies.

- HyVista Corporation's HYMAP imagery over Dixie Valley will be analyzed.

- At Steamboat Springs, analysis of MASTER airborne data will continue.

STRUCTURAL AND GEOPHYSICAL ANALYSIS AND CHARACTERIZATION OF THE DESERT PEAK-BRADY GEOTHERMAL FIELD: IMPLICATIONS FOR UNDERSTANDING LINKAGES BETWEEN NORTHEAST-TRENDING STRUCTURES AND GEOTHERMAL ANOMALIES

Reporting Period: FY 2002 (March 20, 2002 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-02ID14311

Performing Organization: University of Nevada, Reno,
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DOE Funding Allocation: $95K (entire amount awarded)

Cost Share Funding: None

Project Objective: We are conducting an integrated geologic, geophysical, and GIS investigation of the Desert Peak-Brady geothermal field in the Hot Springs Mountains of western Nevada. Two power plants and one vegetable dehydration plant currently operate in this field. The geologic investigations involve detailed mapping of critical areas, delineation of Tertiary stratigraphy, analysis of faults and folds, and $^{40}Ar/^{39}Ar$ dating and geochemical correlation of key units. These data will delineate the late Cenozoic three-dimensional strain field in the area, elucidate relations between faults, stratigraphic features, and thermal aquifers, and help define the current stress field. Gravity data are being utilized to reveal significant structures and their intersections, as well as define patterns in pre-Tertiary basement depth. This is important because pre-Tertiary rocks host the *blind* Desert Peak reservoir. The geologic and gravity studies, as well as existing drill-hole, temperature, and electrical conductivity data, are being incorporated into a GIS database. Collectively, these data sets will permit comprehensive three-dimensional visualization and modeling of the geothermal field. The initial goals of this project are to (a) characterize the links between thermal aquifers and structural and stratigraphic features and (b) better define the boundaries of the geothermal reservoirs.

Background/Approach: A broad region of high heat flow, the Battle Mountain heat flow high, covers much of northern Nevada and includes an east-northeast-trending zone extending from near Reno to Carlin. The Steamboat, Desert Peak-Brady, Soda Lake, Rye Patch, Dixie Valley, and Beowawe geothermal fields lie within this zone. Northeast-striking faults that roughly parallel the Battle Mountain high appear to host most of these geothermal fields. This belt of east-northeast- to northeast-striking faulting and high heat flow has been referred to as the Humboldt structural zone. The abundance of producing geothermal fields and regional extent of the heat flow anomaly indicate high potential of discovering additional geothermal reservoirs in this region.

Despite the economic significance of the Humboldt zone, its structural and geophysical framework has not been comprehensively studied. Although significant contributions have recently been made, the temporal and spatial relationships between various structural features within the zone and how individual faults, stratigraphic units, or sets of structures control fluid pathways and geothermal resources are generally poorly understood. Consequently, this study aims to integrate structural, geophysical, geochronologic, and Geographic Information Systems (GIS) data of the Desert Peak-Brady geothermal field in the Hot Springs Mountains of western Nevada. This area was chosen for study, because it is one of the better exposed geothermal fields in the Humboldt structural zone. This study will help to characterize features that localize geothermal reservoirs in the Humboldt zone and may therefore facilitate future exploration and discovery of geothermal resources in northern Nevada.

Status / Accomplishments: Major accomplishments through September 30, 2002, include:

1. Existing isothermal, well, and geologic data from Benoit et al. (NBMG Bulletin 97, 1982) were compiled into a GIS database. Three-dimensional diagrams of the geothermal anomalies were prepared to gain insight into the structural and stratigraphic controls of the thermal aquifers.

2. A new detailed gravity survey (323 stations covering 200 km^2) was completed for the northern Hot Spring Mountains and integrated with an existing industry data set (provided by ORMAT).

3. A new contoured Bouguer gravity map of the northern Hot Springs Mountains was produced by integrating the new and preexisting data sets. An overlay of the new gravity map on the existing geologic map greatly elucidates the stratigraphic and structural framework of the northern Hot Spring Mountains, including depth to basement and geometry of faults, particularly in the vicinity of the Desert Peak and Brady geothermal anomalies.

4. Detailed geologic mapping and structural analysis of an E-W transect across the Hot Springs Mountains also began in FY 2002. This transect includes both the Brady and Desert Peak power plants and associated geothermal fields, as well as the EGS site currently under investigation by ORMAT International. Major findings include (a) significant refinement of the Tertiary stratigraphy in the area, which will facilitate interpretation of drill logs and estimation of depth to basement; (b) discovery and sampling of several datable tephras and lava flows, which should permit tight bracketing of the age of the Tertiary strata and will better constrain the timing of deformation; (c) observation that at least some of the folds in the area result from a combination of normal drag and tilting on listric (concave upward geometry) normal faults; (d) acquisition of slip data from several fault surfaces, which will help constrain the orientation of stress fields responsible for the faulting and folding and elucidate the structural controls of geothermal aquifers, and (e) X-ray diffraction analysis of the matrix of a basalt-breccia unit (which underlies massive flow unit), which indicates the presence of a smectite clay (montmorillonite) and a zeolite (probably clinoptilolite). Clay and zeolite mineral formation could be syngenetic or diagenetic (possibly related to the present geothermal system). In conjunction with the already completed gravity work by Gary Oppliger, we are now gaining significant insight into the geometry of faults

and depth to basement in the Hot Springs Mountains. For example, both geologic and gravity data suggest that a major NNE-striking fault dies out toward the northeast near the Desert Peak power plant. The *damage zone* associated with this fault termination may play an important role in channelizing fluids in that area.

5. A paper describing our initial findings concerning the structural and stratigraphic framework of the Hot Springs Mountains, including a possible model for the structural control of geothermal aquifers, was presented at the September GRC meeting in Reno.

6. We are also working closely with several other groups studying the Hot Springs Mountains and other geothermal fields in the region, including the EGS investigation by ORMAT International and the remote sensing study by Wendy Calvin and Mark Coolbaugh. The latter group has mapped the location of fumaroles in the vicinity of the Brady power plant. The distribution of these fumaroles suggests that the Brady geothermal anomaly is centered on a small left step in a northeast-striking fault system that has probably accommodated left-lateral motion.

Reports & Articles Published in FY 2002:

Faulds, J., L. Garside, G. Johnson, J. Muehlberg, and G. Oppliger, 2002, "Geologic Setting and Preliminary Analysis of the Desert Peak-Brady Geothermal Field, Western Nevada." *Transactions,* Geothermal Resources Council 26: 491–494.

Presentations Made in FY 2002:

Presentations at the *Annual Geothermal Resources Council Meeting,* Reno, NV, September 23-5:

Oppliger, G., "Preliminary Assessment of a New Gravity Survey of the Desert Peak-Brady Geothermal Field, Western Nevada."

Planned FY 2003 Milestones:

- The transect of detailed geologic mapping will be completed to further define the stratigraphic and structural framework of the Hot Spring Mountains.

- Studies of sinter and tufa will be completed to determine their potential relationship with the active geothermal systems.

- Structural analysis of faults and folds will be completed.

- Obtain high-precision geochronologic data ($^{40}Ar/^{39}Ar$ and tephrochronology) to constrain both the age of major stratigraphic intervals and timing of deformation.

- The geologic, gravity, and GIS data will be integrated to develop a three-dimensional subsurface model in digital format of the Brady-Desert Peak geothermal field and better define the structural and stratigraphic controls on the geothermal aquifers.

- Collaborate with and contribute to the EGS study by ORMAT International. We will contribute our geologic and gravity data to their study, while they plan to contribute aeromagnetic and well data (samples and petrography) to ours. We will refine our final products, where possible, to address some of the questions and needs of the EGS study.

DEVELOPMENT OF TOOLS FOR MANAGING INJECTION IN GEOTHERMAL RESERVOIRS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-FG07-00ID13891, Task VI

Performing Organization: Energy & Geoscience Institute at the University of Utah
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DOE Funding Allocation: $217K

Cost Share Funding: None

Project Objective: Our objective is to identify and characterize tracers suitable for use in moderate- to high-temperature geothermal systems. Operators of geothermal reservoirs claim that many more tracers than are currently available are needed in order to effectively track fluid flow in reservoirs having many injection wells. Such tracers must be environmentally benign, resistant to adsorption on geothermal rock, affordable, thermally stable and very detectable. Whereas all of these qualities are essential, only the latter two are design drivers. Therefore, our primary objectives are to identify tracers that are thermally stable and to develop methods of analysis that improve their detection limits and thereby reduce the quantity of tracer required to conduct a tracer test.

Background / Approach: Cost-effective operation of geothermal fields requires the recirculation of huge volumes of water through the subsurface in order to efficiently mine heat trapped within the reservoir. Key to the reinjection process is the strategic placement of injection wells. If injection wells are placed too close to producers, thermal breakthrough of the cooled injectate will result in the premature cooling of production wells. If injection wells are placed too far from producers, the reservoir will soon lose pressure with a concomitant drop-off in power production. Thermally stable and detectable tracers are the most effective tools available for optimizing the placement of injection wells within geothermal fields.

Recently, we have discovered a family of fluorescent tracers that is environmentally friendly, affordable, and very detectable and that possesses extraordinary thermal stability. Our approach has been to evaluate this family of polyaromatic sulfonate tracers for high temperature geothermal tracing applications through laboratory decay-kinetics studies as well as field tests in operating geothermal reservoirs. In addition, in order to make geothermal tracer testing more cost effective, we have initiated a program to develop online tracer methods that allow for the automatic detection and analysis of fluorescent tracers using the emerging spectroscopic technologies of long-pathlength flow cells, fiber optics for light delivery and collection, and CCD-based spectrometers.

Status / Accomplishments: Over the past three years, we have successfully developed and demonstrated a family of thermally stable fluorescent tracers for use in geothermal reservoirs. Six compounds from among the naphthalene sulfonates were tested in the laboratory and in the field and shown to be suitable for use in liquid-dominated geothermal systems with temperatures in excess of 300°C (see Figure 1). Our approach this year, therefore, was to continue the investigation of the polyaromatic sulfonates in order to identify and qualify one additional thermally stable geothermal tracer.

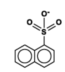
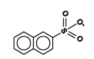
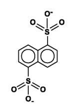
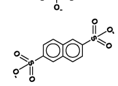
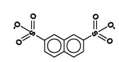
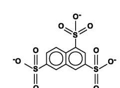
Compound	Structure	Excitation / Emission (nm)
1-naphthalene sulfonate		*217 / 333*
2-naphthalene sulfonate		*220 / 336*
1,5-naphthalene disulfonate		*218 / 334*
2,6-naphthalene disulfonate		*225 / 342*
2,7-naphthalene disulfonate		*226 / 339*
1,3,6-naphthalene trisulfonate		*228 / 342*

Figure 1. Chemical structures of the thermally stable fluorescent compounds that have been tested in the laboratory and in the field and found to be suitable for reservoirs with temperatures exceeding 300°C.

A new candidate tracer compound, 1,6-naphthalene disulfonate, was identified and shown to be available in bulk at a reasonable cost. Accordingly, during FY 2002 we studied the decay kinetics of this compound in order to determine its suitability for use in a high temperature geothermal environment. Our experimental approach was to subject it to simulated geothermal reservoir conditions using an autoclave batch reactor. We then set out to model its thermal decay using first-order kinetics. We then modeled the temperature dependence of the decay rate constant using an Arrhenius relationship. This allows for a prediction of the tracer concentration over time at any temperature within the range of study.

Shown in Figure 2 is an Arrhenius plot of ln(k) vs. inverse temperature over the temperature range 320°C to 335°C. The points approximate a straight line, indicating that the Arrhenius model is adequate to describe the temperature dependence of the decay rate constant for 1,6-naphthalene disulfonate over this temperature range. In addition to the laboratory studies, the 1,6-naphthalene disulfonate was used in a tracer test at a commercially operated high-temperature geothermal reservoir. Tracer breakthrough was evidenced at several production wells, confirming the thermal stability data as measured in the laboratory.

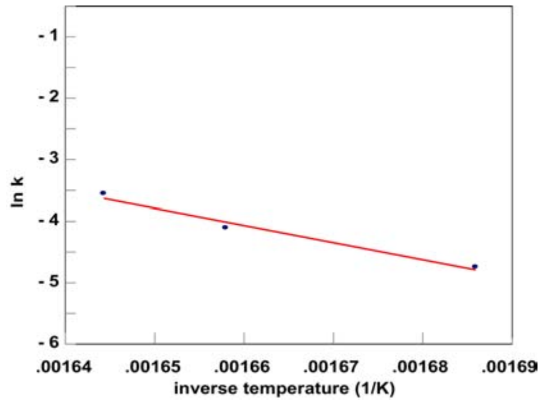


Figure 2. Arrhenius plot for the candidate tracer 1,6-naphthalene disulfonate between 320°C and 335°C.

We have designed a laser-induced-fluorescence detector that makes use of recent advances in laser light sourcing, fiber optics and CCD spectrometry. Using this instrument, our laboratory demonstrated the lowest detection limit for a fluorescent compound ever reported in the literature for this application. The instrument is, however, both too bulky and too sensitive to be deployed within a geothermal reservoir. We have therefore designed a field-deployable version of the fluorimeter that takes advantage of a new, low-index-of-refraction Teflon AF liquid-core waveguide. The excitation source could be a low-energy lamp or a blue LED. Shown in Figure 3 is the design for our field-deployable fluorescence detector.

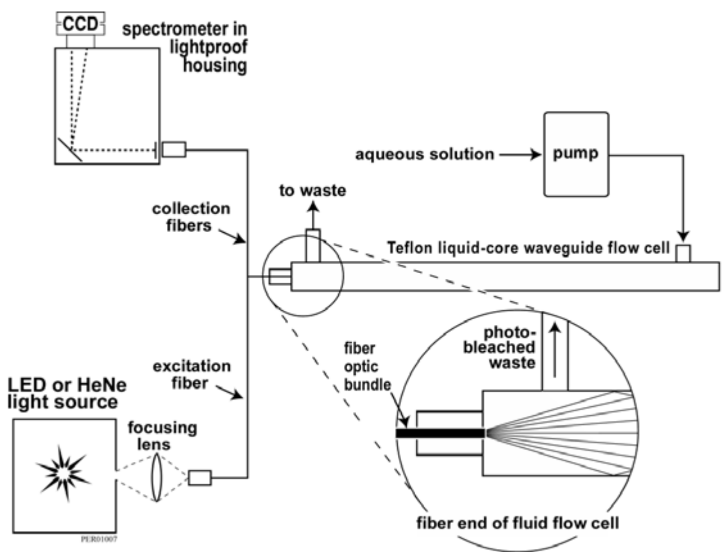


Figure 3. Schematic drawing of the field deployable fluorimeter.

Reports & Articles Published in FY 2002:

Rose, P. E., S. D. Johnson, Y. L. Wong, T. Carter, C. Kasteler, and P. Kilbourn (2002) "Sub Part-Per-Trillion Detection of a Fluorescent Tracer at the Dixie Valley and Beowawe Geothermal Reservoirs," *GRC Transactions*, 26, 113–117.

Nimmo, J. R., Perkins, K. S., Rose, P. E., Rousseau, J. P., Orr, B. R., Twining, B. V., and Anderson, S. R., (2002), Kilometer-scale rapid transport of naphthalene sulfonate tracer in the unsaturated zone at the Idaho National Engineering and Environmental Laboratory: *Vadose Zone Journal*, 1, pp. 89-101.

Rose, P. E., Johnson, S. D., and Kilbourn, P. M., and Kasteler, C. (2002) Tracer Testing at Dixie Valley, Nevada Using 1-Naphthalene Sulfonate and 2,6-Naphthalene Disulfonate: *Proc. Twenty-Seventh Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-171.

Presentations Made in FY 2002:

Rose, P. E., S. D. Johnson, Y. L. Wong, T. Carter, C. Kasteler, and P. Kilbourn (2002) Sub Part-Per-Trillion Detection of a Fluorescent Tracer at the Dixie Valley and Beowawe Geothermal Reservoirs: GRC Transactions, 26, 113-117.

Rose, P. E., S. D. Johnson, P. M. Kilbourn, and C. Kasteler, (2002), "Tracer Testing at Dixie Valley, Nevada Using 1-Naphthalene Sulfonate and 2,6-Naphthalene Disulfonate," *Proc. Twenty-Seventh Workshop on Geothermal Reservoir Engineering*, Stanford University, SGP-TR-171.

Planned FY 2003 Milestones: The planned FY 2003 milestones include:

- The development and demonstration of an affordable, detectable and thermally stable tracer for use in high temperature geothermal reservoirs

- The demonstration of an instrument for the field detection and analysis of fluorescent geothermal tracers

II. EXPLORATION AND DRILLING PROJECTS

EXPLORATION

DIXIE VALLEY GEOLOGIC AND GEOPHYSICAL STUDIES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $250K

Cost Share Funding: None

Project Objective: Develop a conceptual understanding of the extensional faulting in Dixie Valley and apply that understanding, and the methods used to develop it, to the general problem of geothermal exploration in the Basin and Range Province of North America.

Background / Approach: The Basin and Range is thought to comprise the largest geothermal exploration province in the United States, but unanswered questions limit the ability of operators to successfully explore for geothermal resources at low cost and with a high success ratio. A better understanding of the geologic setting and the native state geophysical signature of geothermal systems in the Basin and Range is essential for successful B&R exploration. The approach for FY 2002 was to further develop high-resolution aeromagnetic survey methodology for defining intra-basin fault patterns in the Basin and Range. This was done by performing a survey in Dixie Valley, where significant fault information already exists from surface mapping, drilling, and ground-based geophysical surveys.

Status / Accomplishments: The test of the high-resolution aeromagnetic survey in Dixie Valley was very successful. The results of the survey provided a complete picture of faulting in basin-fill sediments of the valley, gave additional support for the existence of a piedmont or rampart fault outboard of the surface expression of the Stillwater Fault, and further established the steep dip of the major basin-bounding fault system on the west side of Dixie Valley. It also showed that the producing geothermal field lies in the area where the fault system on the east side of the valley merges with that on the west side of the valley, providing rationale for further exploration by focused geophysical studies and drilling in Dixie Valley and in other Nevada basins.

Reports & Articles Published in FY 2002:

R. P. Smith, V. J. S. Grauch, and D. D. Blackwell, 2002, "Preliminary Results of a High-Resolution Aeromagnetic Survey to Identify Buried Faults at Dixie Valley, Nevada," Geothermal Resources Council *Transactions*, v.26, p.543–546.

Presentations Made in FY 2002:

R. P.Smith, 2002, "Fault patterns at Dixie Valley, Nevada," presentation to the DOE-Sponsored Workshop, *Dixie Valley Geothermal Research, June 12–13, Desert Research Institute, Reno, Nevada*.

R. P. Smith, V. J. S. Grauch, and D. D. Blackwell, 2002, "Preliminary Results of a High-Resolution Aeromagnetic Survey to Identify Buried Faults at Dixie Valley, Nevada," presentation to the *2002 Annual Meeting of the Geothermal Resources Council, September 22–25, Reno, Nevada*.

R. P. Smith and V. J. S. Grauch, 2002, "High-resolution aeromagnetic survey reveals distribution of faults in Dixie Valley, Nevada," poster presented at the *2002 Annual Meeting of the Geological Society of America, Denver, Colorado, October 26–30*.

Planned FY 2003 Milestones: Present a paper at the 28th Stanford Workshop on Geothermal Reservoir Engineering in January 2003. The title of the paper is "Geothermal exploration strategy for the Basin and Range province." This paper will draw on the experience at Dixie Valley, and on examination of the characteristics of other basin and range geothermal systems to put forward a low-cost, rapid exploration strategy for "blind" geothermal systems in extensional environments such as the Basin and Range province of the western U.S. The work for FY 2003 will focus on further development and refinement of this exploration model.

RECONNAISSANCE FOR HIDDEN RESOURCES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: W-7405-Eng-48

Performing Organization: Lawrence Livermore National Laboratory

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Collaborating Researchers: Greg Nash, University of Utah
Wendy Calvin, UN-Reno
Eli Silver and Don Potts, UC-Santa Cruz
Brigette Martini, HyVista Corp
Don Vasco, LBNL, and the Caithness Corp.

DOE HQ Program Manager: Alan Jelacic
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DOE Funding Allocation: $350K

Cost Share Funding: None

Project Objective: We are developing combinations of advanced overhead imagery techniques and regional strain studies for focusing exploration for locations of new geothermal resources in the U.S. The goal is to provide two levels of screening of potential geothermal drilling sites in the Basin and Range and in the volcanic regions in the western U.S. The first level is a set of regional screening tools that will help with the identification of regions likely to have productive drilling sites. The second level is to develop a set to tools that will refine the locations of potential drilling sites to approximately a hundred meters. These relatively precise surface locations would then be used with other exploration data and subsurface modeling to select candidate locations for trial drilling.

Background / Approach: The twenty-year-old USGS survey of geothermal resources in the U.S. estimated that the undiscovered resource was substantially larger than the known resource. Most of the known-resource areas have since been explored or tested, but little exploration is targeted towards the undiscovered resource. We are studying ways to identify targets for exploration of hidden resources. Two methods have potential for covering large areas and detecting anomalies associated with those systems. The DOE-funded Hyperspectral Imaging Project has demonstrated airborne geobotanical remote sensing at Long Valley. It detected surface effluents, historical signatures, subtle hidden faults and the botanical effects of low level chemical and thermal emissions that, in other locations, might indicate hidden geothermal systems. A combination of satellite-based techniques including InSAR, and ground-based strain measurements such as GPS can detect localized strain around hydrothermal systems, and regional strain that may show where faults are favorably oriented to maintain vertical permeability.

Figure 1. The Stillwater Range front at Dixie Meadows

Status / Accomplishments: The regional overhead imagery techniques that we are using are very-high-resolution commercial satellite images and INSAR satellite radar imagery. The technique we are using for identifying very localized potential drilling sites is airborne high resolution hyperspectral imagery. Through many discussions with all our collaborators we selected our study region for this year as the area centered on what is called Dixie Meadows, Nevada.

Dixie Meadows is several kilometers south of the Dixie Valley geothermal field. Airborne high-resolution hyperspectral imagery of that area were successfully collected in August 02 by the HyVista Corp. As Figure 1 shows, the weather was perfect for imaging on that day. Eighteen flight lines imaged the entire Dixie Meadows region from the Clan Alpine Range down across the Lake Dixie basin and up across the Stillwater Range. The hyperspectral images acquired have a spatial resolution of about 3 meters. We had a site visit for ground-truth measurements during the day of the overflight. The Hyperspectral imagery was post-processed by the HyVista Corp. and delivered to LLNL in November 2002.

The very-high-resolution satellite imagery of the Dixie Meadows area will be purchased from Digital Globe Corp. The Quickbird satellite imagery has 0.6 meter spatial resolution panchromatic, which is the legal limit for spatial resolution for commercial imagery by a US company. The Quickbird satellite imagery also comes with 4 band multispectral images with spatial resolution of 2.5 meters. Two new graduate students, one at UC Santa Cruz and one at U of Utah have joined our collaboration and will be analyzing the Dixie Meadows imagery during the winter and spring of 03.

Analysis of synthetic aperture radar (SAR) data during this first year has focused on better defining the tectonic and hydrological factors that appear to be responsible for localization of the geothermal resource at the Dixie Valley field within a regional context. The objective of this analysis is to refine a set of attributes characterizing this relatively well-studied extensional system that can then be applied in the regional search for similar resources. The primary tool utilized in the analysis is SAR interferometry (InSAR), which is capable of detecting and mapping cm-level deformation of the Earth's surface at high (~10 m) resolution a regional scale. The main emphasis of this work has been analyzing the relationship of production-related subsurface processes that produce ground surface deformation at Dixie Valley to structure along and basinward of the Stillwater fault zone and to regional-scale east-west- and northwest-trending structures revealed as lineaments in the SAR phase difference and backscatter intensity images, in the regional digital elevation model (DEM), and in panchromatic and multi-spectral satellite images. We have also briefly scrutinized the differential interferograms for evidence of deformation suggestive of localized tectonic strain anomalies within the region.

We purchased five European Space Agency ERS-1/2 C-band SAR scenes of the same 1° × 1° frame centered on Dixie Valley. The frame covers the Stillwater Range and the eastern half of the Carson Sink and Vista Valley to the west, the Edwards Creek, Smith Creek and Antelope Valleys to the east, and Pleasant Valley and Jersey Valley to the north and northeast. From the five scenes we were able to construct five differential interferograms spanning the following time intervals: 8/92–3/97 (4.5 yr); 8/92–4/96 (3.5 yr); 4/96–8/97 (1.3 yr); 4/96–3/97 (10.5 mos); 3/97–8/97 (4.8 mos).

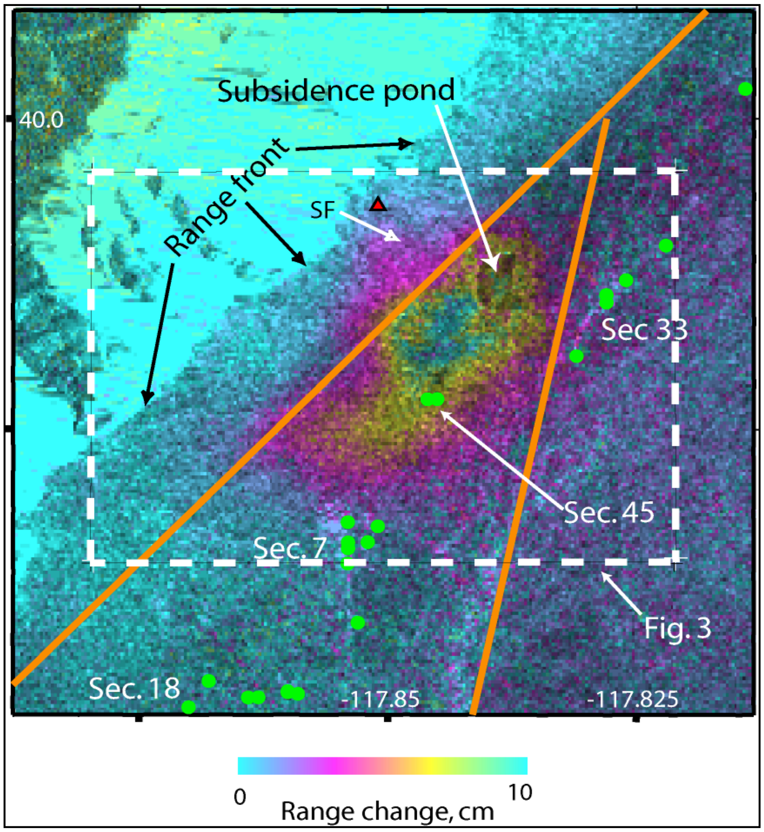

Figure 2. Map of subsidence over the Dixie Valley geothermal field. Red triangle, Senator fumarole; SF, Senator fan.

All of the differential interferograms show significant surface subsidence above the Dixie Valley field. The deformation is most clearly imaged on the interferograms spanning the shortest time intervals (4.8 mo.–1.3 yr.), and we selected the 10.5 mo. interferogram for detailed analysis that included inversion for subsurface fluid volume change sources. The subsidence pattern (Fig. 2) is centered slightly north of the Section 5 injection wells, extends to the SW from the subsidence pond that has developed valley-ward of the Senator fumarole (Allis et al., 1999), and is entirely located NE and west of the Section 7 and Section 33 producers, respectively. The inversion results show that the dominant source of the subsidence is most likely very shallow within the valley fill, rather than fluid volume depletion resulting directly from geothermal production at 2.5–3 km depth. The distributions of subsidence and volume sources in the vicinity of the Senator fan support the model proposed by Allis et al. (1999). In this model production-induced drawdown within an upflow zone localized beneath the Senator fumarole caused a large reduction in the pressure of hot water discharged into the valley fill. We are carrying out additional inversions to investigate whether an additional source of subsidence could be production-related fluid volume reduction within a steeply dipping piedmont fault zone located under the valley SE of the range front.

Of the greatest interest to our long-term research objectives is the relation of the subsidence and its source to both local- and regional-scale geologic structures. The overall area of subsidence is elongated NE-SW and closely parallels the range front. The zone of most intense deformation is largely confined between intra-basin faults mapped by Smith et al. (2001) (shown in orange on Fig. 2), which suggests that the deformation source is structurally controlled by faults that extend to the surface or shallow subsurface. The SW end of the deformation zone is also remarkably straight, which suggests that it is also structurally controlled. This edge is not associated with a mapped fault, but it coincides with the western extension of a prominent WNW-trending lineament seen on both the interferograms and SAR backscatter intensity images (Figure 3), as well as on Landsat and Ikonos imagery. The lineament has striking topographic expression and is mapped as a seasonal drainage flowing WNW from the Augusta Mountains to the middle of Dixie Valley, where the topographic lineament ends about 4 km east of the geothermal field. We have also tentatively traced the lineament on the SAR backscatter image west of the field across the Stillwater range, but this remains to be confirmed on the other imagery. If this lineament reflects a structure, then the apparent relationship between the lineament and the deformation would suggest that shallow groundwater flow parallel to the valley is structurally compartmentalized along strike as well as laterally, and the same structures may influence fluid circulation at production depths.

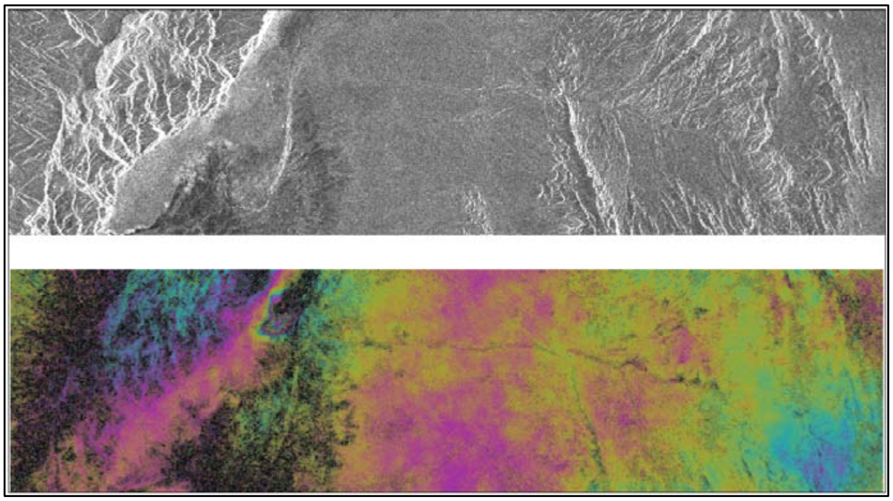

Figure 3: SAR backscatter and interferogram showing WNW-trending lineament.

On a regional scale, the location of the Dixie Valley field is distinguished by several tectonic factors. The geothermal significance of the location of the field between the ruptures of the 1915 Pleasant Valley and 1954 Dixie Valley earthquakes is the subject of ongoing DOE-funded research. The field is located immediately to the SW of the end of the 1915 rupture where active faulting changes from east side down on the eastern flank of the Stillwater range side to west side down on the western flank of the Tobin Mtns. This corresponds to a change from horst movement and westward tilting of the fault block to the SW to eastward tilting to the NW. The Basin and Range province as a whole is divided into a pattern of large domains within which fault blocks are either west- or east-tilting. In Nevada and Utah, the domains are separated by WNW-trending boundaries, parts of which follow prominent lineaments. We are investigating whether the lineament seen on the SAR images is part of one of these domain boundaries and, if so, the possible significance of this and other boundaries in the region to localization of geothermal resources. This work will begin with examination of the regional-scale and high-resolution data from Dixie Meadows. Based on the Dixie Valley InSAR results, the regional-scale structure we have tentatively identified appears to play a significant role at the local field scale.

Reports & Articles Published in FY 2002:

Martini, B. A., 2002, *New insights into the structural, hydrothermal, and biological systems of Long Valley Caldera using hyperspectral imaging*, Ph.D Thesis: UCSC Earth Sciences Department. November 15, 2002

Presentations Made in FY 2002:

INSAR imagery of Dixie Valley, William Foxall, DOE Dixie Valley Workshop in Reno NV, August 02

Planned FY 2003 Milestones:

Paper on Dixie Valley at Stanford Workshop	Jan 03
Acquire SAR data for additional areas and for signal stacking	Jan 03
Extensive field site visits in the Dixie Meadows	Apr 03
Preliminary regional InSAR analysis, and analysis of hyperspectral imagery acquired in 02	Jun 03
Publication of hyperspectral and Quickbird results	Aug 03
Integrate remote sensing with regional tectonics, strain inversion	Sep 03

References:

Allis, R. G., S. D. Johnson, G. D. Nash, D. Benoit (1999), "A model for the shallow thermal regime at Dixie Valley geothermal field, *Geothermal Resources Council Trans.*, 23, 493–498.

Smith, R.P., K.W. Wisian, and D.D. Blackwell, 2001, "Geological and geophysical evidence for intra-basin and footwall faulting at Dixie Valley, Nevada", *Geothermal Resources Council Trans.*, 25, 323-326.

EVALUATION OF NEW THREE-DIMENSIONAL MAGNETOTELLURIC DATA ACQUISITION SYSTEMS AND IMAGING ALGORITHMS FOR GEOTHERMAL RESOURCE EXPLORATION AND DELINEATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Earth Sciences Division
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DOE Funding Allocation: $13K

Cost Share Funding: $40K, Sandia National Laboratory; $25K + $10K in kind, USGS

Project Objective: The project is conducting a 3D MT survey over the East Rift Zone to map the lateral and depth extent of the rift as well as the primary magma chamber beneath Kilauea. We will acquire enough high-quality MT sites (on the order of 50) to perform full 3D electromagnetic inversion using Sandia's new massively parallel inversion codes. These inverse images will be interpreted in terms of geologic structure with the aid of USGS geologists working on Kilauea. In addition the survey area is replete with gravity and seismic data sets giving this project an excellent potential for demonstrating the utility of combined geophysical data interpretation for geothermal resource delineation. This project will serve to develop three-dimensional imaging capabilities and data integration techniques that will be applicable to exploration and delineation of geothermal system associated with volcanism anywhere in the U.S.

Background / Approach: In 1999 LBNL, UC Berkeley and the USGS preformed a feasibility study to evaluate using magnetotelluric (MT) data to image the volcanic East Rift Zone and deeper magma chambers on the Kilauea volcano in Hawaii. The tests highlighted a number of operational difficulties in deploying MT in a volcanic environment, never the less the data showed the ability to image near surface aquifers (potential recharge zones for geothermal systems) as well as deeper magma structures (heat sources). It was decided to put together a collaborative group consisting of researchers from Sandia, LBNL, UC, Hawaiian USGS, and Electromagnetic Instruments Inc. to return to Kilauea in early 2002 to conduct a state-of-the-art 3D MT survey. Sandia agreed to contribute up to $40K and virtually unlimited time on their massively parallel computer system for data interpretation, UC will contribute staff time for the crew chief of the proposed survey, the USGS will provide support personnel, vehicles, a staging area as well as survey design and planning time of a senior geophysicist, EMI will donate 5 new state-of-the-art MT systems and operational personnel.

Status / Accomplishments: In August 2002 we acquired 33 MT sites around the Kilauea caldera and over the East rift zone. The data has been processed and initial interpretations based on two-dimensional inversions were presented at the AGU fall meeting in San Francisco. The conductivity images produced from the data correlate with recently published seismic tomographic images of acoustic and shear velocity south and south west of the caldera. The MT conductivity images map out zones in the 2 to 4 km depth range of partial melt. In addition, the "Summit magma reservoir" (Ryan 1988) was imaged down to a depth of 6–8 km. The conductivity images also show large amounts of magma beneath the eastern rift zone where active eruptions are taking place.

We demonstrated that we could acquire high quality tensor impedance estimates over the East Rift zone by using remote magnetic sites. This has a major impact on the ability to acquire high quality MT data over any geothermal site where access is difficult. The magnetic field instruments are heavy and require considerable installation time. By setting up semi-permanent magnetic measurement sites on the periphery of the data collection area and only directly measuring the electric field over the area of interest, we were able to cut the setup time by 40%.

Three-dimensional modeling has been conducted to assess the effects of land-ocean contact on the MT data. The land-ocean interface on MT data is due to distortions of the electric currents flowing in the highly conductive ocean when they encounter the resistive land. Based on modeling we were able to determine that these effects became significant below a period of 100 seconds. Therefore, in our initial 2D we chose to limit the frequency range to 100 Hz to 100 sec. This limits our depth of investigation to between 5 and 10 km, depending on the intervening conductivity. The full frequency range of the data will be used in future 3D modeling, which translates to a 20 km investigation depth.

Full scale 3D numerical models of the entire island of Hawaii have been constructed to access the computational load of doing 3D inversion of large aerial extent data sets. This work has made use of the massively parallel computing systems at Sandia National Laboratories and brings a level of numerical complexity to geothermal system models that has not previously been available. The August 2002 data set is currently undergoing 3D inversion testing to determine the optimal finite difference meshes for inverting the data. The full 3D inversion of the data will be done in the first half of 2003.

Figure 1 shows two lines of data inverted to produce two-dimensional conductivity images running roughly parallel and perpendicular to the East Rift zone. The figure shows two seismic tomographic images from Dawson et al. 1999 (V shaped section to the left of image) and two parallel velocity lines from Haslinger et al. 2001 to the right of the image. The V_p/V_s images from Dawson et al. (left side) show two zones of anomalously high V_p/V_s ratio. These directly co-locate with areas of high electrical conductivity and are interpreted to be areas with up to 20% partial melt and a high degree of fracturing. To the south on the left most conductivity image is a south dipping conductor that is co-located with the interpreted summit magma reservoir described by Ryan (1988). To the east, beneath the active surface vents, the MT maps a large conductor to depths of 10km that is on a trend with anomalously low acoustic velocity previously mapped by Haslinger et al. (2001).

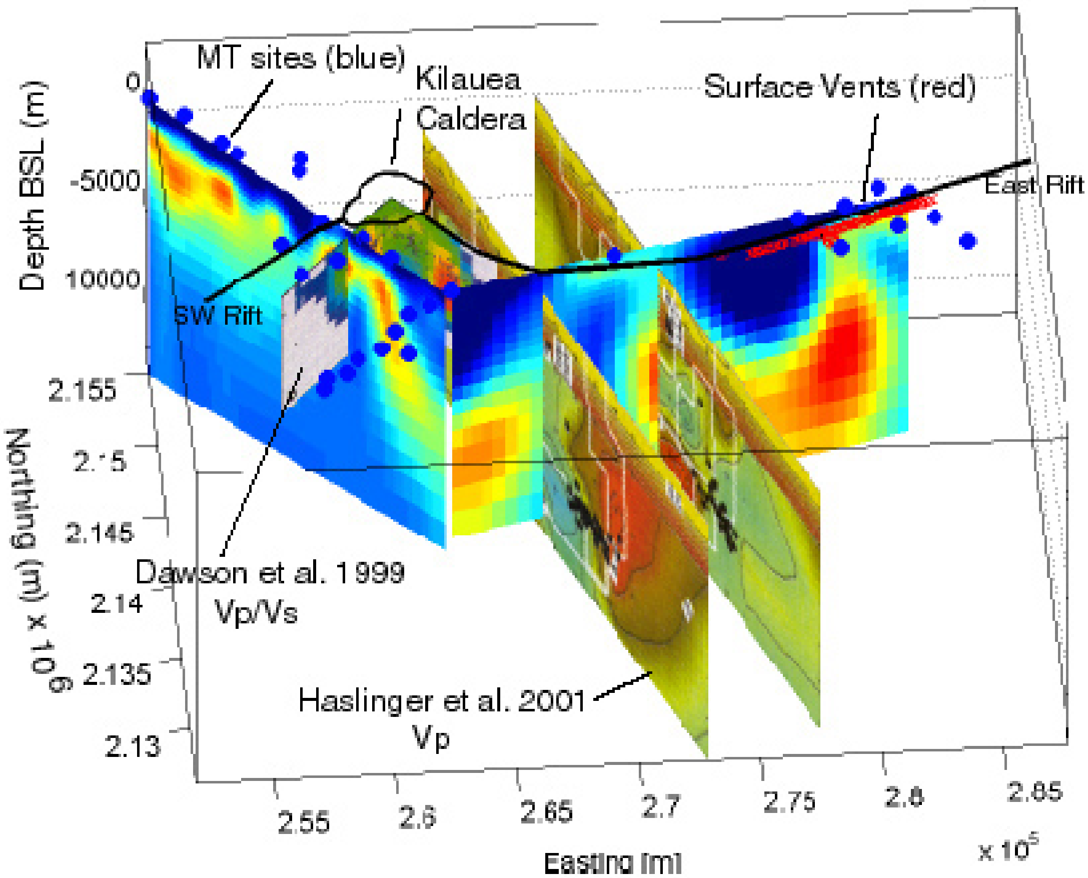

Figure 2. 3D perspective view looking from the southeast toward Kilauea caldera. High conductivity in red, low conductivity in blue. The caldera is the black loop to the east of the picture, MT site location are marked by blue dots, surface expression of the south-west rift and east rift zones are shown by black lines. The location of active surface vents over the last 20 years is shown as red circles to the west of the image. Two conductivity inversions are shown with tomographic velocity models from two recent publications.

Overall the conductivity images produced form the August 2002 data are quite exciting. They demonstrate a high degree of correlation with previously published geophysical images and correlated in space with known volcanic activity. They demonstrate the ability of MT to map deep underground melt and partial melt zones. Further work in 2003 will concentrate on full three-dimensional imaging of the entire data set and correlations with drill hole data and water saturation estimates in the near surface.

Reports & Articles Published in FY 2002:

Hoversten, G. M., Gritto, R., Washbourne, J., Daley, T., 2002, "Fluid saturation and pressure prediction in a multi-component reservoir by combined seismic and electromagnetic imaging," 2002 SEG Conference, Salt Lake City Utah. Submitted to *Geophysics*.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones:

1. Successful MT data acquisition.
2. Acquired data processed and readied for modeling and imaging.
3. Two and three-dimensional inverse images of conductivity structure produced.
4. Geologic interpretation of conductivity images.
5. Integrated MT, gravity and seismic data interpretation.
6. Review of interpretations by USGS volcano observatory staff.
7. Publication in peer reviewed journals of research results.

Milestones 1 and 2 have been achieved. Milestone 3 is half complete with the 2D interpretations of the data. Milestone 4 has been completed for the 2D inversions but will continue on the fully 3D images to be produced in 2003. Milestone 5 is partially complete. We have compared the conductivity images to both seismic and gravity models previously produced. In general the conductivity images correlate well with published velocity images. Previous gravity inversion work has produced models of density that do not correlate well with either the seismic or conductivity images. Work in ongoing to understand these differences. Milestone 6 is ongoing. USGS staff have reviewed the work to date and collaborated on a paper presented at the 2002 AGU meeting. This collaboration will continue in 2003 on all aspects of the project. Milestone 7 is under way. A manuscript is currently being prepared for submission in early 2003 on the 2002 work.

TECHNICAL ASSISTANCE

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $68.3K

Cost Share Funding: Only in kind (data on operation and future plans)

Project Objective:

Objectives: The main objectives of the work are: (1) to assist U.S. industry, trade organizations, DOE's Office of Geothermal Technologies, and other federal, state and local agencies in activities related to the exploration and development of high- and low-temperature geothermal systems; (2) to assist DOE's Operations Offices in the evaluation of proposals received in response to DOE-sponsored geothermal solicitations; (3) to keep DOE and U.S. geothermal organizations informed of the latest geothermal developments and plans, especially in the U.S. and Latin American countries; and (4) to support DOE in its technical transfer activities.

Work Scope: LBNL provides technical assistance to U.S. private and government organizations involved in geothermal activities. LBNL's staff helps in the evaluation of proposals, plans and other relevant materials, in the transference of DOE-funded technology to U.S. industry, and participates in technical panels, workshops and meetings. .

Background / Approach: Since the late 1970s, LBNL has provided technical assistance to the U.S. private sector, to DOE and other government organizations involved in projects and investigations related to geothermal energy. The work performed in FY 2002 continued these technical support activities, which include technology transfer efforts.

The work focussed on obtaining technical and other information on geothermal development activities in the U.S. and abroad and transferring it to interested U.S. companies and organizations. In addition, LBNL personnel assisted U.S. organizations in their interactions with geothermal groups abroad.

Information on geothermal plans and projects is gathered by way of personal contacts, checking technical publications, daily review of newspapers and by "surfing" the Web.

Status / Accomplishments: During FY2002, LBL personnel reviewed numerous proposals, participated in Merit Review Committees for DOE's Enhanced Geothermal Systems (EGS), Geothermal Resources Exploration and Definition (GRED), University Research (UR) Programs, and served on the program committee for the 2002 Geothermal Resources Council Meeting.

Information on Central American geothermal developments and plans was provided to DOE and U.S. organizations (i.e., Geothermal Energy Association, Bob Lawrence and Associates, Geothermal Resources Council) as soon as it became available (E-mail messages were sent on an irregular basis, varying between 1 and 10 per month).

Reports & Articles Published in FY 2002: Apart from the Merit Review Committee reports and e-mail messages mentioned under the section Status/Accomplishments, no reports/articles were published.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: LBNL personnel will participate in Merit Review Committee and issue proposal evaluation reports on DOE request. It is anticipated that one or more DOE-geothermal solicitations will be issued during FY 2003.

LBNL will continue to prepare short reports and e-mail messages on geothermal activities in the U.S. and abroad for distribution to DOE and U.S. organizations.

NOBLE GAS ISOTOPE GEOCHEMISTRY IN GEOTHERMAL SYSTEMS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

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DOE Funding Allocation: \$143.3K

Cost Share Funding: None

Project Objective: In support of the geothermal industry, provide noble gas abundances and isotopic compositions of fluids to (1) identify past and present heat and fluid sources, (2) provide sensitive natural tracers for monitoring the invasion of injectate fluids into production reservoirs, (3) study the transition from magmatic to geothermal production fluid, identify the source and fate of corrosive acidic fluids, (5) enhance reservoir simulation models by providing complementary information regarding fluid source and flow regime, and (6) develop new techniques for identifying hidden geothermal systems.

Background / Approach: To provide a significant increase in available electric power from geothermal resources will require (1) a more thorough understanding of known geothermal resources and (2) identification and development of new and innovative techniques for finding "hidden systems". Chemical characterization of soil gases and fluids associated with geothermal reservoirs is essential for locating and realizing optimum utilization of the resources. The isotopic composition of elements in fluids provide a quantitative measure of material balance, therefore isotopes are extremely powerful in unraveling fluid source, history and tracing fluid flow. Locating anomalous fluxes of magmatic or metamorphic gases (e.g., CO_2) through surface soil horizons, and identifying them as such, may provide a new exploration method for finding deeper hidden systems.

Status / Accomplishments: Task 1: Salton Sea Geothermal Field (SSGF): We completed the CalEnergy initiated program to establish a comprehensive database of reservoir fluid compositions as part of their mineral recovery program. We provided analyses of noble gas concentrations and isotopic compositions to (1) identify fluid sources and (2) trace and monitor injection fluids. Due to the high temperatures and salinities encountered at SSGF identifying a reliable tracer for re-injected production fluids has proven to be extremely difficult. The chemically inert noble gases may be the only viable tracer for injectate in this environment. The data has been transferred to CalEnergy. We will conduct future sampling as requested by CalEnergy as part of an ongoing monitoring program.

Task 2: Reassessment of geothermal potential in the western United States: Initially this task has concentrated on developing an extensive data base of the isotopic and elemental compositions of noble gases in fluids associated with known geothermal resource areas (KGRAs) through out the western United States. During FY 2002, the sampling emphasis was restricted to KGRA features in the Basin and Range of Nevada. Samples have been collected and analyzed from springs, seeps, wells, and fumaroles throughout the Basin and Range Province of Nevada. The data has been made available to researchers from University of Nevada, Reno, NV. We will continue our sampling campaign in FY 2003.

Task 3: Hidden geothermal systems: We concluded several feasibility studies into the identification of new potential exploration techniques for finding hidden geothermal systems. The initial phase of this task concentrated on the potential use of the fluxes of CO_2 and other volatile species through soil cover to identify the presence of deep geothermal systems that have no other surface manifestations (e.g., springs, fumaroles). This work was done in collaboration with other feasibility studies designed to (1) investigate the coupling of the LBNL geothermal simulator TOUGH2 with the LBNL sub-aerial gas flow simulator VarDen to evaluate the range of expected CO_2 (and other volatile species) concentrations expected in soil horizons overlying deeper source faults/reservoirs (see summary report for AOP 2.1.1.7 and 2.1.1.10), (2) evaluate the use of airborne EM and gravity for rapid resource evaluation (see summary report for AOP 2.1.1.8), and (3) investigate the use of satellite and other remotely obtained data as a geothermal exploration tool (see summary report for AOP 2.1.1.9). An additional project focused on the isotope geochemistry of springs associated with the Three Sisters Volcanic complex in southern Oregon which is a site of recent uplift as observed using INSAR data. Evidence that the uplift may be related to renewed volcanic activity was provided by elevated helium isotope compositions. Monitoring of this system continues.

Reports & Articles Published in FY 2002:

Christenson, B. W., E. K. Mroczek, B. M. Kennedy, T. van Soest, M. K. Steward, and G. Kyon, 2002, “Ohaaki reservoir chemistry: characteristics of an arc-type hydrothermal system in Taupo Vocabic Zone, New Zealand,” *Journal of Vocanology and Geothermal Research*, v.115, 53–82. LBNL #48570.

Evans, W. C., M. L. Sorey, B. M. Kennedy, D. A. Stonestrom, J. D. Rogie, D. L. Shuster, 2001, “High CO_2 emissions through porous media: transport mechanisms and implications for flux measurement and fractionation, *Chemical Geology*, V177, 15–29. LBNL #46482.

Evans, W. C., M. L. Sorey, A. C. Cook, B. M. Kennedy, D. L. Shuster, E. M. Colvard, L. D. White, and M. A. Huebner, 2002, “Tracing and quantifying magmatic carbon discharge in cold groundwaters: lessons learned from Mammoth Mountain, USA,” *Journal of Volcanology and Geothermal Research*, v. 114, 291–312. LBNL #50610.

Evans, W. C., R. H. Mariner, S. E. Ingebritsen, B. M. Kennedy, M. C. van Soest, and M. A. Huebner, 2002, “Report of hydrologic investigations in the Three Sisters area of central Oregon,” Summer 2001. USGS Water-Resources Investigation Paper, 02–4061, 2002.

Presentations Made in FY 2002:

Kennedy, B. M., 2002, "Noble gas isotope geochemistry at the Dixie Valley Geothermal Field," presented at the *Workshop on Dixie Valley Geothermal Research, University of Nevada, Reno, June 12–13, 2002.*

van Soest, M. C., B. M. Kennedy, W. C. Evans, R. H. Mariner, and M. Schmidt, 2002, "Helium and Carbon Isotope Systematics of Springs in the Separation Creek Drainage System, Three Sisters area, Central Oregon Cascades," *Trans. Am Geophys*, Un., Fall Meeting, Dec., 2002.

van Soest, M. C., B. M. Kennedy, W. C. Evans, and R. H. Mariner, 2002, "Mantle helium and carbon isotopes in Separation Creek geothermal springs, Three Sisters Area, Central Oregon: evidence for renewed volcanic activity or a long term steady state system," *Trans. Geothermal Res. Council*, Reno, NV, Sep., 2002.

Shevenell, L., L. Garside, G. Arehart, M. van Soest, and B. M. Kennedy, 2002, "Geochemical sampling of thermal and nonthermal waters in Nevada to evaluate the potential for resource utilization," *Trans. Geothermal Res. Council*, Reno, NV, Sep., 2002.

Planned FY 2003 Milestones:

(1) Continue mapping helium isotopic compositions throughout the Basin and Range Province as part of the DOE effort to re-evaluate the geothermal potential of the western United States.

(2) Initiate an Enhanced Geothermal Systems program at LBNL and within DOE. Isotope techniques are expected to play an important role in monitoring geochemical and hydrodynamic process to insure that injection strategies provide optimum production of hot fluids in an engineered system.

ELECTROMAGNETIC METHODS
FOR GEOTHERMAL EXPLORATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $43K

Cost Share Funding: Direct funding of $ 35 K from Electromagnetic Instruments, Inc. (EMI)

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 instruments used for borehole EM surveys in geothermal fields. Initial 3-D inversion work conducted in FY 2002 is an extension of 2-D inversion work completed in FY 2001.

Background / Approach: Inversion study in 2-D (Lee et al, 2002) has been further extended to include 3-D problems. For 2-D problems, direct application of the extended Born, or localized nonlinear approximation (Habashy et al., 1996) of integral equation solution has been successful because of the cylindrical symmetry. For 3-D problems, the Habashy algorithm cannot be directly used because of the discontinuity in EM fields. So, the algorithm has been further modified to partially account for the discontinuity, resulting in the modified extended Born approximation (MEBA, Tseng et al., 2002). The MEBA is less accurate than a full integral equation solution but superior to the conventional Born approximation. The resulting inversion algorithm based on the MEBA modeling scheme is simple enough to be implemented on PCs.

Status / Accomplishments: To begin, the inversion algorithm based on MEBA modeling scheme has been tested using a synthetic data generated from a thin horizontal conductor embedded in an otherwise homogeneous earth. We chose a 3-D inversion model consisting of 49×49×40 cells (24×24×20 m) for the inversion. It took six iterations and about six hours of CP time to achieve a convergence. Twelve transmitters at a frequency of 6 kHz were involved and two receiver positions with constant vertical offsets of 2 and 5 m were located below each transmitter. All three orthogonal components of the magnetic fields were used for the inversion.

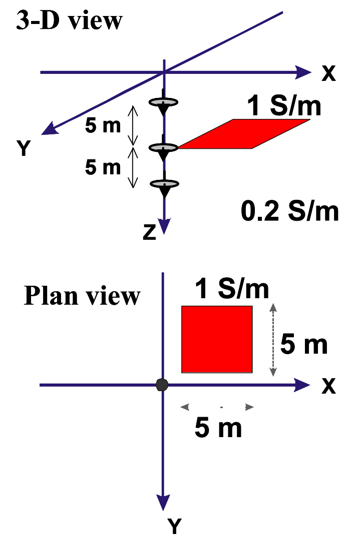

Figure 1a. A thin conductor simulating a horizontal fracture.

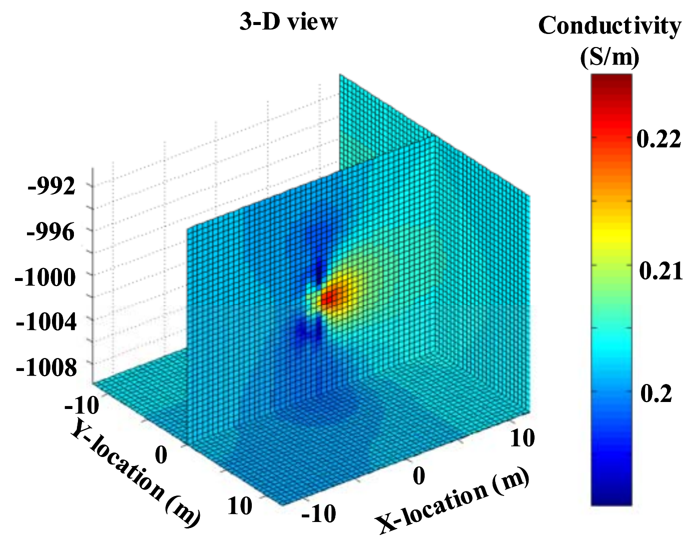

Figure 1b. 3-D view of the inverted conductivity imaging. Data used for the inversion was obtained from model in Fig. 1a.

References:

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

Lee, K. H., H. J. Kim, and M. Wilt, 2002, "Efficient imaging of single-hole electromagnetic data," *GRC Transactions*, 26, Geothermal Energy – The Baseload Renewable Resource, 399–404.

Tseng, H. W., K. H. Lee, and A. Becker, 2002, "Three-dimensional interpretation of electromagnetic data using a modified extended Born approximation," *Geophysics*, in press.

Reports & Articles Published in FY 2002:

Lee, K. H., H. J. Kim, and M. Wilt, 2002, "Efficient imaging of single-hole electromagnetic data," *GRC Transactions*, 26, Geothermal Energy – The Baseload Renewable Resource, 399–404.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones:

Acquire 3-D data from field tests jointly conducted by EMI and LLNL	Mar 03
Analyze data using the 3-D inversion code	May 03
Present paper at GRC2003	Sep 03

RAPID RESOURCE EVALUATION VIA AIRBORNE EM & GRAVITY PRINCIPAL COMPONENT ANALYSIS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $43.3K

Cost Share Funding: None

Project Objective: Techniques for rapid evaluation of large amounts of airborne electromagnetic (EM) data have been developed in the mineral exploration industry, which allow interpreters to evaluate and high-grade thousands of line-miles of airborne EM data quickly. These techniques rely on decomposing the transient EM response into principal components (eigen vector analysis) and making color assignments (red, green, blue) to the top three components. A correlation analysis is preformed over known mineral deposits between the color-coded data displays and the presence or absence of mineralization. With the data thus calibrated large amounts of data can be quickly scanned and high-graded for follow-up on-the-ground analysis.

Background / Approach: We proposed to adapt and extend this technique to geothermal resource evaluation. Gravity and gravity gradients provide additional data components that can be simultaneously gathered with airborne EM with little additional cost. This additional data can be combined with the transient EM response and subjected to principal component analysis. We proposed to develop the necessary algorithms and test them on existing data sets as well as realistic 3D numerical models.

Status / Accomplishments: In FY 2002 we conducted a feasibility study for evaluating rapid analysis methods with application to geothermal exploration. Techniques for rapid evaluation of large amounts of airborne Electromagnetic (EM) data have been developed in the mineral exploration industry, which allow interpreters to quickly evaluate hundreds of line-miles of airborne EM data. One of such promising techniques relies on decomposing the transient EM response into a series of exponential time functions.

Each of these exponential functions is characterized by its amplitude and time constant that carry information about the electrical property of the target under investigation. In analyzing airborne EM data, Stoltz and Macnae (1998) proposed an efficient numerical method using singular value decomposition (SVD) technique. We propose to investigate application of the SVD approach with geothermal fields as potential target. Large amount of data can be quickly analyzed and high-graded for follow-up on-the-ground analysis using other methods.

To begin, the proposed analysis method will be tested using data generated by 2-D and/or 3-D time-domain EM modeling codes available at LBNL. The study will be focused on correlating a potential geothermal target and SVD decomposed amplitudes and its singular values.

References:

Stoltz, E.M, and J. Macnae, 1998, "Evaluating EM waveforms by singular-value decomposition of exponential basis functions," *Geophysics*, 63, 64–74.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: Project terminated at end of FY 2002.

FIELD CASE STUDIES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $93K

Cost Share Funding: In kind (access to field data)

Project Objective: The goal of this task is to analyze field data and document the results of exploration, evaluation, and development activities carried out in geothermal areas by private and government organizations. The information will be useful to evaluate exploration and development efforts and to identify new approaches to assess and exploit U.S. geothermal resources. In addition, the results of this work should help the U.S. geothermal industry in their efforts to optimize operations and reduce related costs.

Background / Approach: A wealth of information on the characteristics and operational history of geothermal fields is becoming available in the open-file technical literature. However, there is a large amount of data that can only be acquired through collaborative projects or studies with the organizations operating the fields. This has led to informal agreements between these organizations and groups funded by the DOE Geothermal Program to jointly analyze existing data sets or to carry out field activities to obtain additional data.

LBNL continued collaborative studies with geothermal organizations analyzing exploration and developmental data from high-temperature geothermal fields under production. One of the main objectives of these activities was to obtain actual field data to use in fundamental studies of geothermal systems; and in the evaluation of reservoir management schemes.

Status / Accomplishments: The analysis of the behavior of the Cerro Prieto geothermal reservoir, where 720 MW of installed electrical generation capacity are already in place, has essentially been completed. In the future, this analysis might be extended as new production and monitoring data becomes available. A paper was prepared describing the effects of processes that resulted from lowering reservoir pressures in response to the large-scale commercial exploitation of the field. The impacts of injection and natural groundwater recharge on the physical and chemical properties of the produced geothermal fluids were also studied.

Reports & Articles Published in FY 2002:

Lippmann, M. J., A. H. Truesdell, A. H. Rodríguez, and A. Pérez, 2002, “Response of Cerro Prieto II and III to Exploitation,” Paper submitted to *Geothermics* (also report LBNL-51748).

Lippmann, M., 2002, “Geothermal and the Electricity Market in Central America,” *Geothermal Resources Council Trans.,* 26, 37–42 (also report LBNL-50931).

Presentations Made in FY 2002:

Geothermal and the Electricity Market in Central America. Oral presentation made during the Geothermal Resources Council 2002 Annual Meeting, September 22–25, 2002, Reno, Nevada.

Planned FY 2003 Milestones:

Technical paper on results of the study of a geothermal field (possibly the Coso geothermal field of eastern California) will be presented at the GRC Annual Meeting	Sept 03
LBNL report with an up-to-date data compilation and discussion	Sept 03

SIMULATION OF COUPLED SUBSURFACE AND SUBAERIAL CO_2 GAS EMISSIONS FOR DESIGN OF INSTRUMENTATION AND SURVEY STRATEGIES FOR LOCATING HIDDEN GEOTHERMAL SYSTEMS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Earth Sciences Division
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DOE Funding Allocation: $28K

Cost Share Funding: None

Project Objective: The objective of this research is to couple the LBNL geothermal simulator TOUGH2 with the LBNL subaerial gas flow simulator VarDen and apply the new capability to simulate expected gas emissions from hidden geothermal systems. TOUGH2 uses an extended Darcy's Law for subsurface flow and transport of variable density gases and liquids. VarDen uses full Navier-Stokes equations for modeling density-dependent gas-phase flow. Coupling of these codes will require interface protocols at the ground surface boundary between the TOUGH2 and VarDen model domains. These protocols will be a function of spatial and temporal information that may vary throughout the solution domain and in time. A test problem will be developed on which the new capability will be demonstrated. Next we will apply the coupled TOUGH2-VarDen code to the problem of determining expected CO_2 concentrations in the subaerial environment above hidden geothermal systems. A range of meteorological conditions and typical topographic surfaces will be tested along with various emission rates and styles. For example, emissions may be diffuse through surface sediments or they may occur in a more focused form through a fault or spring. The flow and mixing of these emissions will be modeled in detail over a range of meteorological conditions. These simulation results can then be used to design instrumentation and sampling strategies for use in exploration for hidden geothermal systems.

Background / Approach: The detection and mapping of elevated concentrations of CO_2 may be useful for locating hidden geothermal systems. However, the range of expected CO_2 gas concentrations in the subaerial environment arising from hidden geothermal systems is not known. Flow and mixing processes in both the subsurface and subaerial environments will tend to dilute CO_2, but can also lead to isolated areas of high concentration as, for example, in calm topographic lows where dense CO_2 can accumulate. In order to design and develop instrumentation and gas sampling and surveying strategies, some knowledge of the expected concentrations of CO_2 must be developed. Simulation capabilities currently exist to model in detail subsurface and subaerial density-dependent flow and transport of CO_2 over variable topography under the influence of actual meteorologic data. Still needed is a coupled simulation capability that will model concentration changes from the top of the geothermal system to the subaerial environment where instrumentation and gas surveys will need to be carried out over large areas.

Status / Accomplishments: We installed and learned to use VarDen for some simple test problems. During this effort we determined that VarDen would not be an appropriate tool for the objective of modeling dilute CO_2 plumes over large distances. Instead we are developing an approach entirely within TOUGH2.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: No milestones planned for this project in FY 2003. Funding for the coupled subsurface-subaerial model development will come from internal sources through an LDRD project. It is possible that we will be able to use this capability in future studies of hidden geothermal systems.

GEOCHEMICAL BASELINE STUDY OF THE NORTHWESTERN GEYSERS AREA

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

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DOE Funding Allocation: $23K

Cost Share Funding: None

Project Objective: The objective of the study is to develop baseline data on the geochemistry of steam that is being produced from the NW Geysers (Aidlin area) before Santa Rosa waste waters are injected into the vapor-dominated reservoir. This area is unique in The Geysers because it produces steam entirely from the deeper, higher temperature reservoir and has done so since 1989–1990.

Background / Approach: The Geysers field in Northern California has declined sharply in production from more than 1,800 MW in the late 1980s, to about 1,000 MW at present. Although some plants were dismantled, about 500 MW of installed capacity are not being used. In order to maintain and increase production, treated wastewater is being pumped to the field, some from the Clear Lake area (the SEGEP project, started in 1997) and more from the Santa Rosa area (expected to start in 2002). Optimal use of this imported water requires understanding the behavior of a vapor-dominated reservoir when the volume of injected water is substantially increased. Earlier we studied the NCPA field in the SE Geysers which received much of the SEGEP water (Truesdell et al., 2001). We found that before the introduction of local surface water and importation of SEGEP water, some wells showed progressive dewatering with decline in steam flow and an apparent increase in the depth of production. With increased injection, the rate of decline was greatly slowed and the depth of production decreased indicating that the reservoir was partially recovering its water contents. The NCPA reservoir is relatively low temperature (originally ~235ºC) and its steam has low gas and essentially no chloride.

The steam reservoir in the northern Geysers, which will receive most of the Santa Rosa wastewater, is very different than that in the NCPA area. Most of the northern reservoir is very high in gas (20,000 to 100,000 ppmw) and many wells produce steam with corrosive HCl. In the northern Geysers, the Unit 15, Bottle Rock and CCPA fields were abandoned because they increasingly produced high-chloride, corrosive steam along with high gas. Some parts of the central Geysers are starting to produce similar fluids. This behavior is thought to result from increasing production from a deeper, higher-temperature reservoir as liquid water contained in the overlying normal reservoir is progressively exhausted.

The injection of Santa Rosa wastewaters has the potential to alleviate the gas and corrosion problems, but there have been no realistic field or laboratory studies to support this assumption. The availability of baseline geochemistry data on the steam produced from NW Geysers wells before the Santa Rosa pipeline begins operation will allow the evaluation of the impact of wastewater injection on steam chemistry. The study proposed was begun in late FY 2001 because of a delay in obtaining data.

This work is performed collaboratively with Joe Beall of Calpine Corp. Calpine has agreed to supply their data on steam chemical and isotopic compositions as well as data on flows and enthalpy. These data will be analyzed to better understand the properties of the high-temperature reservoir fluids with limited injection. Marcelo Lippmann (LBNL) will interpret the existing reservoir data and Mack Kennedy (LBNL) will analyze noble gas isotopes on samples collected in 1997 and on new samples to be collected in 2002. These analyses will compliment noble gas isotope data from the nearby CCPA Geysers Coldwater Creek field, which was studied earlier and showed magma-derived fluids. Data on other wells drilled into the high-temperature reservoir will be included as available. The proposed study will be useful to follow changes that occur from the increased volume of injection water delivered to The Geysers by the Santa Rosa pipeline project.

Status / Accomplishments: In collaboration with Thermochem, a suite of samples were collected for noble gas and other isotope studies from selected wells in the NW Geysers that are affected by HTR steam along with samples from the SE Geysers for comparison. A representative sample suite of samples was also collected from the Ottoboni Ridge area. These collections were made in conjunction with the normal Thermochem mid-summer, full-field sampling. In late summer, we obtained samples for noble gas and other isotope analyses from wells in the Aidlin portion of the NW Geysers. All samples collected will be analyzed for noble gas and gas isotope ($\delta^{13}C$ in CO_2 and CH_4, possibly δD in CH_4 and H_2). A total of twenty-one samples were collected for this project. Archived information on fluid/gas chemistry and production histories of the sampled regions have been obtained from Calpine.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: During FY 2003, all collected samples will be analyzed. This portion of the project has been delayed due to a delay in the field-wide sampling campaign and the need for well workover to be completed in the Aidlin Field. As analyses become available, data and preliminary interpretations will be provided to Calpine. With their approval, the preliminary results will be presented at the 2003 meeting of the Geothermal Resources Council.

IMAGING GEOTHERMAL RESERVOIR DYNAMICS USING HIGH RESOLUTION OBSERVATIONS OF SURFACE DEFORMATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Earth Sciences Division
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DOE Funding Allocation: $43K

Cost Share Funding: None

Project Objective: Our objective is to develop and examine techniques utilizing observations of surface deformation to image reservoir dynamics associated with geothermal production. These methods will be important for enhancing field development, (for example for identifying faults controlling fluid flow) and production optimization.

Background / Approach: Geothermal production involves mass and heat transfers accompanied by changes in fluid pressure within the reservoir as hot fluids are pumped out and cooler fluids are injected in. These flow processes cause stress and temperature changes within the host rock, through poroelastic coupling and by thermal expansion and contraction as parts of the reservoir are heated and cooled. Geodetic surveys at several geothermal fields have shown that the resulting deformation is often measurable at the Earth's surface. Satellite observations, such as Interferometric Synthetic Aperture Radar (InSAR) provide dense spatial sampling, while instruments such as borehole tiltmeters provide dense temporal sampling. Our approach will be to combine the high resolution provided by integrated sets of InSAR, Global Positioning System (GPS), leveling, and tilt observations. We will use selected geothermal fields as case studies. The images of deformation enable us to better constrain models of the underlying reservoir dynamics. Particular geothermal fields include Dixie Valley, Coso, and possibly

Long Valley. In addition, it may be possible to monitor reservoir dynamics at the Geysers using GPS observations. This work is in collaboration with investigators at Lawrence Livermore National Laboratory (Bill Foxall, Paul Kasameyer).

Status / Accomplishments: We have developed and tested software for utilizing surface tilt, leveling, GPS, and InSAR observations. The methodology was used to analyze tilt and leveling observations from a geothermal site in Okuaizu, Japan. Based upon transient surface motions we were able to image fluid migration along fault zones in the geothermal field. The results were published in the journal *Geothermics* this year. In addition we have examined InSAR observations from the Coso geothermal field (Figure 1). These data were used to examine volume changes in the geothermal reservoir associated with production as well as deeper volume changes below the geothermal field proper. These results were published in the Geophysical Journal International this year. Currently, we are examining InSAR observations from the Dixie Valley geothermal field (Figure 2). We are able to image volume change associated with geothermal production (Figure 3). The volume change must extend to depths of less than 1 km in order to satisfy the InSAR range change data. Work on Dixie Valley will continue in FY 2003 and we shall interpret the preliminary results in more detail.

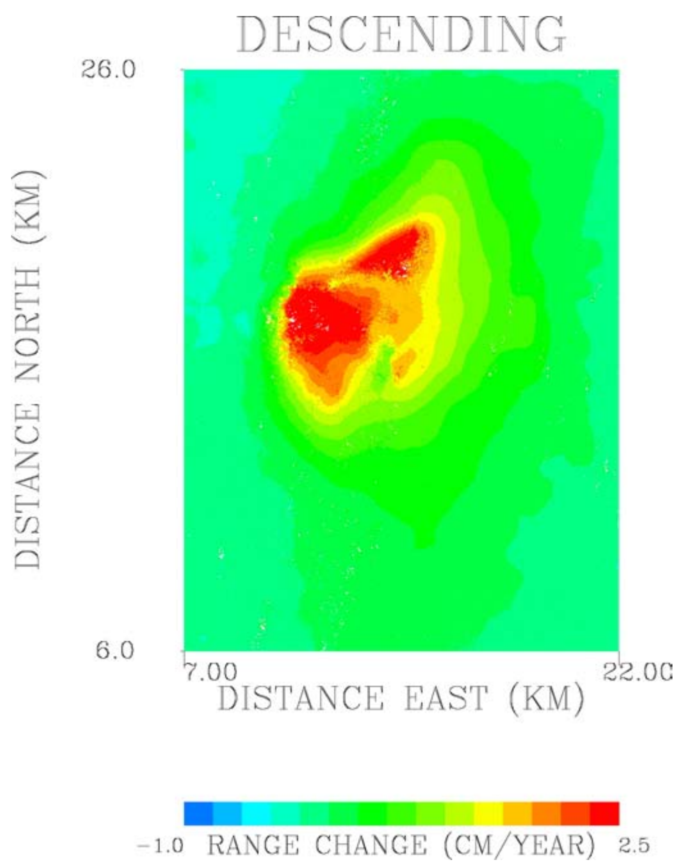

Figure 1. InSAR range change observations from the Coso geothermal field.

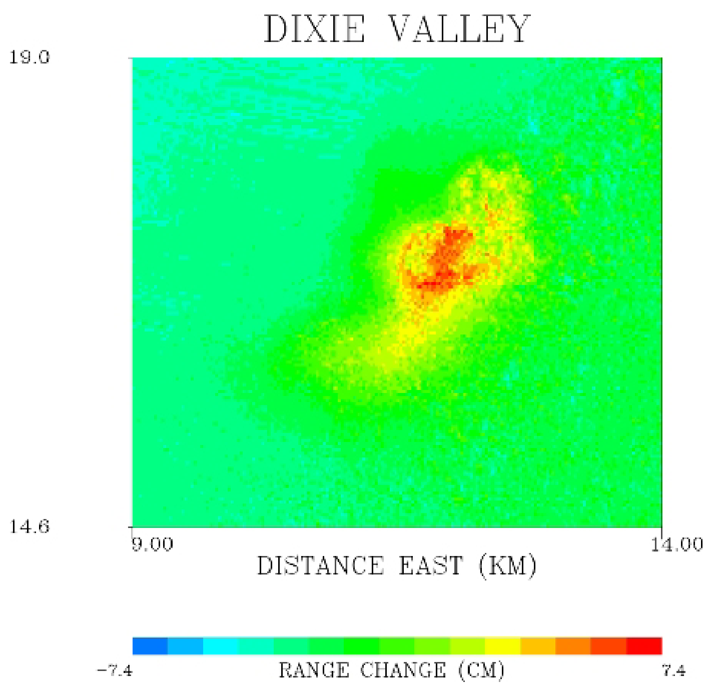

Figure 2. InSAR range change observations from the Dixie Valley geothermal field.

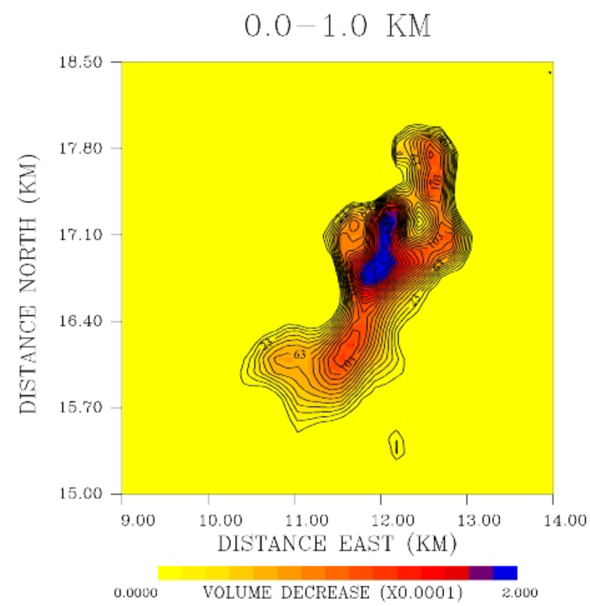

Figure 3. Subsurface volume change compatible with the InSAR observations from the Dixie Valley geothermal field.

Reports & Articles Published in FY 2002:

Vasco, D. W., K. Karasaki, and O. Nakagome, 2002, "Monitoring production using surface deformation: the Hijiori test site and the Okuaizu geothermal field, Japan," *Geothermics*, 31, 303–342.

Vasco, D. W., C. Wicks, K. Karasaki, and O. Marques, 2002, "Geodetic imaging: reservoir monitoring using satellite interferometry," *Geophys., J. Int.*, 149, 555–571.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: None.

(1) Software routines for the imaging of geothermal reservoir dynamics, based upon InSAR, GPS, leveling, and tilt data; Tests with sets of synthetic deformation values – 08/2003

(2) Application to Dixie Valley and Coso – 12/2004.

INVESTIGATION AND DEVELOPMENT OF INNOVATIVE GEOTHERMAL EXPLORATION TECHNIQUES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	
Performing Organization:	Earth Sciences Division Lawrence Berkeley National Laboratory 1 Cyclotron Rd. Berkeley, CA 94720
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DOE Funding Allocation:	$28K
Cost Share Funding:	None

Project Objective: In general, the primary objective is to develop new techniques for finding hidden geothermal systems and assisting industry in their development. Specific objectives include: development of new geochemical and isotopic techniques capable of indicating the presence of "hidden" hydrothermal systems that do not have surface manifestations. Development of new methods that can be used to delineate the presence of subsurface temperature anomalies associated with fluid and permeability and that can improve identification of productive and non-productive systems. The development of better numerical simulation techniques that take full advantage of the geochemical, geophysical and geologic information needed to model the flow of fluid and heat in fractured reservoirs and overlying horizons. The development of improved geophysical tools that can monitor movement of fluid within reservoirs to optimize the efficiency of reservoir management. This project provides technical support in development of innovative exploration technologies.

Background / Approach: To assist the geothermal industry in finding and operating geothermal fields we must develop (1) a more thorough understanding of known geothermal resources and (2) new innovative techniques for finding "hidden" geothermal systems. The project will take an integrated approach by calling on geophysical, geochemical, geologic, and remote sensing techniques as potential tools for expanding exploration capabilities for U.S. geothermal industries.

Status / Accomplishments: The project will oversee the integration and progress of several projects aimed at evaluating and applying new exploration techniques. Separate Summary Reports are provided for each project and each project is listed below.

- Combined airborne electromagnetic and gravity principal component analysis for rapid resource detection. See Summary Report for Project 2.1.1.8

- Imaging geothermal reservoir dynamics using high-resolution satellite observations. See Summary Report for Project 2.1.1.9

- Fluid flow through soil horizons. See Summary Report for Project 2.1.1.10

- Isotope geochemistry applied to locating and characterizing “non-conventional” surface manifestations of hidden geothermal systems. See Summary Report for Project 2.1.1.5.

Reports & Articles Published in FY 2002: See appropriate Summary Reports.

Presentations Made in FY 2002: See appropriate Summary Reports

Planned FY 2003 Milestones: We will continue to investigate high-resolution satellite observations for monitoring geothermal reservoir dynamics. See milestones listed in summary report for project 2.1.1.9.

We will continue isotopic characterization of springs, wells, seeps, and fumaroles throughout the Basin and Range Province and selected areas of the Cascade Ranges in the western United States.

This project will also provide funding to initiate Enhanced Geothermal Systems program at LBNL and within DOE. Planned work includes isotopic studies in support of the EGS projects at the Coso, Raft River, and Medicine Lake Geothermal Fields.

3-D MAGNETOTELLURIC MODELING AND INVERSION FOR GEOTHERMAL RESOURCE EVALUATION AND DELINEATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	DE-AC04-94AL85000
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DOE Funding Allocation:	$107K
Cost Share Funding:	$200K from GSY-USA, Cumming Geoscience, LBNL, EMI, UC, USGS

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

Background / Approach: Electrical and electromagnetic (EM) methods are currently used in geothermal exploration to detect subsurface resistivity patterns that indicate geothermal resources. Of the EM methods, the magnetotelluric (MT) method is the most effective and commonly used tool used in geothermal exploration and is finding increasing application in development. By mapping the geometry of the 200 to 2000m thick, conductive argillic alteration that normally lies over and adjacent to high temperature geothermal systems, MT is used to target wells and assess reservoir generation capacity.

Despite recent significant progress in EM data collection and processing, significant issues regarding MT data interpretation still act as barriers to routine use by the geothermal industry. Development of standard data sets to act as test beds for imaging schemes will provide the needed standards for testing MT interpretation. This type of synthetic data set has proved invaluable for the interpretation of 2D, and now 3D, seismic methods used in the petroleum industry. Sandia is participating in a large-scale, collaborative 3D MT modeling study, similar in concept to the recent synthetic reflection seismic 3D SEG/EAGE Modeling Project (collaborative between DOE and the petroleum industry). Consulting and industry partners are providing their own funding for the project. Sandia has already developed the massively parallel 3D EM finite difference modeling and inversion codes that will be applied in the project for large-scale 3D MT simulations, and has access to the required high-end computational resources needed to complete the data simulation phase of the project (Newman and Alumbaugh, 2000; Newman et al., 2002a and 2002b).

The field data component of the project comprises a feasibility study to evaluate using magnetotelluric (MT) data to image in 3D the volcanic East Rift Zone and deeper magma chambers on the Kilauea volcano in Hawaii. In collaboration with other institutions (Lawrence Berkeley [LBNL], University of California [UC], United States Geological Survey [USGS], and Electromagnetic Instruments Inc.[EMI]) a state-of-the-art 3D MT survey was carried out over the Kilauea volcano in 2002 (Hoversten et al., 2002). Sandia has participated in the field survey and will provide virtually unlimited time on SNL massively parallel computer systems for 3D data interpretation and modeling in close collaboration with LBNL. The successful 3D interpretation of the Kilauea field data set will push the envelope of large-scale 3D magnetotelluric and inverse modeling forward in the presence of rugged topography and coastal effects.

Status / Accomplishments: In the first year of the project (FY 2002), we initiated the realistic MT data simulation effort by generating several 3D synthetic data sets of geothermal resource targets in complex volcanic terrains. The above-mentioned data sets were generated from geothermal reservoir models provided by our industrial partners (Figure 1). The 3D volcanic models reflect the resistivity geometry typical of a distributed permeability, 230–330^{0}C geothermal reservoir beneath an andesitic-silicic volcanic massif, like Medicine Lake, California. The simulations clearly demonstrate the complex 3D character in the apparent resistivity and phase responses, which clearly cannot be interpreted using 2D data interpretation schemes (Figure 2).

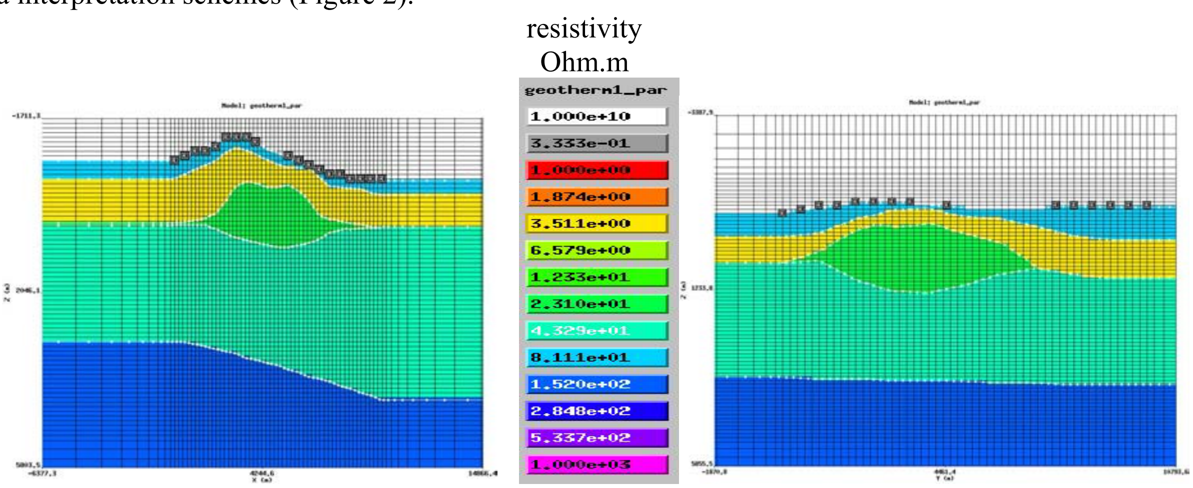

Figure 1. The 3D volcanic model (illustrated in two perpendicular cross-sections; top y=5 km and bottom x=5 km) of a distributed permeability, 230–330^{0}C geothermal reservoir beneath an andesitic-silicic volcanic massif, like Medicine Lake, California. The model was simulated using 252 nodes, and comprises approximately 1 million cells.

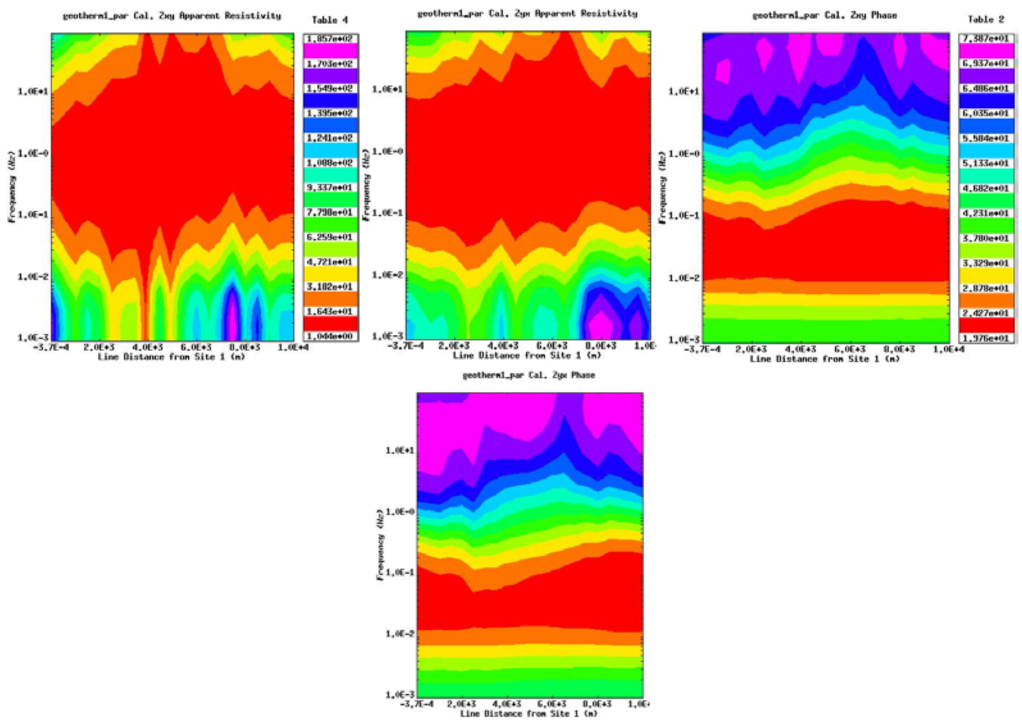

Figure 2. Pseudosections of apparent resistivity (left panels) and phase (right panels) are illustrated along the x-z model cross-section (y=5 km) shown in Figure 1. The simulated data show the phase response at the lowest frequencies approach limiting values of 45 and –135 degrees, indicating sensitivity to only the deepest model structure, comprising a 300 Ω.m basal half-space. On the other hand the apparent resitivity pseudosections indicate static shift effects are present at the lowest frequencies. In the high to mid frequency band topography and reservoir affect both the apparent resistivity and phase responses.

Three-dimensional MT modeling has also been conducted to access the effects of the land-ocean contact on the MT Kilauea data set. The land-ocean interface produces distortions on MT data due to the distortions of the electric currents flowing in the highly conductive ocean when they encounter the resistive land. Based on rigorous 3D modeling of the entire island we were able to determine that these effects became significant below 100 seconds period (Figure 3). Therefore, initial modeling of the field data set carried out by our collaborators employed two-dimensional inversion codes, where we chose to limit the frequency range to 100 Hz to 100 sec (Hoversten et al., 2002). This has the practical effect of limiting our depth of investigation to between 5 and 10 km, depending on the intervening conductivity. The full frequency range of the data will be used in the three-dimensional modeling to come and will translate to a 20 km depth of investigation for fully 3D data.

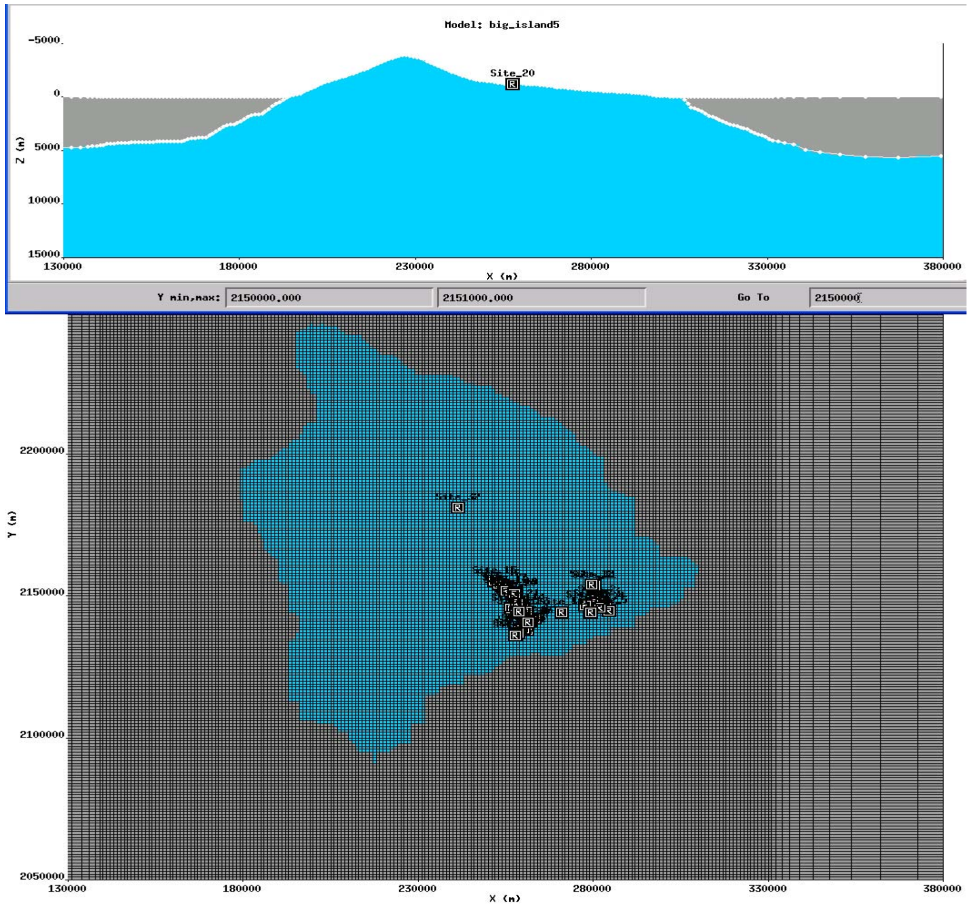

Figure 3. Full scale 3D numerical model of the entire island of Hawaii and surrounding sea floor. The model comprises over 14 million cells. Results below show that the 3D topography and coastal effects depart from 2D below 100 seconds This model was simulated using 512 processors on Sandia National Laboratories Ascii-Red and brings a level of numerical complexity to geothermal system models that have not previously been possible.

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

Presentations Made in FY 2002:

Hoversten, G. M., E. Gasperikova, G. Newman, and J. Kauahikaua, "Magnetotelluric Investigations of the Kilauea Volcano, Hawaii," AGU Fall Meeting, San Francisco, CA.

Planned FY 2003 Milestones:

Realistic 3D MT data simulation project	(I)	Apr 03
Improvements in 3D MT modeling and Inversion software	(I)	Mar 03
3D inversion of the Kilauea MT data set	(I)	Sep 03
3D inversion of realistic synthetic field data sets	(I)	Sep 03

References:

Newman, G. A., and D. L. Alumbaugh, 2000, "Three-dimensional magnetotelluric inversion using nonlinear conjugate gradients," *Geophys. J. Int.*, 140, 410–424.

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

Newman, G. A., S. Recher, B. Tezkan, and F. Neubauer, 2002b, "Three dimensional inversion of a scalar radio magnetotelluric field data set," *Geophysics*, (in press).

Hoversten, G. M., E. Gasperikova, G. Newman, and J. Kauahikaua, 2002, "Magnetotelluric Investigations of the Kilauea Volcano, Hawaii," AGU Fall Meeting Abstracts, San Francisco, CA.

DRILLING

HIGH-TEMPERATURE ELECTRONICS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	DE-AC04-94AL85000
Performing Organization:	Sandia National Laboratories Geothermal Research Department MS 1033, P.O. Box 5800 Albuquerque, NM 87185-1033
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Collaborating Researchers:	None
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DOE Funding Allocation:	$600K
Cost Share Funding:	$50K

Project Objective: The project objective is to seed the geothermal industry with high-temperature electronics and designs to alter the way the geothermal industry does exploration, drilling, power production and reservoir maintenance. This activity brings oil and gas technology to the geothermal industry by removing the temperature barrier. The results of this work will be a 50 to 75 percent cost saving in exploration costs and long-term reservoir maintenance.

The first activity is to break down the drilling and logging industries perception of what can be accomplished at temperatures above 200°C. To this end, Sandia developed and demonstrated new high-temperature geothermal SOI (silicon-on-insulator) electronics. Sandia is providing designs and software to seed the industry and created a new self-sustaining industry capability. The three principal objectives in FY 2002 are:

1. to further demonstrate SOI by actually logging in geothermal wells without any heat-shield and staying within those wells longer than any instrument has done before
2. to make this development commercially available to the geothermal industry by providing Honeywell with the rights to sell the technology
3. to provide samples and design instructions to all geothermal service companies so they can begin their own in-house development programs

Background / Approach: In FY 2001, Sandia developed an SOI IC to enable the design of a pressure/temperature tool. This device has been named the HT83SNL00. In FY 2001, Sandia tested this device and found it completely functional and an SOI demonstration tool was built. Sandia's approach is to test this SOI tool and provide the industry with:

1. a complete SOI base design
2. a complete low temperature development prototype for plugging into their PC to enable learning
3. a set of programming examples to speed software development.

The above activities directly involve geothermal service companies. However, building a viable industry requires reaching out to other industries for sustainable infrastructure support. By focusing on the inherent long life of high-temperature geothermal electronics, Sandia can encourage the use of geothermal electronics in other industries.

Status / Accomplishments: To date, we don't know of a single service company or drilling company that is not watching advancements in high-temperature electronics. Most companies like this have active high-temperature tool development programs. Even in Europe, the direction has changed from bulk silicon to SOI component development for drilling and logging applications. Much of the "new" private sector work would not have started if Sandia had not produced an SOI logging tool. This one tool helped to change the industry's perception of what is possible at higher temperatures.

Task 1 — First Geothermal Log Ever Built NOT Requiring a Heat Shield

At the end of FY 2001, we had a working HT83SNL00 chip. This chip was designed to be the heart of a complete high-temperature geothermal tool. With the addition of the HT83SNL00 chip, we were able to design and build a prototype pressure-temperature (PT) tool capable of sustained operation at 250°C. The tool was designed to acquire not only the wellbore pressure and temperature but also 8 additional analog measurements and two frequency measurements. These additional measurements help to characterize the tool's performance. The electronic design includes the capability of adding additional sensors such as a spinner, when they are desired. By November of 2001, this PT tool was built, oven tested, and was ready for field deployment. The tool was used to successfully log three geothermal wells ranging in temperature from 204 to 240°C. In each case, the tool remained downhole for 30 to 40 hours. When we returned from the field tests, additional long-term oven tests were initiated to help establish a baseline for determining tool life at sustained high temperatures. To date, the tool has been operating in the oven for approximately 1,200 hours at 225°C and more than 600 hours at 250°C without failure. The data from one of the wells that was logged is shown in Figure 1. The tool is shown in Figure 2.

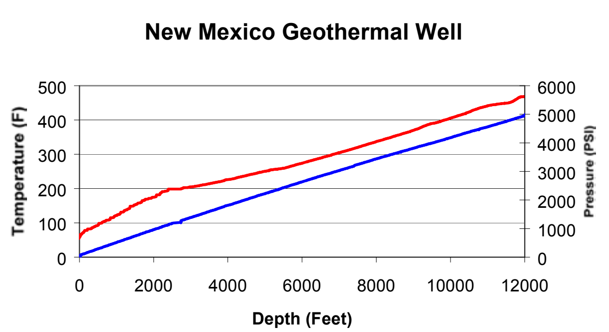

Figure 1. 240°C well log data.

Other areas that required further research were potting compounds, printed circuit (PC) board materials, solders and fluxes. Sandia is aware of these issues and is presently researching other methods of lead attachments including improved solder and fluxes. Currently available high temperature solder is difficult to use, resulting in less than ideal electrical properties. This shortcoming is recognized by the industry and advances in this area will increase the reliability of high temperature tools.

Field-testing the SOI based pressure/ temperature tool revealed the need to further test resistors. The tool was initially tested and calibrated in an environmental chamber with favorable results. During field-tests, a long-term calibration shift appeared over time. It was determined that hydrogen present in the wells was having an adverse effect on the resistors used in the tool. Additional testing determined that wire wound resistors will tolerate hydrogen and are now being utilized in the second tool design.

Figure 2. Photo of SOI tool electronics.

Sandia has continued to test capacitors, which are the weakest link in tool reliability. Several manufacturers have sent Sandia test samples hoping Sandia will use them in our tool design. Sandia is the only organization willing to publish their high-temperature tool designs. Service companies protect their component lists. By making our components available we are helping both component manufacturers as well as ALL service companies.

Working within Sandia weapon programs, we have gotten weapon SOI repackaged for very high geothermal temperatures. Testing of these parts was initiated in FY 2002 and assuming they pass, a new list of SOI components could became available to the U.S. geothermal industry.

Task 2 — Industry Interactions

Sandia has offered this technology to all known geothermal service companies and companies willing to sell electronics/tools in the geothermal market. Sandia is now working with several geothermal service companies (Pruett and Welaco) to design and build high temperature tools based on SOI technology. We are also working with tool suppliers (PhotoSonic and E-Spectrum). In addition, we provided the complete design to four additional companies and provided component details to the larger oil and natural gas service companies. Honeywell will need a larger market than the geothermal industry to justify their product line.

By providing this technology to a large number of private companies and helping those companies design new tools, we are seeding the industry such that a dollar of DOE funding is multiplied many times.

Task 3 — Industry Workshop

An industry workshop was held, June 3, 2002. The workshop was titled, "Making HT Electronics Commercially Viable in Support of the Geothermal Wellbore, +200° Celsius." A number of geothermal service companies attended along with Honeywell, Schlumberger, and the USAF. Again, we are building support for geothermal electronics. The workshop identified the following three critical needs for moving forward.

1. List the SOI electronic components needed by industry, ranked by priority. A SOI FPGA (Field Programmable Gate Array) is the most needed electronic device. Batteries and capacitors tied for second/third with a 16-bit A/D and a 16-bit microprocessor taking forth and fifth.

2. Develop a component standard. A high-temperature long life standard would greatly benefit large and small industries completing against the over whelming PC and mobile phone markets for electronic components. This activity is on going and called the HT2L (High-Temperature Long Life Standard).

3. Organize the drilling industry to jointly fund component development. This activity has taken the direction of a JIP (Joint Industry Partnership) being lead by Honeywell. A JIP proposal is presently being reviewed by the drilling and logging industry.

Task 4 — Working with the Fraunhofer Institute
The German Fraunhofer Institute has an SOI EEPROM in development. This is an important electronic device used in MWD tools. We had a verbal agreement to work together in FY 2002 to use the EEPROM with Honeywell SOI in the Sandia tool. It now appears that the Fraunhofer maybe in competition with Honeywell. Sandia will continue email discussions with Renee Lerch at the Fraunhofer Institute to make this component available to the American geothermal industry.

Task 5 — Assist in additional field testing with industrial partners
Tested the new PT tool in Americulture's well in the Animas Valley of SW New Mexico.

Reports & Articles Published in FY 2002:

J. Henfling and R. Normann, "Advancement in HT Electronics for Geothermal Drilling and Logging Tools," 2002, GRC, Reno, NV.

Industry Manual for building HT systems, by Joseph Henfling. This publication is only available through the Geothermal Research Office of Sandia National Laboratories.

Presentations Made in FY 2002:

DOE Geothermal Drilling and ESR&T Review, National Renewable Energy Laboratory, Golden, CO, March 26, 2002: R. Normann, "High Temperature Electronics."

2002 HiTEC conferences presentation by Randy Normann, "Sandia Efforts to Produce a 300°C Logging Tool for Geothermal Applications," June 3, 2002, Albuquerque, NM.

2002 GRC presentation by Joseph Henfling, "Advancement in HT Electronics for Geothermal Drilling and Logging Tools."

Workshop on "Making HT Electronics Commercially Viable in Support of the Geothermal Industry, +200°C," held June 3, 2002, HiTEC conference, Albuquerque, NM 87015

DEA (Drilling Engineering Association) presentation on "SOI electronics for Upstream Applications" by Randy Normann, March 2002.

Emerging Technology Forum Presentation on "High-Temperature Electronics Development for Upstream Applications," by Randy Normann, Oct 2002.

Planned FY 2003 Milestones:

Task 1 — Component Development and Evaluation

Provide Poseidon with SOI demonstration electronics	(I)	Oct 02
Deliver HT83SNL00 chips to commercial partners	(C)	Jan 03
Provide Welaco results from SOI gamma electronics	(I)	Mar 03
Field-Test EPI thermal batteries	(C)	Jun 03
Conduct joint field test with Photosonic	(I)	Jul 03

Task 2 — High-Temperature Standards and Key Component Development

Hold tool developers standards meeting	(C)	Oct 02
Prepare draft Joint Industry Partnership (JIP) proposal	(I)	Jan 03
Write and publish a HT long life component standard document	(C)	Mar 03
Publish report at the GRC as well as other accepted electronics publications	(I)	Sep 03

Task 3 — HT Print Circuit Board

Build coupons using copper/ceramic plasma spray	(I)	Feb 03
Complete feasibility report on printed circuit board concept	(C)	Jun 03

WELLBORE INTEGRITY AND LOST CIRCULATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	DE-AC04-94AL85000
Performing Organization:	Sandia National Laboratories Geothermal Research Department MS 1033, P.O. Box 5800 Albuquerque, NM 87185-1033
Principal Investigator:	A. J. Mansure
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Collaborating Researchers:	None
DOE HQ Program Manager:	Raymond LaSala
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DOE Funding Allocation:	$691K
Cost Share Funding:	$50K including both “in-kind” or direct funding.

Project Objective: Reduce lost circulation costs by 30% and the cost of drilling a typical geothermal well by 5% through (1) development of a practical polyurethane grouting system to treat geothermal lost circulation zones and (2) by promoting best-available wellbore integrity systems that integrate lost circulation mitigation, drilling on to the next casing point, and cementing in next the casing.

Background / Approach: Lost circulation occurs when formation-fluid pressure is less than the fluid column pressure in the wellbore, so that drilling fluid escapes into the formation instead of recirculating back up the well annulus to the surface. Lost circulation is often accompanied by further loss of wellbore integrity including sloughing, caving, washing out, or bridging. These phenomena are persistent in geothermal drilling, are very expensive — often accounting for 10–20% of the total cost for drilling a typical geothermal well — and cause many additional drilling problems such as stuck drill pipe, damaged bits, slow drilling rates, and collapsed boreholes.

In FY02 these problems were addressed in two separate tasks: (1) Polyurethane Grouting of Lost-circulation Zones and (2) Advanced Wellbore Integrity. The latter of these focused on identifying new technologies that can revolutionize drilling as well as the application of best available technology that is not currently practiced in geothermal drilling.

In civil engineering, polyurethane grout has become the material of choice for sealing boreholes with large voids and high water infiltration, conditions closely related to the worst geothermal lost circulation problems. A recent field trial of polyurethane grout at Rye Patch demonstrated its ability to stop severe cross-flow lost circulation in a geothermal well. While the emplacement technique deployed on that project is practical, it is not optimal. Commercially available polyurethanes should work at the temperatures of most geothermal lost-circulation zones (<250°F, i.e., above the reservoir); furthermore, Sandia researchers believe polyurethane formulations for higher temperatures may be formulated through adaptations of existing polymer chemistry.

To develop a practical polyurethane grouting system to treat geothermal lost circulation zones, Sandia worked with well site service companies, polyurethane-grouting contractors, and polyurethane distributors to foster the development of the infrastructure needed to commercialize polyurethane grouting. This focused on designing a simpler polyurethane grouting system that can be applied deeper and at hotter temperatures than that successfully applied at Rye Patch. The objective: an improved simpler delivery system with fewer parts, requiring less manpower, allowing faster pumping rates and lower pressures. Polyurethane formulations, including both one-part and two-part formulations, were evaluated to "down select" to the best currently available formulation for the next field demonstration. Each candidate material was evaluated in the lab for durability. Work was begun both in-house and by contractors, to develop high temperature formulations.

The cost of drilling geothermal wells can be reduced in various ways ranging from the application of the best of currently available technologies to the development of new revolutionary technologies. The advanced Wellbore Integrity task focuses on, given that severe lost circulation / cross flow is expected or encountered, what should be done to get the next casing string properly cemented in place at the least cost. While a technology specifically for lost-circulation control, e.g., polyurethane grouting, may be the only sure way of stopping severe cross flows, to minimize overall drilling costs, there is a need to take a broad system perspective considering how lost circulation impacts cementing, casing, well design, etc. The ultimate goal isn't lost-circulation control; it is maintaining wellbore integrity. That is, preparing the wellbore so that the next casing string can be cemented in properly. To reach this goal one should both use the best currently available technology and seek new revolutionary technologies.

A systems study of wellbore integrity was done to assess the state-of-the-art in wellbore lining, particularly with respect to commercial or near-commercial systems that might be employed with minimal modification from conventional oil and gas applications. These included: (1) casing drilling, in which casing is used as the drill string, thereby emplacing itself as the hole is drilled; (2) expandable tubulars, which provide a method to run a length of casing through an already-cemented casing string and then to expand it to a larger diameter that will provide a partial lining or "patch" to the wellbore; and (3) continuous wellbore lining with some sort of chemical, perhaps polyurethane, that is deposited as the drill bit passes and then hardens into a permanent or temporary lining. With the recommendations of this study in hand, the merits of advanced wellbore lining techniques vs. a three step wellbore integrity via 1) drilling ahead, 2) restoring wellbore integrity, followed by 3) advanced cementing techniques was reviewed to recommend work for FY 2003.

Status / Accomplishments: A critical step in the development of a practical polyurethane grouting system to treat geothermal lost circulation zones was down selection candidate materials to best polyurethane grout formulation for next field demonstration. This was done systematically using nine selection criteria. A one-part prepolymer supplied by Green Mountain International with higher-temperature stability than the two-part used at Rye Patch was chosen. Green Mountain supplied the two-part formulation used at Rye Patch. The one-part prepolymer reacts in the presence of moisture. A one-part formulation was chosen because it minimizes the problems of premature polymerization and simplifies the development of deep deployment systems. This choice was made in consultation with the polyurethane manufacturer, service companies, polyurethane grouting experts, and drilling engineers.

Based on the selection of a one-part formulation, a simplified coiled tubing deployment was designed in conjunction with Cudd Pressure Control. The deployment includes running an inflatable packer on the end of drill pipe, running coiled tubing down the inside of the drill pipe, stabbing in, and squeezing the prepolymer out below the packer.

In preparation for Rye Patch, low temperature packers were built specifically for that project. Concepts from the straddle packer were used, but the detailed design was different. The requirements for a packer for next polyurethane-grouting job were reviewed and it was been determined that it is possible to build a generic low-cost, higher-temperature packer that can be used both for traditional cement plugs and polyurethane grouting. A contract has been placed with Peterson Products to build a prototype. The advantage of such a packer was confirmed when reviewing the concept with BJ services who has need for such a packer in non-polyurethane-grouting work in The Geysers.

To respond to industry requests to cure and test polyurethane plugs at downhole temperature and pressures, special testing apparatus were assembled: one to cure the polyurethane at borehole conditions, and the other to test for polyurethane plugs for leakage as a function of differential pressure.

One of the leakage tests identified a previously unknown failure mechanism: hydrolysis. Hydrolysis may be the key to understanding past failures of polyurethane grouts in geothermal field tests 15 years ago. At high temperatures, water can hydrolyze or decompose certain polyurethanes. This reaction has only recently been documented in chemical literature as a possible way to digest or recycle polyurethane. Previously, polyurethane had been pressure tested for leakage or, separately, tested for temperature stability in the absence of water. Hydrolysis tests have been conducted on standard polyurethane grouts showing reversal of the polymerization reaction at 275ºF. While high pressures slightly accelerate this process, in general, the only pressure needed is that to keep the water from boiling. These tests confirm the need to develop geothermal polyurethane grout formulations.

To provide additional support in developing new polyurethane formulations that will resist hydrolysis, Sandia contracted with a small business with expertise in testing and developing new polyurethane formulations. Adherent Technologies will perform baseline hydrolysis testing of off-the-shelf one and two-part polyurethane formulations. They will be using Thermal Mechanical Analyses (TMA) to measure the glass transition point (point below which a polymer is not "rubbery"). TMA provides a quantitative measure of the onset degradation of mechanical properties by hydrolysis. Previous testing has been qualitative, i.e., visual determination of the temperature at which the polyurethane becomes friable or "dissolves." These qualitative tests showed softening before hydrolysis. The advantage of proper quantitative measurements is that they can be used to predict durability at extended times as a function of temperature.

The systems study of the state-of-the-art in wellbore lining recommended chemical lining, e.g., polyurethane grouting, as the most likely technology to have a revolutionary impact in the near term. Prior to embarking on developing polyurethane grouting for lost-circulation control, Sandia conducted a study and found no alternative materials with the advantages of polyurethane. To determine if polyurethane grout should be the starting point for developing a wellbore chemical lining system, another review of best-available lost-circulation control technologies was done. This review identified a new class of lost-circulation control materials: reactive pills. In particular a Schlumberger product, InstanSEAL™ provides many of the features desired in a chemical wellbore lining system.

InstanSEAL™ is a two phase emulsion that when pumped through the bit uses shear forces to allow the two parts to chemically react. The resulting material is not rigid, but is stiff enough to stand on. When lost circulation is encountered, the material is pumped through the bit into the loss zone, sets in minutes, and then is drilled out. In many applications the resulting plug allows drilling ahead as if no loss zone had been encountered. A contract has been placed with Schlumberger to demonstrate the product in a geothermal application. Testing will be performed to determine its high temperature stability.

Review of the merits of chemical lining vs. three step wellbore integrity via (1) drilling ahead, (2) restoring wellbore integrity, followed by (3) advanced cementing techniques resulted in significant findings. To change from a plug each lost-circulation zone as it is encountered to a drill ahead paradigm requires that the drilling engineer have multiple options. If sufficient options exist, drilling ahead will have a higher near term impact than chemical wellbore lining.

Additional drilling ahead options, tremie pipe cementing and dual-tube flooded reverse-circulation drilling were demonstrated in a step-out well at Soda Lake. Tremie cementing is not new to geothermal drilling as a remedial process, but it has not been "the plan" using procedures perfected in minerals drilling. The concept of using a mobile rig designed to handle large diameter pipe to set the surface casing followed by a smaller pipe-diameter deep rig was demonstrated cost effective. Drilling the surface casing hole at Soda Lake was trouble free, but had sever lost circulation been encounter, the use of the dual-tube flooded reverse-circulation rig would have allowed drilling to continue without the usual cost increases of severe lost circulation.

The logical next step for advanced wellbore integrity work is to focus on best available, but not current-practice technologies. This choice was confirmed in a meeting with Halliburton. Sandia's recommendation of best-available technologies for next years work was the three step approach to cementing in the next casing string at the least cost: (1) drilling ahead through lost circulation zones to the next casing point, (2) restoration of wellbore integrity, followed by (3) primary cementing. This three-step approach has become practical with 1) dual-tube reverse-circulation drilling providing an additional option to drill ahead when drilling blind and aerated mud don't work, 2) with improved wellbore integrity restoration materials (reactive pills), and 3) nitrogen foam cementing providing a backup to conventional primary cementing.

Halliburton has suggested an additional best-available technology for consideration, reverse-circulation cementing. The concept of reverse-circulation cementing is not new; however, in the last few years new supporting technologies, such as downhole monitoring of the cement progress, has made the control of this process reliable. Halliburton has completed over twenty of these jobs in the last few years in wells that have defied other approaches to cementing. However, they have not been well publicized and thus have not been considered in geothermal cementing. This technology nicely complements Sandia's recommendation, because at the time the decision is made to drill ahead, it gives the drilling engineer another option.

Reports & Articles Published in FY 2002:

Mansure, A. J., "Polyurethane Grouting Geothermal Lost Circulation Zones," presented at the *IADC/SPE Drilling Conference held in Dallas, Texas, 26–28 February 2002*.

Finger, J. T., and B. Livesay, "Alternative Wellbore Lining Methods: Problems and Possibilities," Sandia National Laboratories (in print).

Presentations Made in FY 2002:

Mansure, A. J., "DOE Geothermal Drilling and ESR&T Review," National Renewable Energy Laboratory, Golden, CO, March 26, 2002: "Advanced Wellbore Integrity."

Planned FY 2003 Milestones:

Task 1 — Field Test of Next Generation Polyurethane Grouting Deployment System

Field demonstration of geothermal deployment system in conventional environment	(C)	Jun 03
Complete report on depleted reservoir polyurethane grouting system	(I)	Sep 03

Task 2 — Laboratory Testing of Improved Polyurethane Grouting Formulations

Complete survivability testing of off-the-shelf polyurethane grouts	(I)	Feb 03
Completion of laboratory testing of geothermal polyurethane grout	(C)	Aug 03

Task 3 — Demonstrations of Advanced Wellbore Integrity Technologies

Complete laboratory testing of "reactive pill" materials	(I)	Mar 03
Field demonstration of reverse-circulation cementing	(C)	Aug 03

HARD-ROCK DRILL BIT TECHNOLOGY

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC04-94AL85000

Performing Organization: Sandia National Laboratories
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DOE Funding Allocation: $1,642K

Cost Share Funding: Task 1 — $10K in FY02 (U S Synthetic);
Task 3 — $310K in FY03 (CRADA partners)

Project Objective: This multi-year project seeks to dramatically expand the range of applications for drag bits to include the hard, hot, abrasive, and fractured rock formations that are predominant at geothermal energy production sites. Specifically, doubled bit life and doubled penetration rates relative to conventional capabilities are sought, which would yield an estimated reduction of 15% in overall geothermal well costs. Such an improvement in drilling economy promises to substantially increase the scope of viably exploitable geothermal resources. The combined benefits of decreased drilling cost and increased resource availability are fully consistent with the stated goals of the DOE Geothermal Energy Program, namely: (1) supplying electrical power and/or heat energy to more U.S. homes and businesses, (2) reducing the generation cost of geothermal power, and (3) increasing the number of States with geothermal electric power facilities. The stated FY02 project objective, which also applies to prior years, is being realized by successive technical innovations and achievements.

Work on the bit-technology project has been divided between four distinct, but interrelated, tasks: (1) PDC (Polycrystalline Diamond Compact) Cutter Development and Testing, (2) Self-Induced Bit Vibrations, (3) PDC Bit Development and Testing, and (4) Mudjet-Augmented PDC bit. The objectives of these individual tasks are:

Task 1. Produce a database that shows the influence of fundamental cutter design parameters on wear and durability and identifies optimal configurations for hard-rock applications. Generate new cutter materials and configurations and validate their performance for geothermal drilling.

Task 2. Develop knowledge and systems to mitigate or eliminate chatter damage to cutters and bits during geothermal drilling.

Task 3. Demonstrate the capabilities of state-of-the-art PDC bits for drilling hard-rock formations.
Task 4. Develop and demonstrate a new mudjet-augmented PDC bit that achieves high penetration rates in hard rock.

Background / Approach: After the introduction of PDC cutters by General Electric in the 1970s, many companies incorporated these cutters in drag bits, which have no moving parts and break rock in a shearing process that is inherently more efficient that the crushing process associated with roller bits. To support an industry that was initially frustrated by persistent PDC failures, Sandia began working with cutter and drag-bit manufacturers in the late 1970s to identify and correct design deficiencies. Since that time, Sandia's landmark work has been instrumental in expanding the range of PDC cutter and bit applications into harder formations, opening up much broader opportunities for this technology that has now captured over one-third of the worldwide bit market.

Sandia continues to collaborate with multiple industry and university partners on research and development efforts aimed at producing drag cutters and bits capable of more efficient drilling in hard-rock geothermal formations. As noted above, this work is currently divided among four separate tasks for which Sandia's in-house resources are employed and supplemented, as needed, by outside laboratory and field-testing capabilities. Unique Sandia testing resources include the Hard-Rock Drilling Facility (HRDF) and Linear Cutter Test Facility (LCTF). Bit performance and wear are computationally simulated and new designs are generated using the Sandia-developed PDCWEAR code. Active industry and/or university involvement in each task contributes significant additional technical expertise and capabilities. The following paragraphs relate the approach for each task:

Task 1. PDC Cutter Development and Testing: Acquire cutters with selected compositions and geometries from several manufacturers (i.e., U.S. Synthetic Corporation, Dennis Tool Company, and Technology International, Inc.) for evaluation. Obtain cutting-force and wear measurements from LCTF and HRDF tests at Sandia and, where available, complementary drop-impact and abrasion data from industry-partner facilities. Evaluate the test results to determine the effects of parameter variations on cutter loads, wear, and survivability. Discern parameter-dependent performance trends and apply this information to the development of improved cutters for hard rock.

Task 2. Self-Induced Bit Vibrations: Self-induced bit vibration (i.e., chatter) occurs in drillstrings equipped with PDC bits due to the bit producing an undulated surface in the rock that in turn modifies a constant weight on bit into a time-variant force that feeds back into the vibration of the bit and drillstring. The approach to this work is to conduct drilling experiments on test fixtures that allow chatter to occur in the laboratory where it can be studied and characterized in a well-understood and controlled environment. Sandia's HRDF has been modified from its original configuration to achieve a substantial increase in longitudinal and rotational compliance, allowing testing under conditions that better represent field drilling. The vibration intensity of the bit is monitored during drilling tests and correlations are produced between the bit/drillstring design, rock properties, and the drilling operational parameters. Data analysis allows theories to be refined and models developed that can be extended to other drilling configurations.

One way to suppress bit vibrations is through the application of controllable damping near the bit. High damping is desirable at low frequencies while lower damping is required at higher frequencies. Hence, the damping must be controllable to introduce the desired control. A test fixture was developed and deployed in the HRDF to allow the dynamic parameters of a controllable damper to be characterized. The fixture allows testing of adjustable spring rates and damping forces and will allow insight into the parameters necessary for a fieldable damper.

Task 3. PDC Bit Development and Testing: Establish a partnership between Sandia and several bit manufacturers to plan and implement a field demonstration of state-of-the-art drag bits in a well-characterized hard-rock drilling interval that simulates a geothermal setting. Conduct controlled, heavily instrumented drilling operations in conjunction with proof-of-concept tests and field-ready system development for Sandia's Diagnostics-While-Drilling (DWD) project. Share detailed bit-specific data with the respective industry partners to facilitate further design improvements, and publicly report overall results to stimulate acceptance of drag-bit technology by the geothermal drilling community.

Task 4. Mudjet-Augmented PDC Bit: Develop passively pulsating, cavitating nozzle designs that encompass both high-pressure/low-flowrate and low-pressure/high-flowrate conditions. Fabricate nozzle orifices from tungsten-carbide-supported polycrystalline diamond to allow orifice throats to withstand cavitation environment. Design test fixtures to support cavitating nozzles in various configurations relative to single and multiple cutters mounted in representative fixed-cutter bit geometries. Conduct research in the Sandia LCTF to measure rock-cutting forces both with and without jet-augmentation. Develop a cutting-force database that represents the reduction in rock cutting forces as a function of various nozzle/cutter interaction geometries and hydraulic operating conditions. Use the database to design a second-generation bit by integrating the bit and cavitating nozzle designs.

Status / Accomplishments: Significant progress was made during FY 2002 on all four tasks involved in Sandia's drag-bit technology effort. A task-by-task summary follows:

Task 1. PDC Cutter Development and Testing: U.S. Synthetic fabricated cutter lots 7 through 12, which featured new combinations of design features that differed from those for the first six lots that were produced in FY 2001. As before, the latest cutters were subjected to extensive LCTF cutting-force tests at Sandia and drop-impact and granite-log abrasion tests at U.S. Synthetic. In addition, HRDF drilling tests were completed in FY 2002 for cutters from all 12 lots. The results of this work were summarized in a report that received the "Best Paper Award" for the Drilling and Completion Session of the GRC 2002 Annual Meeting. This investigation clearly demonstrated that variations in design and processing parameters have a pronounced effect on the drilling, abrasion, and impact performance of PDC cutters during the penetration of hard rock. The rotary drilling tests indicated more than a factor of 10 between the best and worst wear rates, which was consistent with the granite-log tests that showed a ratio of almost 13 between best and worst abrasion resistance. The drop-impact data revealed a wide range of design-dependent failure rates, with excellent impact performance observed for several cutter formulations.

Task 2. Self-Induced Bit Vibrations: Subtasks were completed to examine the relationships between the dynamic properties of an in-line damper and the resultant drillstring stability. Specifically, the requisite dynamic properties (mass, stiffness, damping) for a controllable, in-line damper were scoped for the HRDF; a damper test fixture was designed, fabricated and deployed in the HRDF; and testing was conducted to characterize dynamic damper response and assess the benefits of controllable damping for suppression of self-induced vibration over a range of conditions. The test fixture allowed parameters to be adjusted and demonstrated the technology as an effective approach for enforcing bit stability. Test results provided guidance for the development of a prototype fieldable damper to be demonstrated in the HRDF in FY 2003.

Task 3. PDC Bit Development and Testing: A single-lab/multi-partner Cooperative Research and Development Agreement (CRADA) was established between Sandia and four leading drag-bit producers, namely Halliburton/Security DBS, Schlumberger/Reed-Hycalog, Smith Bits – GeoDiamond, and Technology International. CRADA Tasks 1 and 2, which entailed testing of baseline rollercone and PDC bits, were successfully completed at the GTI Catoosa Test Facility in conjunction with the Phase 1 and 2 Proof-of-Concept tests for Sandia's DWD project. These tests included operations with, and without, the provision of DWD feedback to the driller while producing separate holes with a conventional drag bit that was refurbished between holes. Extensive dynamic downhole (DWD) and surface data were acquired, and detailed observations were made of bit wear and damage. These results were conveyed to the CRADA partners to support their development of individual "best effort" bit designs for upcoming tests under Task 3 of the CRADA.

Task 4. Mudjet-Augmented PDC Bit: Nozzle designs have been developed to allow investigation of the range of conditions that may be anticipated in a cavitating nozzle deployed in a prototype bit. Cavitation-resistant orifices have been fabricated in preparation for testing. Fixtures to accommodate this research have been designed and are being fabricated. Communications are under way with industry to develop a technique to fabricate polycrystalline diamond orifices using a direct-sintered process.

Reports & Articles Published in FY 2002:

DOE Geothermal Energy Program: Drilling Program Peer Review, March 2002: (1) J. L. Wise, "PDC Cutter Development and Testing;" (2) D.W. Raymond, "Self-Induced Bit Vibrations;" (3) J. L. Wise, "PDC Bit Development and Testing;" and (4) D.W. Raymond, "Mudjet-Augmented PDC Bit."

J. L. Wise, D. W. Raymond, C. H. Cooley, and K. Bertagnolli, "Effects of Design and Processing Parameters on Performance of PDC Drag Cutters for Hard-Rock Drilling," Geothermal Resources Council (GRC) *Transactions*, Vol. 26, September 22–25, 2002, pp. 201–206.

Presentations Made in FY 2002:

DOE Geothermal Drilling and ESR&T Review, National Renewable Energy Laboratory, Golden, CO, March 26, 2002: (1) J. L. Wise, "PDC Cutter Development and Testing;" (2) D. W. Raymond, "Self-Induced Bit Vibrations;" (3) J. L. Wise, "PDC Bit Development and Testing;" and (4) D. W. Raymond, "Mudjet-Augmented PDC Bit."

J. L. Wise, "CRADA Status: Advanced Drag Bits for Hard-Rock Drilling," Meeting of the DWD Technical Advisory Committee, Schlumberger Technology Corporation, Houston, TX, May 15, 2002.

J. L. Wise, "Drag-Bit Damage and Wear Observations for CRADA Tasks 1 and 2," Meeting of the DWD Technical Advisory Committee, Advantage Engineering, Houston, TX, September 18, 2002.

J. L. Wise, "Effects of Design and Processing Parameters on Performance of PDC Drag Cutters for Hard-Rock Drilling," GRC 2002 Annual Meeting, Reno, NV, September 22–25, 2002.

Planned FY 2003 Milestones:

Task 1 - PDC Cutter Development and Testing

Complete claw-cutter testing	(I)	Feb 03
Complete next round of PDC cutter testing for fundamental parameter study	(C)	May 03
Complete TSP/PDC testing with Technology International	(I)	Sep 03

Task 2 - Self-Induced Bit Vibrations

Develop prototype controllable damper	(I)	May 03
Demonstrate prototype controllable damper in the HRDF	(C)	Jun 03
Complete preliminary design of the Drill string Dynamic Simulator	(C)	Sep 03

Task 3 - PDC Bit Development and Testing

Receive "best effort" bits from bit companies	(C)	Nov 02
Initiate CRADA Task 3 drilling with "best effort" bits	(I)	Feb 02
Complete report on CRADA drilling results	(C)	May 03
Complete report on stabilized PDC bit field tests	(I)	Sep 03

Task 4 - Mudjet-Augmented PDC Bit

Complete fabrication of LCTF test fixtures	(C)	Feb 03
Conduct nozzle/cutter interaction testing	(I)	Aug 03
Complete nozzle/cutter cutting-force database	(I)	Sep 03
Complete report for external distribution on the phase one development	(C)	Sep 03

COST DATABASE AND SIMULATORS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC04-94AL85000

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DOE Funding Allocation: $125K

Cost Share Funding: $2K, in-kind contribution from operators in collecting and transferring data

Project Objective: Collect cost data from additional geothermal well fields. Develop a unified system for classifying trouble costs and for benchmarking standard operating performance. Use the Sandia spreadsheet cost model, in conjunction with the actual field data, to predict the impact of various technology improvements (such as those being pursued in the Geothermal Research Department).

Once a standard system is in place, Sandia should document U.S. geothermal drilling costs annually and should benefit industry by giving them the cost-analysis capability to predict drilling situations and either refine their drilling practices or pursue appropriate new technology. This database should be coordinated with the IEA Geothermal Implementing Agreement Annex VII.

Background / Approach: A detailed understanding of drilling costs and their sources is necessary to focus efforts on work that has the highest payoff for the geothermal industry. In an effort to define field costs for typical geothermal wells, Sandia has collected well-cost files from three different geothermal fields. These files, which are all in the electronic database format RIMBase, include not only new production wells drilled from surface, but workovers, abandonments, and injection wells. We also have access to many (hundreds) of paper well files that are not in electronic format. The RIMBase files have been summarized, but we now need to examine the data in more detail in an effort to refine our understanding of the impact that various technology improvements can have on cost reduction.

There are two distinct ways to reduce drilling cost – eliminate abnormal, or "trouble", costs and improve performance in standard operations. Analysis of the well data will enable us to assign dollar values to each kind of cost improvement, measure progress in reducing the cost of drilling geothermal wells, and help prioritize technological investment opportunities.

Status / Accomplishments: Our current database in RIMBase format comprises more than 200 well files, but many of these are workovers, re-drills, and abandonments that do not illustrate the complete process of drilling a well from the surface down. This is especially important because the larger hole and casing diameters mean that the upper stages of the hole are very expensive. A large number of well files are available in traditional paper format, but transforming these into RIMBase files is extremely time-consuming. We are trying to find an intermediate format for displaying this data that will enable cost analysis without the time-consuming step of transforming them into RIMBase files. A major accomplishment in FY02 was acquisition of paper well files that increase our database on Geysers wells more than threefold.

As an aid to analyzing RIMBase files, we have also solved the problem of different operators using different accounting codes for their costs in their well files. We have developed a "Sandia" accounting code for detailed well costs and have a modified version of RIMBase that incorporates a translator from operators' cost codes into the Sandia standard. This enables unification of well files from multiple operators into a standard format.

We intend to continue pursuit of additional cost data from other operators in other fields, and to refine presentation of the collected data. This will be directed toward the objective of producing cost-reduction scenarios based on priorities established by analysis of the cost data.

Reports & Articles Published in FY 2002:

FY 2001 Project Update

Presentations Made in FY 2002:

Review for DOE Project Officer, Sandia Labs, Albuquerque, NM, January 2002

DOE Geothermal Drilling and ESR&T Review, National Renewable Energy Laboratory, Golden, CO, March 26, 2002: "Cost Database"

Planned FY 2003 Milestones:

Contact geothermal operators to solicit cost data	(I)	Nov 03
Complete examination and classification of existing well data	(I)	May 03
Develop a suite of cost-reduction scenarios showing the effect of new technology	(C)	Aug 03

ACOUSTIC MEASUREMENT-WHILE-DRILLING

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC04-94AL8500

Performing Organization: Sandia National Laboratories
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Collaborating Researchers: None

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DOE Funding Allocation: $559K

Cost Share Funding: $350K - Fossil Energy Program;
$300K - Extreme Engineering;
$200K - Baker Oil Tools

Project Objective: Complete the construction of a new 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.

Background / Approach: 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 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. Also 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. Over the last year these tools have seen approximately 30 days of service in both drilling and production application, including the drilling of a 2,700-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. Outstanding subcontract commitments for the wireless surface acoustic receiver are 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.

Major milestones achieved in FY 2002 include: (1) Field test of the low-temperature acoustic tool in a static environment in October 2001, (2) Field test of the low-temperature acoustic tool under actual drilling conditions in Nov. 2001, and (3) Field test of the wireless surface acoustic receiver June 2002.

Reports and Articles Published in FY 2002:

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

Drumheller, D. S., and S. S. Kuszmaul, "Acoustic Telemetry," SAND-XXXX. (in preparation)

Drumheller, D. S., "Wave Impedances of Drill Strings and other Period Media," *Journal of the Acoustic Society of America*. (in press)

Presentations Made in FY 2002:

DOE Geothermal Drilling and ESR&T Review, National Renewable Energy Laboratory, Golden, CO, March 26, 2002: D. Drumheller, "Acoustic MWD."

Planned FY 2003 Milestones: Project was terminated in FY 2002 per DOE direction.

DIAGNOSTICS-WHILE-DRILLING (DWD)

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC04-94AL85000

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

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DOE Funding Allocation: $1,197K

Cost Share Funding: $50K, in-kind participation of operators and service companies in providing technical advice, conference facilities, laboratory testing time and equipment, and data-reduction consultation

Project Objective: Improve the DWD system by completing the following tasks. Evaluate and/or develop advanced data communication links for a field-ready high temperature system including wireline, wired pipe, and optical fiber. Based on geothermal requirements and results of the POC, define design changes in the downhole measurement sub. Three general areas of improvement will be (1) upgrade electronics and sensors for high temperature, (2) establish optimum data rate, and (3) incorporate lessons learned from operational and assembly experience to date. Gain more experience both with the existing DWD measurement tool and data analysis via tests at GRI/Catoosa as well as other locations, with preferably harder, more geothermal-like formations. The data-analysis task will focus on improving the way data is collected and displayed for the user during both real-time and playback modes, learning to recognize indications of bit dysfunction, and developing algorithms to convey those indicators to the driller in an easily understandable way.

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

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

Status / Accomplishments: The principal accomplishment in FY02 was completion of a Proof-of-Concept test (POC) that validated several of the assumptions on which DWD is based. This test comprised drilling two holes through the same interval of hard rock (at the GTI Catoosa test site near Tulsa OK) with identical PDC bits and drilling assemblies, while recording a wide array of dynamic downhole measurements. The crux of the experiment was that the downhole information was not used for drilling control in the first hole (Phase 1) but was used in the second hole (Phase 2). This enabled comparison of bit life and penetration rate with and without DWD as feedback to the driller, and also provided the opportunity for extended evaluation of the system's performance under actual drilling conditions.

Although the POC was the culmination of this fiscal year's testing, it was preceded by other crucial test activities. In addition to the static pressure and strain-gauge calibration tests, the downhole measurement sub was subjected to vibration testing in Sandia's in-house lab, and full-scale laboratory drilling at a bit company's lab in Houston. The laboratory drilling provided an opportunity to use the data display system for identifying various bit dysfunctions, which proved to be valuable experience in the field drilling POC.

During the POC, the DWD system – downhole measurement sub, wireline data link, and surface data display – performed very well during more than 26 hours and 1,400 feet of drilling. Bit life was also increased with DWD feedback; in Phase 1, total life until the bit failed was 390 feet, with 105 feet in the hard formation, while total life in Phase 2 was 515 feet with 230 feet in hard formation. In Phase 2, the test ended because the scheduled testing time was expended; the bit was still drilling when time expired.

The wireline that served as a high-speed data link also demonstrated that transmission of downhole data at rates near 200 k-bits/second is feasible. Receiving data at this rate means that the driller can choose among many different measurements as indicators of drilling problems and can get almost instantaneous notification of imminent problems.

The POC also provided conclusive proof that downhole sensors show conditions having the potential to damage bits while those conditions cannot be identified from surface measurements alone, or at least cannot be identified until the bit is already damaged. On more than one occasion, the surface weight-on-bit indicator appeared to show that weight was increasing relatively smoothly up to the operating point, but downhole readings showed that the bit was actually bouncing off bottom, creating severe axial and torsional impact. These conditions are very destructive to PDC bits.

Given the results described above, the next tasks for this project include the following:

Gain experience in other conditions – To compare performance across a realistic spectrum of drilling conditions, it is essential to drill in other formations with other bits and bottom-hole assemblies. Ideally, this experience will include early tests in a geothermal or geothermal-like hole.

Investigate and evaluate alternative data links – Although the wet-connect wireline performed well, many drilling companies object to have the wire inside the drill pipe as a normal condition. Our next step is to work with industry in their attempts to develop a "wired" drill pipe that has the signal-carrying medium embedded into the pipe. This system is relatively transparent to the drilling process, while maintaining the data-handling capacity of the wireline.

Modify and upgrade the downhole measurement sub – Our approach to the POC was to make as many measurements as possible at as fast a sample rate as possible. If the total data-rate requirements can be reduced, then the choice of data link and design of the downhole sub will be greatly simplified. In addition to a re-design based on data requirements, an upgrade to high temperature is a high priority.

Improve data display and analysis – As we acquire more data, it will become increasingly important to have a versatile, efficient analysis capability. This development will focus on learning to recognize indications of bit dysfunction, improving data playback and plotting, and displaying information to the driller in an easily understandable way.

Reports & Articles Published in FY 2002:

FY 2001 Project Update on DWD, January 2002.

Minutes of Technical Advisory Committee meetings (Nov. 2001, March 2002, Sept. 2002).

"Diagnostics While Drilling Proof of Concept Test Report", J. Finger. (Draft delivered to DOE-HQ in August 2002.)

Presentations Made in FY 2002:

J. Finger and A. Mansure, "DWD Status Update," Meeting of the DWD Technical Advisory Committee, BP Facilities, Houston, TX, Nov 2001.

J. Finger, "DWD Proof of Concept Update," Review for DOE Project Officer, January 2002.

J. Finger, "DWD Overview," IEA Geothermal Implementing Agreement, Annex VII, Paris, France, March 2002.

J. Finger, "Diagnostics-While-Drilling," DOE Geothermal Drilling and ESR&T Review, National Renewable Energy Laboratory, Golden, CO, March 25-26, 2002.

J. Finger, A. Mansure, and R. Jacobson, "DWD Status Update," Meeting of the DWD Technical Advisory Committee, Schlumberger Technology Corporation, Houston, TX, May 2002.

J. Finger, A. Mansure, and R. Jacobson, "DWD Status Update," Meeting of the DWD Technical Advisory Committee, Advantage Engineering Facilities, Houston, TX, Sept. 2002.

Planned FY 2003 Milestones:

<u>Task 1 — Define Second-generation (Field Ready System) Data Link</u>

Complete evaluation of commercial wired pipe	(I)	Feb 03
Issue recommendation on development of field-ready data link technology	(C)	May 03

<u>Task 2 — Modify/upgrade Downhole Measurement Sub</u>

Define optimum data rate for second-generation system	(I)	Apr 03
Complete "baseline" high-temperature electronics design for second-generation sub	(C)	Feb 03
Complete "baseline" mechanical design for second-generation sub	(I)	May 03
Propose DWD for DEA Joint Industry Project	(C)	May 03

<u>Task 3 — Support Field Operation</u>

Support tests for Hard-Rock Bit CRADA	(I)	Dec 02
Field drilling tests for hard-rock formations	(C)	Jun 03

<u>Task 4 — Develop Improved Data-analysis Capability</u>

Develop recognition criteria for bit dysfunction	(I)	Mar 03
Complete SAND Report on first generation DWD development	(C)	Apr 03
Transfer recognition criteria into analysis and display optimization	(I)	Jul 03

ACID-RESISTANT CEMENTS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC02-98CH10866

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DOE Funding Allocation: $140K

Cost Share Funding: $200K

Project Objective: The purpose of this work is to further increase the acid-resistance of calcium aluminate phosphate (CaP) cement developed at BNL, and also to improve its toughness-related properties. In collaboration with Halliburton Energy Services and Unocal Corporation, the primary goal of this program is to develop superior acid-resistant CaP cement that shows less than a 5 wt% loss after 30 days immersion in 5,000 ppm CO_2-laden H_2SO_4 brine (pH <1.2) at temperatures up to 180°C. A secondary goal is to design tough yet flexible CaP cement composites that provide a fracture toughness of > 0.08 $MN/m^{3/2}$ and water permeability of < 0.1 millidacrys after exposure for 30 days in an autoclave containing a 40,000 ppm CO_2-laden brine at a temperature of 280°C.

The highly concentrated CO_2 and H_2S environments encountered in the upper regions of the well's (~ 3,800 ft below the well's surface) at temperatures up to 180°C occasioned the former research objective, acid resistance. The latter one was related to the problem of stress cracking caused by a slight thermal expansion of the CaP cement during the passage of superheated geothermal fluid through the cement-sheathed steel pipes in production wells, and also due to the brittleness of the cement. Severe acid erosion and the development of numerous cracks in the cement leads to downtime or even failure of the wells, and the requirement for expensive time-consuming remediation involving redrilling and recementing operations. Thus, the improved CaP cement would not only significantly extend the useful lifetime of the cement, but also would save in excess of $150,000 per well in avoided remedial operations. Wells completed with improved CaP cement are projected to have service lifetimes of 20 years, thereby increasing the electric generation output of geothermal plants.

Background / Approach: Before FY 2002, the cementitious materials to be developed were required to meet the following criteria: (1) maintenance of pumpability for at least 3 hours; (2) compressive strength,

> 1,000 psi at 24 hours; (3) water permeability, <0.1 millidarcy; (4) bond strength to steel casing, >100 psi; (5) carbonation rate, <5 % after 1 year in brine at 300°C containing 40,000 ppm CO_2; (6) fracture toughness, >0.08 $MN/m^{3/2}$ at 24 hours; (7) extent of resistance to acid, <5 wt% loss after 30 days in 5,000 ppm CO_2-laden H_2SO_4 (pH, <1.2) at temperatures up to 180°C; and (8) cost, <$15/bag.

Halliburton's CaP cement known commercially as "ThermaLock®" was originally developed at BNL for use as CO_2-resistant cement for cementing steel well casings to geologic formations in mild acid (pH ~ 4.5), CO_2-rich (>40,000 ppm CO_2) brine environments at temperatures up to 320°C. Over the past four years, Unocal Corporation, Halliburton Energy Services, and Japan Petroleum Exploration Co. have used this cement to complete nearly twenty-four geothermal wells in Japan, Indonesia, and the United States. In recent years, this cement has become increasingly popular for completing geothermal, oil, and gas wells worldwide. Thus far, the original CaP cement met all criteria, except for items 6 and 7. So in developing advanced CaP cement, we must focus on improving two properties, its acid resistance and its toughness.

Resistance to Acid

Our previous work on the acid-erosion mechanisms of CaP cement consisting of calcium aluminate cement (CAC), Class F fly ash, and sodium polyphosphate, revealed that the extent of acid erosion depended primarily on the ratio of fly ash/CAC. Exposed specimens made with a low ratio of fly ash/CAC included a substantial amount of hybrid phases consisting of $Ca(HPO_4).xH_2O$, gypsum, and, $Al_2O_3.xH_2O$, that promoted the development of a densified microstructure in the cements and improved their mechanical behavior. Although the formation of water-soluble gypsum was thought to be one factor governing the loss in weight of the cements, the major cause for serious acid erosion was the porous structure of specimens brought about by the large amount of non-reacted fly ash remaining in the cement. Their porosity allowed the acid solution to permeate easily, diminishing the protection offered by the $Ca(HPO_4).xH_2O$ and $Al_2O_3.xH_2O$ phases formed as reaction products in the cement.

Since these reaction products were formed by chemical and hydration reactions between the sodium polyphosphate solution and the CAC, but not fly ash, one approach to enhancing resistance to acid is to gain an understanding of the role of the CAC reactants play in reducing acid attack. Thus, in 2001, the plan was to assess the effectiveness of CAC with various mole ratios of CaO/Al_2O_3 and different mineralogical phase compositions in reducing the rates of acid erosion. From our research, we identified CAC containing two major phases, monocalcium aluminate (CA) and calcium bialuminate (CA_2), and a moderate CaO/Al_2O_3 ratio of 0.4 as the most effective one in satisfying the above requirements. One important factor in abating acid attack was to have a sufficiently low porosity of 25.5 %, which diminishes the permeability of acid solutions through the cements. However, another problem encountered was that the remaining non-reacted CA and CA_2 components underwent carbonation to form calcite, which is very susceptible to reactions with H_2SO_4. These reactions led to the deposition of gypsum scales as the acid corrosion product on the cement's surfaces. However, the neutralization by a passive gypsum layer not only protected the cement from an acid corrosion, but also promoted the chemical and hydration reactions of sodium polyphosphate (NaP) with CA, CA_2, and fly ash to yield three crystalline phases, hydroxyapatite, boehmite, and Na-P type zeolite, as the reaction products. These reaction products, particularly boehmite and Na-P type zeolite, were relatively insensitive to acid attack, so further protecting the cements against acid erosion.

Improvement of Toughness

Our approach to increasing the toughness of the CaP cement is to incorporate strong fibrous materials into it. The following criteria are used for selecting fibers to improve the toughness of the cements: (1) good dispersiveness to achieve a uniform distribution in the cement slurry; (2) thermal resistance of >300°C;

(3) lack of susceptibility to reactions with brine solutions containing alkali metals, alkaline earthmetals, CO_2, and H_2S; and (4) moderate adherence to the cement matrix. Advanced ceramic fibers such as alumina and aluminosilicate were very attractive as alternative fibrous materials because of their stability at high temperatures and their great mechanical properties. Thus, in 2001, the plan was to assess the usefulness of two ceramic fibers, corundum (α-Al_2O_3) and corundum/mullite ($3Al_2O_3.2SiO_2$) blend for improving the fracture toughness of the CaP cement. At a hydrothermal temperature of 280°C, the reactions between the α-Al_2O_3 phase-based fiber's surfaces and silicate in the cement slurry were responsible for the development of a moderate bonding at the interfaces between the fibers and the CaP cement matrix. This bonding improved fracture toughness to 0.059 $MN/m^{3/2}$, corresponding to an increment of 2.7 times above than that of non-reinforced cements. In contrast, adding α-Al_2O_3/mullite mixed phases-based fibers did little to improve the fracture toughness because of the transformation of the mullite into zeolite. This mullite $\rightarrow$ zeolite phase transition was caused by the hydrothermal reaction of mullite with the Na in the cement. This transition generated a strong linkage between the fibers and the matrix; however, it also converted the strong, flexible, and tough fibers into fragile, brittle ones. Correspondingly, cracks generated in the cement composites propagated through the fibers, but not at the fiber/matrix interfaces.

Status / Accomplishments:

Resistant to Acid

In 2002, our work focused on inhibiting the phase transition of the remaining non-reacted CA and CA_2 into gypsum. Two anti-acid admixtures, water-dispersible high-temperature silicon emulsions and alkaline metal hexafluoro compounds, were used. The former additive showed a better performance in enhancing the resistance of cement to acid compared with the latter one. Among the various silicon emulsions, silanol-terminated polydimethlysiloxane (PDMS) was selected because of its excellent thermal stability, high water-repellency, great flexibility, and outstanding resistance to acid. A solid film of PDMS made at 150°C withstood a hydrothermal temperature of 200°C. The crystalline phase composition of both 150°C-autoclaved PDMS-modified and unmodified CaP cements consisted of three hydration reaction products: hydroxyapatite (HOAp), boehmite, and Na-P type zeolite, one carbonation product, calcite, and three unconsumed reactants: monocalcium aluminate, perovskite, and quartz from calcium aluminate cement and fly ash. When unmodified cement was exposed for 20 days to hot CO_2-laden acid, its surface was covered with the crystalline bassanite ($CaSO_4.1/2H_2O$) phase as the acid corrosion product of cement. Bassanite was formed not only by reactions between H_2SO_4 and calcite or moncalcium aluminate, but also by reaction of HOAp with acid, reflecting a weight loss of 16.5 % due to acid erosion. In contrast, PDMS protected the cement against acid corrosion in two ways: it considerably reduced the formation of calcite, which was generated by carbonation of the cement surfaces and it abated the rate of reaction of HOAp with acid. Consequently, the weight loss after 20-day exposure was only 7.8 %. The newly formulated cement was delivered to Halliburton for their independent evaluation before beginning field trials.

In the period of October 25 through October 27, 2002, the N_2-foamed "ThermaLock" CaP cement was successfully pumped down into one of the geothermal wells at the Coso geothermal project located near Ridgecrest, CA. The foamed cement was used to avoid a problem with lost circulation, and to protect the steel casing against corrosion by CO_2-laden acid attack. It was applied to the upper well region (~ 3,800 ft below the well's surface), where the steam zone contained CO_2 and H_2S at temperatures up to 160°C. This was the first use of N_2-foamed CaP cement in any domestic geothermal wells. To support the post-placement assessments and monitoring of the cement's useful lifetime by Halliburton and Coso Operating Company, BNL will provide them with data on the microstructure, phase composition, and mechanical properties of the aged cements. In addition, we are investigating the effectiveness of citric acid and NaCl as setting retarders in enhancing the acid resistance of CaP cement. Further, new types of alkali-activated advanced cements that significantly enhance resistance to the combination of acid and carbonation are being developed in collaboration with Halliburton.

Improvement of Toughness

In 2002, we concentrated on assessing the usefulness of the milled carbon microfibers (~ 7.5 μm diam. × 100–200 μm long) in improving the toughness and ductility of CaP cement for geothermal wells operating at hydrothermal temperatures of 280°C. The chemical composition occupying at the outermost surface site of the fibers consisted of graphite as the principal component coexisting with functional oxidized carbon moieties, such as carbonyl and carboxyl. These functional moieties contributed significantly to improving the following three properties, deemed essential for good reinforcing fibers; (1) the extent of dispersiveness of the fibers in the cement slurry, (2) the minimization of air-trapping by fibers during mixing with the slurry, and (3) their affinity for the chemical species present in the pore solution of the cement. We found that large amounts of fibers could be incorporated into the cement slurry, so greatly enhancing the first and second properties. Further, such large amounts had no critical influence on the porosity of the hardened cement bodies. For the third property, we showed that the preferential uptake of quartz in the cement slurry by these surface moieties led to an excellent adherence of the fibers to the cement matrix. Integrating all these factors was reflected in a rise in the fracture toughness and displacement of the non-reinforced cements by 3.1- and 2.7-fold, respectively, by incorporating 14 wt% (21.8 vol.%) fibers. In early 2002, Halliburton applied this fiber-reinforced cement as the anti-corrosive internal lining material to the geothermal well-head pipe in CalEnergy Power Plant. BNL will monitor the changes in both the mechanical and physical properties of the aged composites.

Reports & Articles Published in FY 2002:

Sugama, T., L. Weber, and L. E. Brothers, "Ceramic Fiber-reinforced Calcium Aluminate/Fly Ash/Polyphosphate Cements at a Hydrothermal Temperature of 280°C," *Advances in Cement Research*, 14 (2002) 25–34.

Sugama, T., 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," *Journal of Materials Science*, 37 (2002) 3163–3173.

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

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones:

Investigate effect of retarders in enhancing resistance of CaP to acid	Mar 03
Complete report describing the results of all tests for acid-resistant retarded CaP	Apr 03
Syntheses new phosphate-based cement systems	May 03
Complete report describing the results of all tests for new cement systems	Jun 03
Report results of field monitoring test for fiber-reinforced CaP cement	July 03
Complete economical assessments of CaP cement	Aug 03

STRUCTURAL RESPONSE ANALYSIS OF WELL CEMENTS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC02-98CH10886

Performing Organization: Brookhaven National Laboratory

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DOE Funding Allocation: $160K

Cost Share Funding: $12K (in kind)

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

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

Status / Accomplishments: A variety of conventional, fiber reinforced and lightweight cements were tested to obtain detailed material properties and definition of behavior, particularly beyond yielding. This information was used to determine parameters necessary for development of appropriate descriptive material models for numerical analysis. Durability tests on fiber reinforced cements were performed to examine corrosion characteristics and long term mechanical properties. Examination of tensile stress-strain behavior of cements with and without fibers was initialized. Detailed finite element analysis was performed by modeling the cement annulus as well as the casing and the formation. These numerical evaluations used the material models for fiber reinforced and lightweight cements determined experimentally. The response of a geothermal well due to pressure and thermal loads was obtained by considering a variety of cements. Comparative studies were undertaken that focus on the effect of fiber reinforcement on the stresses developed in the well. Such studies compare response results with those for conventional cements. In addition, a systematic effort was undertaken to investigate the steady-state as well as the transient thermal response of geothermal wells using different materials to represent the cement annulus taken from our experimental program. For this purpose, several thermal stress finite element analyses were carried out. In order to provide material data for transient analysis, thermal property tests were performed for a variety of cement formulations. Collaboration with Halliburton Energy Services continued and in FY 2002 emphasis was placed on performing and interpreting triaxial material tests of our cements. We have also interacted with other companies involved in drilling and completion and with geothermal operators all of whom have expressed strong support for our research on the mechanical behavior of cemented well systems and the need for this knowledge in order to improve well performance.

Reports & Articles Published in FY 2002:

Berndt, M. L., and A. J. Philippacopoulos, "Incorporation of Fibres in Geothermal Well Cements," *Geothermics*, Vol. 31, pp. 643–656, 2002.

Philippacopoulos, A. J., and M. L. Berndt, "Structural Analysis of Geothermal Well Cements," *Geothermics*, Vol. 31, pp. 657–676, 2002.

Philippacopoulos, A. J., and M. L. Berndt, "Mechanical Response and Characterization of Well Cements," *SPE Annual Technical Conference*, Paper: SPE-75930, 2002.

Philippacopoulos, A. J., and M. L. Berndt, "Mechanical Property Issues for Geothermal Well Cements," *Geothermal Resources Council Transactions*, Vol. 25, 119–124, 2001.

Presentations Made in FY 2002:

U.S. Department of Energy Geothermal Energy Program, Drilling Peer Review, March 2002, SPE Annual Technical Conference and Exhibition, San Antonio, October 2002

Planned FY 2003 Milestones:

Complete tensile tests on well cements.	Aug 03
Prepare technical report.	Sep 03

PRIOR YEAR SOLICITATIONS
(CARRYOVER FUNDING)

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC04-94AL85000

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Collaborating Researchers: Thermasource, Mauer Engineering APS Technology, Drill Cool, Two-Phase Engineering, Caithness, Weatherford Completion Systems, Cal Energy, GWB Consultants, Bill Rickard Inc.

DOE HQ Program Manager: Ray LaSala
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DOE Funding Allocation: $0K (Carryover of $596 K in contractual commitments)

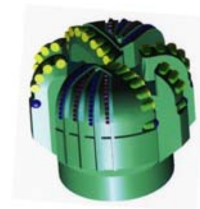
Cost Share Funding: ~$600K in kind

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. (Industry share is substantially greater than 50%.)

Background / Approach: Solicit jointly funded projects addressing near term drilling and well maintenance related needs of industry. The projects determined through solicitation are selected using 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 provide support for each project (instrumentation, analyses, etc.) as needed, consistent with available funds. Exchanges between industry experts and the National Laboratories occur on a daily basis. This project funds cost-shared, near-term, broadly applicable technology development projects for reducing drilling, well maintenance, and related costs. This support to industry is vital, largely because the geothermal industry is small and represents a limited, specialized market and the technical well construction challenges it faces are among the toughest. The projects discussed below are carryover projects from the Geothermal Drilling Organization and from the FY 2000 and FY 2001 solicitations. Support for these projects comes from $596 K in carryover funds.

Status / Accomplishments:

Hybrid Drill Bit-Thermasource (FY 2000 Solicitation)



Testing is needed on a hybrid bit that uses both PDC and thermally stable polycrystalline (TSP) diamond cutters to improve bit life and expand the range of formations that can be drilled with drag bits. TSP cutters do not have the cobalt binder used in PDC cutters. This makes them more thermally stable and wear resistant. TSP cutters have shown the ability to cut hard rock in a number of single-cutter laboratory tests. Conventional PDC bits cannot drill, or are severely damaged by, conditions found in geothermal drilling environments. If the hybrid bit can drill through hard zones while maintaining performance in softer formations, then drilling costs could be substantially reduced by decreasing the down time to replace worn out roller bits. During the reopening of the Bottle Rock geothermal steam field in northern California, hybrid bits will be used for drilling tests. Thermasource, Maurer Engineering, Sandia, and Diamond Products International designed the hybrid drill bits. Diamond Products International fabricated the bits. Due to permitting problems and problems in financing no substantial progress was made in FY 2002. Problems encountered by Thermasource in financing and permitting caused large delays. However testing this bit at either Bottle Rock or an alternative site should be accomplished early in CY 2003.

Slim hole Production Testing-Trans Pacific (FY 2000 Solicitation)

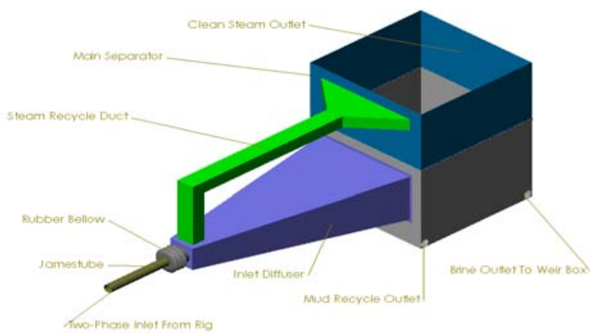
Political and legal complications in Nicaragua and Honduras precluded consummating this project and plans were made to cancel the contract with TransPacific late in FY 2002.

High-Temperature Turbine-Alternator for Geothermal Drilling-APS Technology (FY 2001 Solicitation)

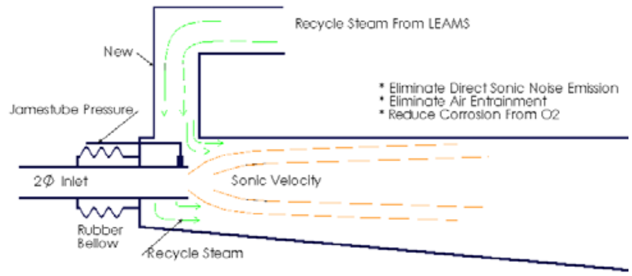
Effective drilling, whether for geothermal power or oil exploration, requires real-time data from downhole to enable timely decision-making. Efforts to develop measurement-while-drilling (MWD) systems for geothermal wells have been hindered by a numerous factors. These include lack of high temperature (HT) components. Finding effective power sources for such tools remains problematical. By providing a reliable, long-lived source of adequate electrical power during geothermal drilling operations, it is hoped that these advances will result in more efficient, cost-effective drilling for geothermal wells. A turbine-alternator suitable for use in geothermal drilling was designed in FY 2002 and fabrication was well toward completion. The power conditioning circuit donated by Gyrodata was finalized and chassis design and interface wiring were near completion. Turbine bearings and seal designs are complete. Design of power section including gearbox design is complete. A downhole test plan was completed. This turbine-alternator will also be used to power a thermoelectric cooling system to cool the critical components of a geothermal MWD system during a field test.

LEAMS II-Two Phase Engineering and Drill Cool (FY 2001 Solicitation)
The Low Emissions Atmospheric Metering Separator (LEAMS) is a new separator for the geothermal industry. This separator controls solid and brine carry-over emissions, acid gas, hydrogen sulfide abatement chemical excess and their byproducts. The separator also provides on-location brine metering, and safety, stability, and a good flow capacity. The field tests of LEAMS I demonstrated high flow capacity and excellent separation performance of steam, brine, and solids. LEAMS is intended to replace the old Blooie Muffler (cyclone separator), known for its high noise and low separating efficiency. The noise levels of LEAMS I were too high, however. Thus LEAMS II has, as a goal, a 20-db improvement of noise abatement over LEAMS I. Other improvements are in the areas of condensation, oxygen induced corrosion scaling, hydrogen sulfide abatement, and separator capacity. During FY 2002 the bench scale

work was completed and design drawings of LEAMS II were completed and sent to Drill Cool for fabrication.

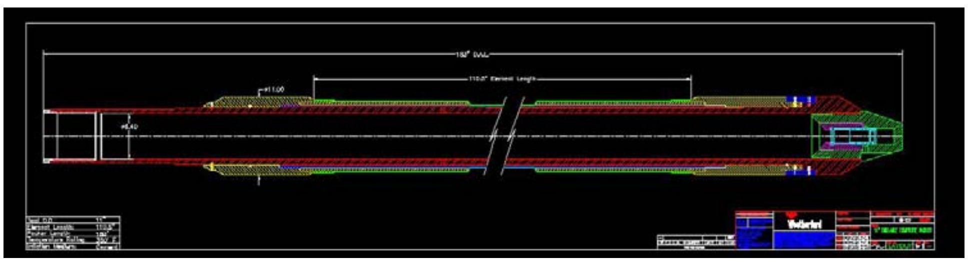


Noise Attenuator For LEAMS



LEAMS Noise Attenuator "Eductor Principal"

__Foam Cement Retainer Packer and Procedures for Deploying Foam Cement-Caithness Energy Weatherford Completion Systems and Bill Rickard Inc. (Carryover GDO Project)__



Foam cement has often been successful in stemming lost circulation in instances where multiple standard cement plugs have failed. This project has taken two parallel tracks, one to test and fabricate a drillable packer for applying foam cement, literally a foam cement squeeze. A second track is to develop procedures for applying foam cement. In FY 2002 the foam cement packer, successfully tested in Weatherford's Houston Yard, was fabricated for use on Caithness' Coso Field. Unexpected lack of lost circulation at a Coso well postponed the test. CalEnergy and Thermasource have potential needs for a similar packer. Bill Rickard completed a draft of the study of the application of Foam Cement at the Coso Field in FY 2002 on contracts for both Cal Energy and Sandia. Preliminary conclusions of this study (subject to further review) suggest:

Primary foam cementing of casing strings has been successful in the Coso Geothermal Field and should be utilized as a cost effective alternative to conventional cementing.

The most economic benefit has been realized when primary foam cementing is combined with the use of lost circulation material (LCM) in the drilling fluid continuously for “proactive” prevention, elimination, and/or reducing the use of lost circulation remedial cement plugs wherever possible.

Investigation and planning for drilling at Coso with high concentrations of LCM in the drilling fluid.

Foam cement lost circulation squeezing (applying foam cement under pressure) at first look was not successful or very economical. (Revisiting the data early in FY 2003 strongly suggested that this technique was much more promising than indicated earlier.) It is hoped that the use of the newly developed cement retainer/packer will put the application of foam cement on a more systematic and successful basis.

Interpretation of Foam Cement Logs-Cal Energy, Cal Energy (Carryover GDO Project)

The use of lightweight cements has become more prevalent in high temperature wells due to its improved elasticity. Additionally, the low density of cement adds benefits for geothermal wells where the fracture gradient is low and the incidence of natural fractures may be large. These cements have been difficult if not impossible to detect by conventional log interpretation. New techniques are now available from service companies that dramatically improve the chances for determining cement integrity with these lightweight cements. Much higher temperatures and larger casing sizes add to the degree of complexity. In FY 2002, existing cement bond logs were studied and guidelines were offered for improving interpretation for these cements. Both extreme temperature changes and pressure testing of casing can create a micro annulus. These extreme temperature changes could change the cement properties, making it even more difficult to understand the expected acoustic impedance from ultrasonic logs. Guidelines for lightweight cement interpretation include:

The correct standoff and frequency used with ultrasonic devices is important in geothermal wells.

Larger size casings reduce acoustic signals significantly. Baker Atlas segmented bond log an alternative.

Micro-annulus effects may be more significant due to heating and cooling in geothermal wells.

Proper inputs for fluid, casing and cement values are critical to interpretation for ultrasonic logs.

New evaluation techniques needed to discern solids from liquids when acoustic impedance is too low.

Additional Schlumberger presentations help with the understanding of data interpretation and quality.

Cal Energy, assisted by GWB consultants and Sandia, prepared to run a suite of cement bond logs in 13 3/8-inch titanium casing that was foam cemented. Guidelines above were followed. Logs would include the Halliburton Cast V log and their conventional cement bond log, the Schlumberger USIT log and their cement bond log, and the Baker Atlas Segmented Bond Log. Results of all logs (run early in FY 2003) will be compared to determine the state of the foam cement job and to refine and optimize the interpretation of foam cement logs.

Reports & Articles Published in FY 2002:

Batcheller, Gary W., Dennis Kaspereit, Fred Pulka, and Todd Van de Putte, “Evaluating Light-Weight Cement in the Geothermal Environment,” in *Proceedings of the GRC, Vol. 26.*

Presentations Made in FY 2002:

Presentation made to Ray LaSala in review of SNL Geothermal Program, January 2002, Albuquerque, NM.

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

HEAT EXCHANGER FIELD TESTS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: National Renewable Energy Laboratory
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DOE Funding Allocation: $200K

Cost Share Funding: $200K in-kind estimated by Bob Curran & Sons and Mammoth Pacific LP

Project Objective: Corrosion, erosion, and fouling by scale deposits are major issues for geothermal-fluid-wetted heat exchanger tubes and other plant equipment in geothermal power plants at several reservoirs. In some cases, expensive corrosion-resistant alloys are used in shell-and-tube heat exchangers or other components because of the need for corrosion resistance. In other cases, frequent heat exchanger retubing or equipment replacement is required to repair corroded tube bundles. Capital and maintenance costs of geothermal equipment in these environments can be reduced considerably if inexpensive carbon steel tubes could be coated with a low-cost, thermally conductive coating that provides corrosion resistance equal to that of high-grade alloy steels, thus reducing the levelized cost of generating geothermal power. Corrosion-, erosion-, and fouling-resistant coatings for carbon steel tubes have been investigated at Brookhaven National Laboratory (BNL) and the National Renewable Energy Laboratory (NREL), in cooperation with industry partners CalEnergy Operating Company, Mammoth Pacific LP, Bonnett Geothermal, and Bob Curran & Sons. These partners have hosted field tests of the coatings at geothermal power plants and have commercialized the coatings.

Objectives in FY 2002 were to start field tests in new locations, maintain tests in current locations, and install a PPS-coated piece of equipment in operating service at a geothermal power plant. All objectives were met.

Background / Approach: The research program is developing coatings for high- and low-temperature applications. On the high-temperature side of the plant, the goal is to develop a coating less susceptible to high-temperature hydrothermal oxidation. We found that polyphenylenesulfide (PPS) is one polymeric material that meets these requirements. Although PPS coatings showed oxidation after exposure to acid brine at 390°F, they played a key role in successfully protecting inexpensive carbon steel heat exchanger tubes against corrosion in wet, harsh, geothermal environments. Our findings suggested that PPS-coated carbon steel tubes can be used in place of expensive titanium alloys, Inconel, and stainless steels, which are frequently used in geothermal power plants. Because of its semicrystalline polymer structure, PPS has good surface hardness and smoothness. Fillers are used to further improve the hardness, thermal conductivity, and surface energy characteristics of the PPS coating.

On the low-temperature side of the plant, we have begun to explore organometallic polymer (OMP) coatings to protect evaporative condensers and aluminum finned tubing that may be sprayed with geothermal fluid or well water. Strategies to use geothermal fluid to augment heat transfer by evaporative means are being explored at a number of geothermal plants in new and retrofit applications. The zinc coating of typical evaporative condensers does not have good resistance to scaling by geothermal fluid and may have a short life in a highly ionic environment. Coating the zinc with a protective coating, or eliminating the zinc in favor of a corrosion barrier coating with anti-scaling properties, is being explored. A strategy for air-cooled plants is to spray geothermal fluid directly on the finned tubes during the summer. The finned tubing has been shown to experience severe pitting and scaling during short tests with relatively clean geothermal fluid. OMP coatings are being considered for both of these applications.

Status / Accomplishments: In FY 2002 field tests were conducted at two current and new sites. Field tests of internally coated heat exchanger tubes continued in an apparatus installed at the Mammoth Pacific binary plant using side streams of production and injection fluids. At this facility tests have been ongoing since August 2000, and some test articles have been in the apparatus for two years. This is the longest exposure test ever achieved in the program and will yield important data on long-term exposure of PPS to the highest temperature at which it has been tested in the field. Other test articles were installed, periodically inspected, and removed over the course of the year with a variety of coating formulations. At the Cove Fort plant, a new test site that uses both flash and binary technologies, the first installation of an operating piece of PPS-coated equipment occurred in the spring of 2002 (see Figure 1). This installation consisted of coated steam vent pipelines that experienced severe corrosion in the past due to exposure to acidic condensing steam. The pipelines will be periodically inspected in future fiscal years to monitor coating performance. Coupon tests were also performed in the Cove Fort cooling tower basins in collaboration with Pete Pryfogle of INEEL. Coupons were prepared for installation at a Salton Sea location and at The Geysers, but placement did not occur in FY 2002. Plans were made to start tests at a high-temperature location in collaboration with Paul Hirtz of Thermochem. Plans were also made to start tests at The Geysers of PPS-coated pipe spools exposed to

Figure 1. PPS-coated steam vent pipelines being installed at the Cove Fort geothermal plant.

treated production brines. And finally, an evaporative condenser salvaged at NREL was refurbished and sent to Mammoth for use in evaluating how materials respond to brine spray heat transfer augmentation. The unit will be fitted with coupons coated with different formulations of OMP. Plans were also made to start field tests at Mammoth of OMP-coated aluminum finned tubing exposed to brine spray.

Results of preliminary economic analysis of the life-cycle costs of coated equipment versus uncoated materials showed that an 80% cost savings can be obtained by the use of PPS applied to carbon steel substrates in comparison to the use of corrosion-resistant materials or to the frequent repair and replacement of uncoated carbon steel components (see Figure 2).

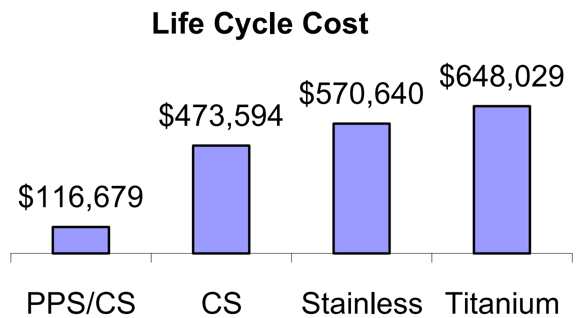

Figure 2. Life-cycle cost comparisons for PPS-coated carbon steel (PPS/CS), uncoated carbon steel (CS), and two corrosion-resistant materials.

Work associated with this research earned an R&D 100 Award for "Smart, High-Performance Polyphenylenesulfide (PPS) Coating System," joint entry with BNL, Bob Curran & Sons Corp., and Ticona Corp.

Reports & Articles Published in FY 2002:

Gawlik, K., T. Sugama, and D. Jung, "Organometallic Polymer Coatings for Geothermal-Fluid-Sprayed Air-Cooled Condensers," *Geothermal Resources Council Transactions*, Vol. 26, pp. 657–661, Sept. 22-25, 2002.

Presentations Made in FY 2002:

Geothermal Resources Council Annual Meeting on above topic.

Planned FY 2003 Milestones:

Complete fabrication of high-temperature test rig (collaboration with Thermochem)		Dec 03
Start coated tube tests at new high-temperature site	(C)	Jan 03
Complete current exposure tests at Mammoth, clean selected tubes, cut and visually analyze samples, ship samples to BNL		Feb 03
Complete exposure tests at high-temperature site, analyze heat transfer and pressure drop results, visually inspect samples, ship samples to BNL	(C)	Apr 03
Complete exposure tests at Mammoth, clean selected tubes, cut and visually analyze samples, ship samples to BNL	(C)	Aug 03

GEOTHERMAL PLANT PROCESS GAS MONITORING

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
Renewable Energy and Power Technologies
2525 North Fremont Drive, P.O. Box 1652
Idaho Falls, ID 83415-3870

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Collaborating Researchers:

DOE HQ Program Manager: Ray LaSala
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E-mail: raymond.lasala@ee.doe.gov

DOE Funding Allocation: $260K

Cost Share Funding: $12K (Industry In-Kind)

Project Objective: This project is directed toward the goal of reducing the levelized cost of geothermal power to 3–5 cents/kWh by 2007 through the development and verification of low maintenance instrumentation for the real-time detection and control of various abatement process parameters.

Background / Approach: 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. The overuse of chemicals for abating hydrogen sulfide in a typical plant is estimated to result in unnecessary expenditures of $75,000 to $100,000 annually. 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. In brine-dominated resources, the deposition of silica and other minerals is a serious concern. The formation of silica scale in pipelines, heat exchangers, and reinjection wells places major constraints in fluid utilization in some geothermal operations, and can result in large maintenance costs for operators. Silica precipitation kinetics is generally not well understood and deposition on plant components can occur quickly without proper controls. Techniques for preventing the deposition of scale include restricting brine temperatures to above that at which silica super-saturation occurs and acidification of the brine phase to inhibit silica deposition. In other approaches, chemical inhibitors are used to sequester or complex with silica, preventing its precipitation. In general, 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 technologies 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 (H_2S) in geothermal process gas streams. A system, based upon a near-infrared, frequency-modulated laser spectroscopy technique that is capable of measuring process hydrogen sulfide levels at the part-per-million level has been successfully developed and field tested. A similar instrument has been evaluated for the detection of hydrogen chloride in steam. has been successfully developed and field tested

In FY 2001, the work was expanded to investigate the feasibility of using optical measurements for the real-time monitoring of fluid properties in geothermal process streams. In particular, the development of a new generation steam quality monitor was explored based upon the selective absorption of infrared radiation. The measurement principle relies on the fact that water vapor (steam) and liquid water exhibit strong rotational and vibrational absorption bands in the middle- and near-infrared range of the electromagnetic spectrum. Typically, two wavelengths are used in the measurements: a wavelength that is strongly absorbed by water and a reference wavelength that is minimally influenced by water and steam which serves as a reference to correct for particulate or droplet scattering. The two wavelengths are chosen to be as close as possible in order to more effectively correct for scattering effects. While these techniques have been known for decades, they are not widely used due to the cost and complexity of the instrumentation required. In general, large-scale, Nerst glowers are needed to provide sufficient infrared radiation for the measurements, which are usually performed in regions of the electro-magnetic spectrum that are not compatible with sensing over optical fibers or the use of room temperature detectors. This project is re-engineering these types of systems to incorporate new semiconductor emitter and detector technologies that are compact, lightweight, and portable (battery operation is possible). All of these components operate at room temperature and could conceivably be packaged as devices that could be directly interfaced to steam lines and used to collect and transmit data from locations throughout the field.

Techniques for evaluating the concentration of solids and dissolved solids found in geothermal fluids are of interest since the presence of these materials even at very low levels can cause significant damage to plant components. Currently, these measurements are performed by conductivity or trace chemistry means. Conductivity measurements are highly impacted by dissolved gases and therefore are not useful for detecting trace amounts of solids. Trace chemical techniques can be very accurate but are labor-intensive and require long time lags between sampling and analysis. Consequently, a real-time capability for monitoring steam purity is under investigation. The monitor 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 and produces 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. The amplitude of the acoustic signal, as a function of the laser energy, can be used to determine the particle size. (Larger energies are required to generate breakdown of smaller particles since they are less absorptive.) The particle concentration, or number density, is then determined by measuring the number of signals as a function of laser energy. While the instrumentation seems complex, new diode-pumped, chip lasers, silicon microphone technology, and compact spectrometers offer the possibility of packaging this type of measurement into a low-cost, fiber-coupled system for plant application.

The steam quality and particulate impurity monitoring techniques have demonstrated the ability in laboratory proof-of-concept testing to detect gaseous and particulate species of interest within the ranges expected in geothermal applications. In FY 2002, the project concentrated on the redesign and packaging of these systems for field deployment and evaluation.

Status / Accomplishments: A field evaluation of the steam quality monitor was conducted at the Bonnett Geothermal Plant at Cove Fort, Utah, June 24-July 5, 2002. During the evaluation, steam from three locations including a well head, a flash/separator vessel exit pipe, and an ejector line was sampled and measured. The experimental setup for the measurement of the well head steam is shown in Figure 1. For the experiments, the process steam was sampled into a well insulated, flow-through cell approximately 0.8 meters in length and 0.25 meters in diameter. The cell was configured with three optical ports so that several transducers could be tested simultaneously. The optical emitters and receivers and associated electronics were housed in the box located to the left of the cell. Changes in the optical signals were digitized and transferred to a personal computer where they were displayed and logged. Since the process streams contained some unknown fraction of moisture the cell was configured with heaters so that the process steam could be dried. This capability allowed the researchers to introduce controlled changes in the process stream and observe the instrument response to these changes. The optical signals were compared with steam quality data collected with an Ellison throttling calorimeter installed in the sampling line near the exit port of the optical cell. (The calorimeter is located just below and near the left side of the cell in the picture.)

Figure 1. Well Head Installation of the Steam Quality Monitoring Instrumentation at Bonnett Geothermal Plant.

Data from the field experiments indicate that the optical technique is quite sensitive to changes in steam quality. Referring to data collected from the ejector inlet experiments, shown in Figure 2, a 93% attenuation of the optical signal was observed for a 0.3% change in quality as measured by the calorimeter. This implies that even with a fairly crude optical measurement sensitivity of 10%, changes in quality on the order of 0.03% are achievable.

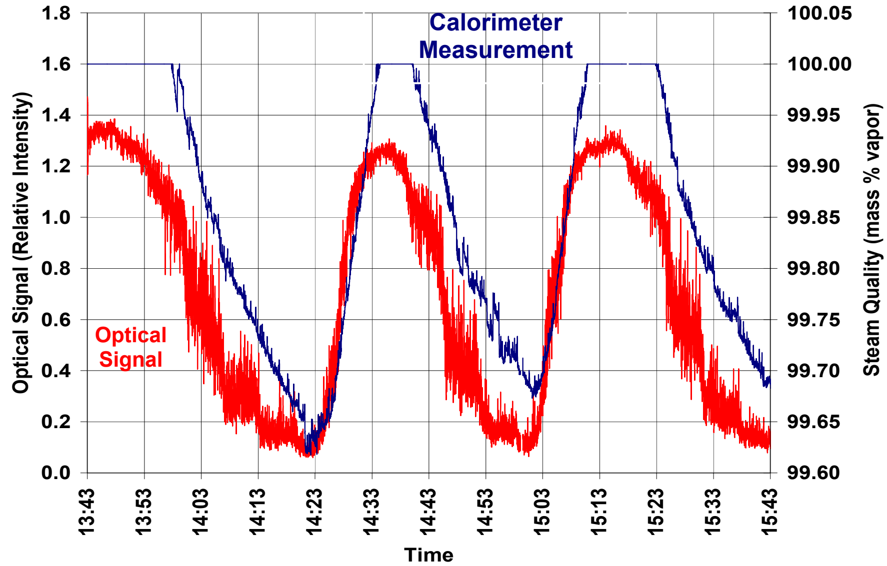

Figure 2. Steam Quality Monitor Data Collected From Steam Ejector Inlet Line.

The practicality of designing and fabricating a remote sampling head for use with the steam purity monitoring instrumentation was also explored. The goal was to determine if the basic features of the laboratory system could be integrated into a device that could be deployed and used for the *in-situ* characterization of particulate in a process stream. A slip-stream sampling apparatus was designed, incorporating off-the-shelf components, that could be implemented and tested in a field environment. Interest in the continued development and application of the technologies has been expressed by industry and include contacts made by Ormat and AMEC corporate representatives.

Reports & Articles Published in FY 2002:

Partin, J. K., and J. R. Davidson, 2002. "Investigation of Optical Technologies for Measuring Geothermal Fluid Properties*," Geothermal Resource Council Transactions*, Vol.26, pp. 739-743.

Partin, J. K., and J. R. Davidson, "Optical Steam Quality Measurement System and Method," Patent Filed 09/19/02.

Presentations Made in FY 2002:

Partin, J. K., and J. R. Davidson, 2002, "Investigation of Optical Technologies for Measuring Geothermal Fluid Properties," 2002 Annual Meeting of the Geothermal Resources Council, September 25, Reno, NV, 2002.

Planned FY 2003 Milestones:

1. Quality measurement sensitivity ≥ 0.03% demonstrated in an extended, *in-situ* steam line deployment
2. Announcement published in Commerce Business Daily soliciting licensing partners.

MICROBIOLOGICAL RESEARCH

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory (INEEL)
Renewable Energy and Power Technologies
2525 North Fremont Drive, P.O. Box 1652
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Allen Sonneville
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DOE HQ Program Manager: Ray LaSala
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DOE Funding Allocation: $235K

Cost Share Funding: $15K (Industry In-Kind)

Project Objective: The objective of this program is to investigate the impacts of microbiological activities on the efficient operation of geothermal power production facilities and to develop techniques for mitigating the costs associated with these effects.

Background / Approach: Heat rejection systems in steam and flash-steam geothermal power plants utilize steam condensate for make-up water for the cooling systems. INEEL sampling activities at these types of plants in California, Nevada and Utah have shown that their cooling waters contain significant densities of bacteria. The steam condensate typically contains impurities such as hydrogen sulfide, ammonia, carbon dioxide, and dissolved solids that provide sources of nutrition for the support of microbial growth. These microorganisms can adhere to the surfaces of critical components in geothermal heat rejection systems and develop complex structures called biofilms. The development of biofilms can impact plant performance in a number of ways. Their development on heat transfer surfaces retards the exchange of heat, which elevates condenser pressure and reduces the amount of power generated. The biofilms can also damage equipment by direct corrosion processes (microbially-induced corrosion), or by accelerating chemical corrosion activity. Microbial growth can reduce the effectiveness of plant chemical abatement systems. In bioreactor studies performed at the INEEL microbial activity increased when organisms were exposed to the iron chelate compound used in hydrogen sulfide abatement systems, indicating that the organisms were using the compound as a feedstock. Biofilms may also interfere with corrosion inhibitors by preventing their contact with the metallic surface.

The impact of microbial activity on the operation of a 100 MWe plant has been estimated to be more than $500,000 annually, primarily due to lost revenue. This impact on revenues is largely due to the impact the formation of a biofilm has on plant performance. Experience at The Geysers indicates that the condensing pressure drops by ~ 0.5 inch-Hg after cleaning (on a two-year maintenance cycle). Although operators apply chemicals to control the microbial growth, fouling in condensers is dominated by biofilms. If one conservatively assumes that the impact of the biofilm on heat transfer is linear with time, $\sim 2.7 \times 10^7$ kW-h of power generation would be lost over the two year operating cycle due to the increased condenser pressure. At $0.03 per kW-h, this lost power revenue would approach a value of $400,000 per year. The lost power revenues due to cleaning (1 day every 2 years) and due to tube failures (1% loss of tubes annually) were estimated to be ~$63,000 annually. In addition to lost revenues, the chemicals operators apply to control biological activity are also costly. (An operator of a small 10 MWe flash plant has indicated that their annual expenses for biocides approach $100,000.) In spite of the high costs associated with biofouling, few plants have biological monitoring programs in place. Most facilities either apply treatments on a predefined schedule, or on as-needed basis, corresponding to the visual evidence of growth. Consequently, there is the potential that an improper dosage of biocide will be added to the process stream. In addition, these treatments are typically designed by the vendors who sell the chemicals; and therefore, have little incentive to reduce their costs.

In order to characterize and evaluate the effect of microbiological growth in geothermal process streams, a multi-year study was conducted, incorporating several plants at The Geysers in Northern California. These initial studies used conventional sampling methods and evaluated a variety of commercially-available techniques. Based upon this evaluation, one instrument, an electrochemical biofilm monitor called the BIoGEORGE™, was selected for an extended field trial initiated at the Bonnett Geothermal Plant in FY-2001. While this monitor appears promising for detecting biofilm development in plant environments, it cannot measure corrosion or the potential for chemical or material degradation. These activities are believed to be associated with sulfur and other metal oxidizing and reducing bacteria. (These types of bacteria are also often associated with biofilms.) Therefore, the program has been evaluating and developing molecular (or DNA) probes to monitor for bacteria participating in these activities. This development is being performed in collaboration with researchers at UC Irvine and the Orange County Water District who are using their DNA database to customize the probes. The probes are based upon the sequence-specific recognition that occurs when two molecules bind together and employ a known DNA sequence which may be either organism-specific or may encode for a the production of an enzyme unique to a metabolic pathway (such as sulfate reduction). Once the target sequence is identified, a complementary strand of DNA is constructed and tagged with a fluorescent compound that can be detected upon exposure to the original molecule.

Status / Accomplishments: The application of fluorescently-tagged, in-situ hybridization (FISH) probes for tracking microbial activity in geothermal process fluids was investigated in the laboratory. Testing was performed using a commercially-available 16S rRNA oligonucleotide probe #385 (CGGCGTCGCTGCGTCAGG) target for general sulfate reducers. The work was performed using samples prepared from cultures of two known sulfate reducers (DSM644-*Desulfovobrio vulgaris* and DSM642-*Desulfovibrio desulfuricans*), samples collected from geothermal fluids inoculated with DSM644, and a culture of *Escherichia coli*, which served as a negative control. A general bacterial stain, DAPI, was used to identify all cells present. The tests were able to distinguish the general population of cells stained with DAPI from the sulfate-reducing bacteria DSM642 and DSM644. These experiments indicate that it is possible to use these procedures with geothermal samples without chemical interference.

Additional probes are currently under development for tracking sulfur oxidation. These probes are being designed around three species, *Thiobacillus neapolitanus*, *Acidithiobacillus caldus*, and *Methylococcus capsulatus*, which were identified in the sampling and characterization studies performed at The Geysers. The first two species are of interest since they are associated with sulfur metabolism, and in particular have the capability of altering the pH of their environments. (Chemists from Calpine at The Geysers and Thermochem, Inc., have indicated that they believe microbially-induced sulfur oxidation is occurring at some of the geothermal facilities, producing more acidic and damaging environments.) *Methylococcus* species are also capable of reducing metals, increasing their motility in solution. In addition to providing a diagnostic for determining the potential for microbially-influenced corrosion in the plants, these probes could be also be valuable in the control of a proposed natural sulfide abatement process under investigation at the Geysers.

An extended field deployment and evaluation of the BIoGEORGE™ Biofilm Monitor has been conducted at the Bonnett Geothermal Plant, Cove Fort, Utah. The probe was installed into a two-inch pipe that bypasses a valve in the cooling water line up-stream of the condenser as shown in Figure 1. The flow in the pipe was set to achieve a fluid velocity approaching that in the condenser tubes.

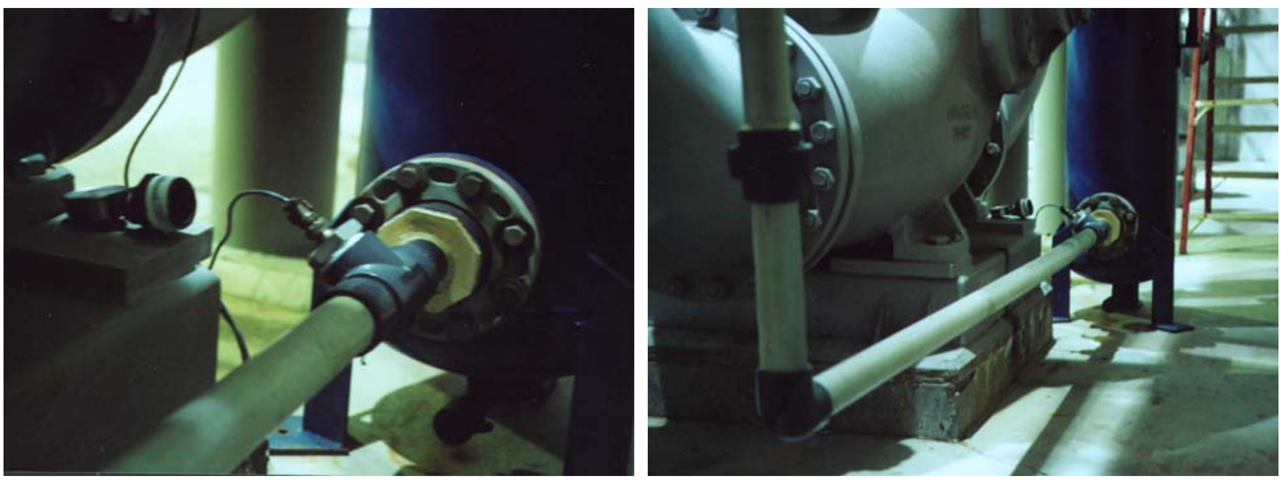

Figure 1. BIoGEORGE Biofilm Probe Installed in Cooling System at Bonnett Geothermal

Instrument readings from the probe appear to track with changes in operational parameters consistent with fouling. A recent fouling event recorded around August 11, 2002, is shown in Figure 2. The probe was removed from the pipe, cleaned and reinstalled following a shutdown at the plant in June 2002. The figure indicates how rapidly fouling can occur in these systems, and the degree of fouling is particularly impressive in light of the fact that chemical treatments were being applied throughout this period.

Project personnel are continuing to work with plant operations in assessing the long-term performance of the device. The goal is to build sufficient confidence in its operation with plant personnel that they would feel comfortable using it to determine the optimal timing and dosage of chemical treatments, thereby reducing costs. A key step in this process is the development of a means of calibrating the instrument to determine what minimum signal change can be reliably detected as an indication of the formation of a biofilm. This minimum signal change could then be used as a setpoint for applying treatments. The calibration will be performed by deploying a series of coupons in the process stream containing the probe and correlating biofilm thickness with the instrument readings. A more user-friendly, real-time display for presenting the data to the operators is also under development.

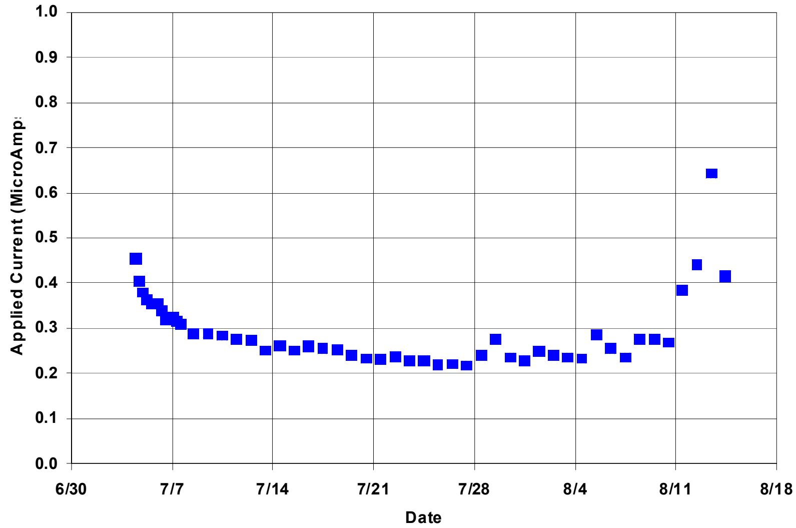

Figure 2. Applied Current Data Indicating Fouling of the BIoGEORGE™ Probe.

Reports & Articles Published in FY 2002:

Pryfogle, P. A., G. L. Mines, T. L. Sperry, and R. G. Allred, 2002. "Investigation of an Electrochemical Monitor for Tracking Biofilm Development at the Bonnett Geothermal Plant, Cove Fort, Utah," *Geothermal Resource Council Transactions*, Vol.26, pp. 745-748.

Presentations Made in FY 2002:

Pryfogle, P. A., "Investigation of an Electrochemical Monitor for Tracking Biofilm Development at the Bonnett Geothermal Plant, Cove Fort, Utah," 2002 Annual Meeting of the Geothermal Resources Council, September 25, Reno, NV, 2002.

Planned FY 2003 Milestones: Display installed that provides real-time BIoGEORGE™ Biofilm Monitor data including fouling trends.

MITIGATION OF IMPACT OF OFF-DESIGN OPERATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	AC07-99ID13727
Performing Organization:	Idaho National Engineering and Environmental Laboratory Renewable Energy & Power Technologies 2525 North Fremont Drive P.O. Box 1625 Idaho Falls, ID 83415-3830
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DOE Funding Allocation:	$137K
Cost Share Funding:	None

Project Objective: The goals of DOE's Geothermal Program include increasing the supply of electrical power produced by geothermal energy by reducing the levelized cost of power to 3–5 cents per KWh. In this task methods are identified that minimize the adverse impact that off-design operation has on geothermal power plants (both new and existing). Successful methods are also expected to provide operational flexibility, which will allow plant operators to maximize power production during periods when a premium price is paid for generated power. Increasing power output during periods of off-design operation and premium power prices will increase revenue streams, thus lowering the cost of power and contributing to DOE's goal of enhancing the economic viability of geothermal power production.

Background / Approach: Power plants are designed to provide a rated capacity that is based upon specific resource (heat source) and ambient (heat sink) conditions. Due to diurnal and seasonal changes in the ambient, and the decline of geothermal resource conditions, plants seldom operate at their design conditions and rated power capacity. Binary plants utilizing air-cooled condensers are particularly sensitive to changes in the ambient; the evaluation of these plants indicates their performance can degrade by more than 50% for a 50˚F rise in the air temperature. Since existing plants are typically designed for an average annual ambient temperature, they experience a significant degradation in performance during the summer when the price for power is typically at a premium.

Because of the significant impact of off-design operation to the performance of air-cooled binary plants, these plants have been the focus of the current studies. This evaluation was conducted by first developing a plant model using the ASPEN Plus process simulation software. Individual components were sized based upon equipment specifications and performance curves from existing power plants. The design resource temperature was 330˚F and the design ambient temperature was 45˚F; both values were typical of existing plants. The design geothermal fluid flow was based upon a design net output of 15 MWe. Once the individual component and system sizes were established to produce the desired power level, their sizes were fixed and the model used to predict and evaluate the effect of operating at off-design ambient and resource (both temperature and flow rate) conditions.

Plant performance was optimized at each resource and ambient condition evaluated. Available energy is a measure of the ability to do work. The available energy of the brine entering the plant establishes the maximum work that could be done by a conversion system with ideal processes. In an actual power cycle, this available energy is dissipated by the non-ideal plant processes and the plant effluent streams. That portion of the available energy that remains is the net power that is produced; the fraction of the inlet brine's available energy that is converted to net power is the second law efficiency. Model results were used to determine how off-design conditions affected the dissipation or consumption of the available energy (irreversibility) in the various plant components/processes. This allowed specific components/processes to be targeted in accessing how to best minimize the associated irreversibility and increase the net power generation. Several methods of minimizing the effects of off-design resource and ambient conditions were identified and incorporated into the modeled plant. Performance of the modified plant was then predicted at the various off-design conditions and evaluated to determine the resulting plant performance benefit.

With the completion of the evaluation of air-cooled binary plant performance, the focus of the investigation will turn to flash-steam power plants. Because these plants utilize evaporative heat rejection systems, the impact of variations in the ambient temperature is likely not be as large as in the air-cooled plants. An approach similar to, if not the same, as that used for the air-cooled binary plants is being used.

Status / Accomplishments: The evaluation of the performance of the air-cooled binary plant at off-design conditions was completed and reported in FY 2002. The results of this study showed that the major factor in the degradation in plant performance as the ambient temperature rises is due to the decrease in the available energy of the brine entering the plant. The available energy of a 330˚F resource would decline by ~1/3 with a 50˚F rise in the ambient temperature. Unless a plant were able to significantly increase its second law efficiency (conversion of available energy to power), it would experience the same decline in power generation. This increase in the second law efficiency could only be accomplished if component performance improved (pump and turbine efficiency increased and/or heat exchanger approach temperatures and friction losses decreased) at the off-design conditions. A similar assessment of the impact of a 30˚F decrease in the resource temperature, indicates the available energy of the geothermal fluid entering the plant would drop by ~20%.

The evaluation of the dissipation of the available energy in modeled plant indicates it is not possible to maintain this constant second law efficiency at off-design conditions; component irreversibilities increase at the off-design conditions, as does the available energy of the streams leaving the plant. The only off-design condition for which this did not occur was a decrease in the brine flow. In this instance, the second law efficiency of the plant increased slightly (at fixed resource and ambient temperatures); total power generation did not because the decrease in the inlet brine's total available energy is proportionate to the brine flow rate. The results revealed the irreversibilities associated with the heat exchange processes did not vary significantly with the ambient temperature. The irreversibilities associated with the rotating equipment (pump and turbine) increased, as did the available energy of the effluent streams (brine and air). When there was a decrease in the brine inlet temperature, the available energy of the brine leaving the plant increased significantly, accounting for a large portion of the degradation in the power output.

Different concepts were then incorporated into the modeled plant to determine the impact on performance at off-design conditions. One concept considered was a modification to the plant operation to remove constraints on the minimum superheat of the working fluid entering the turbine. Removal of this constraint improves plant performance as resource productivity declines, especially at lower ambient temperatures. Though the impact is small (<3%), the cost to implement is small (possible upgrade to turbine instrumentation). The use of variable frequency drives (VFDs) to manage house loads can have significant impact on performance as resource productivity declines and as the ambient temperature rises. The analysis indicated the improvement in power output could be up to 18% at the worst off-design condition (high ambient temperature and a decline in both resource temperature and flow). The analysis also indicated that the VFDs have the greatest benefit when applied to the working fluid pumps. Evaporative pre-cooling of the air entering the air-cooled condenser was also evaluated. Depending upon assumptions made relative to the pre-cooler performance (pressure drop, water flow, approach to wet-bulb temperature) and the resource and ambient, the power output could be increased by up to 40% at high ambient temperatures.

These concepts involve the incorporation of commercially available technologies. The impact of increasing the UA (product of heat transfer coefficient and surface area) value for the brine heat exchangers and the air-cooled condensers was also examined (this could be accomplished by increasing heat transfer performance or installing additional surface area). Results suggested that a 25% increase in the UA value for either heat exchange process would increase power output by 3 to 5%, depending upon the ambient temperature. At off-design conditions, the irreversibility associated with the turbine increases (efficiency decreases). It was postulated that by using a device similar to a VFD one could vary the turbine speed, and minimize the decrease in efficiency at these conditions. (Any limitations on turbine speed due to critical shaft speeds were not considered.) The results indicated there was a performance increase at higher ambient temperatures (up to 7%), however the probable power losses associated with the VFD-like device would off-set a significant portion of this power gain.

The binary plant model was also used to examine the impact of using the VFDs on the production and injection pumps. Injection pumps were considered because the temperature of the effluent brine increases as the ambient temperature rises. If this effluent brine has to be injected at pressure, the plant operation can become brine limited if the injection pumps are not sized for the summer operation. (As the fluid temperature rises, the weight of the column of liquid in the well bore decreases and additional pumping head is necessary.) For a case considered where the plant was injection limited, the use of the VFDs increased net power output from the plant by up to 5% at the higher ambient temperatures (100˚F). A scenario was also considered where VFDs were used to increase brine flow during periods when demand for power was high (hot summer days); increasing the brine flow by 10% produced increases in net power up to 14% in the scenario considered.

A similar evaluation was initiated for a flash steam plant. Plant and component data were accumulated from two facilities and models were developed. Work on this task was not completed in FY 2002 because of difficulties encountered with the modeling cooling towers and steam ejectors with the process simulator software used (ASPEN).

Reports & Articles Published in FY 2002:

Mines, G. L., *Impact of Off-Design Operation on an Air-Cooled Binary Power Plant*, INEEL/EXT-02-00815, June 2002.

Presentations Made in FY 2002:

Mines, G. L., *Evaluation of the Impact of Off-Design Operation on an Air-Cooled Binary Power Plant*, Geothermal Resources Council, 2002 Annual Meeting, Reno, NV, September 2002, pp 701-706.

Planned FY 2003 Milestones:

Complete cost analysis showing benefits of mitigating effects of off-design operation.

GEOTHERMAL CO-PRODUCTION OF SILICA AND OTHER COMMODITIES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Lawrence Livermore National Laboratory
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DOE HQ Program Manager: Allan Jelacic
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DOE Funding Allocation: $97K

Cost Share Funding: $383K from California Energy Commission (CEC)

Project Objective: Our objective is to develop extraction techniques for silica and other commodities from geothermal fluids. We will optimize the extraction methods to minimize their cost and facilitate their implementation in existing power plants. If successful, the results of this project would lower the cost of geothermal power by adding a new revenue stream from sale of byproducts. A successful silica extraction process would also allow more energy extraction per mass of geothermal fluid by lowering the cutoff temperature below which silica scaling is problematic. Project success would lower operations and maintenance costs by reducing silica scale formation in surface facilities and in reinjection wells. Reinjection wells would last longer and the surrounding formation would be better able to retain permeability.

Background / Approach: Produced geothermal brines contain large quantities of dissolved silica that often forms scale in power production facilities. During FY 2002, we collaborated with Mammoth Pacific LP (Mammoth) to convert dissolved silica into a marketable silica precipitate. We are developing an understanding of how to produce silicas with optimum properties for commercial use by varying the precipitation conditions and characterizing the silica precipitates. We used both laboratory experiments with simulated fluids, and on-site work in a mobile laboratory with actual fluids, to carry out these tests. Future work will be carried out at CalEnergy's geothermal site near the Salton Sea.

The goal of our project is to develop working silica precipitation processes for each geothermal site such that it is possible to produce silicas with properties that match a targeted silica market. We are working with technical contacts from the rubber industry and colloidal silica distributors to help identify material properties and likely markets for our produced silicas. Once silica has been extracted from spent geothermal brines, it becomes technically feasible to extract additional metals, such as lithium, from the brines without interference from silica precipitates.

Status / Accomplishments:

- Carried out scooping laboratory tests using synthetic fluids to determine best methods for silica extraction at the Mammoth site.
- Install stirred reactor and necessary plumbing into mobile laboratory for on-site testing.
- Carried out three sessions of on-site work at the Mammoth geothermal site using our mobile laboratory. The tests consisted of reacting salts and/or commercial precipitation agents with geothermal fluid discharge in a stirred reactor inside our mobile laboratory. The silica precipitates were then characterized for comparison to commercial silicas.
- Conduct preliminary tests of metals extraction from the Mammoth fluids using ion exchange resins. Fluids for these tests were removed downstream from the concurrent silica extraction tests.

The first phase of our work was to perform silica precipitation tests on simulated Mammoth fluids to determine the effectiveness of various precipitation methods. We prepared fluid compositions based on compositions supplied to us by Mammoth staff. We performed a matrix of tests with varying amounts and types of added salts and at various pH values. The rate of silica polymerization was determined by measuring monomeric silica over time. These tests showed that precipitation rates of silica in these low salinity fluids are very slow, with time scales of hours to days.

We then performed on-site silica precipitation tests at the Mammoth plant. We outfitted a trailer with a 20 liter stirred reactor in which we could induce silica precipitation in incoming geothermal fluids by mixing with salt solutions, commercial precipitation agents, and acid/base solutions. We placed cartridge filters downstream from the reactor to catch the silica particles. Over the year we tested fluids from three locations in the plant, as indicated by numbered dots one through three in Figure 1. We found that silica precipitation rates are slow in all of these fluids due both to the very low salinity (1,200 ppm salt) and low silica concentration (250 ppm). Even the cooler more silica supersaturated fluids coming off the evaporative panels had very slow silica precipitation rates. Slow precipitation rates necessitate a long residence time and therefore a large volume reaction vessel. This translates into more costly equipment that would be needed for full-scale silica removal.

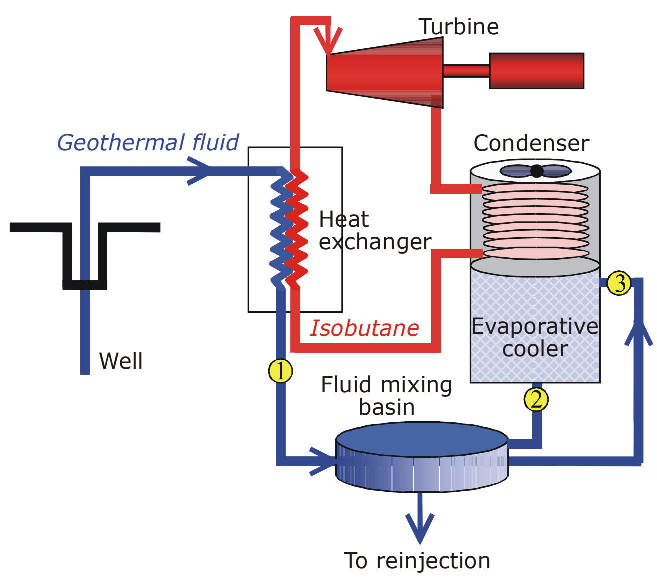

Figure 1. Schematic of Mammoth geothermal plant showing fluid sampling locations 1-3.

For this reason, we used a reverse osmosis unit to process the geothermal fluid. The reverse osmosis unit produced a concentrate enriched in silica and other salts, and a low salinity permeate. The concentrate was used in subsequent silica removal tests. The permeate could be used as input to the evaporative cooler used to cool the isobutane working fluid at Mammoth (see Figure 1). Silica removal from the concentrated fluid containing 500–700 ppm silica was more rapid. Residence times of 10 to 30 minutes produced high purity, high surface area silica precipitates. However, our silica yield from these tests was low, averaging only about 20% of the total silica. We suspect that the cartridge filters were not capturing many of the smaller silica precipitates and we are looking into alternate methods for capturing silica.

FY 2003 work will be targeted at improving silica yield, reducing the amounts of additives needed, and optimizing the process for use in a cooling tower currently being planned for a new geothermal plant at Mammoth. Work will also begin on silica extraction at CalEnergy's site near the Salton Sea. The main goals of the work at CalEnergy will be to develop methods to improve the purity of their silica byproduct, and identify appropriate markets for their silica.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002:

Bourcier, W., A. Wallace, B. Ralph, and C. Bruton, 2002, "Silica extraction at the Mammoth California geothermal site." Poster presentation at Geothermal Resources Council, 2002, Annual Meeting in Reno, Nevada.

Planned FY 2003 Milestones:

Continue to improve silica extraction process at Mammoth to maximize total yield, and minimize amounts of additives and reaction time.

Begin silica extraction work at CalEnergy's Salton Sea site.

Carry out metals extraction work at Mammoth targeted at lithium, cesium, rubidium, and tungsten.

SILICA SCALE INHIBITION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Lawrence Livermore National Laboratory
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DOE Funding Allocation: $200K

Cost Share Funding: None

Project Objective: The objective of this project is to inhibit the formation of silica scale in geothermal power plants. Effective and economical scale control allows more efficient utilization of geothermal heat by lowering the fluid temperature at which scaling occurs, and lengthening the time that brine can reside in surface facilities. Extraction of waste heat through addition of flash and bottoming cycles improves the economics of geothermal energy and makes geothermal development more attractive. It allows the use of geothermal and other water supplies for water make-up and cooling uses, especially in areas where water supplies are limited (e.g., western U.S.). Control of scaling and efficient use of inhibitors reduces operations and maintenance costs by reducing the costs of scale removal and disposal, reducing the cost of cleaning and drilling new injection wells, and reducing the cost of scale-inhibiting chemicals. Overall, economical means of controlling silica scaling in geothermal power plants will reduce the cost of generating geothermal power.

Background / Approach: Silica scaling commonly occurs in geothermal power plants. Silica scaling problems can be moderate, or so extreme that the power generation process must be specially designed to limit scaling. Even small amounts of scaling are deleterious to binary plants because of 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. There are a number of chemical additives (inhibitors) that are commercially available for scale control. However, variations in fluid chemistry, different plant operating conditions, and the complex nature of silica reactions cause the effectiveness of an inhibitor to vary widely within and among geothermal fields. The growing use of brine acidification is promising with regard to scale control, but issues remain even with this technology.

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 one or more of these key steps leading to scale deposition. For example, threshold inhibitors delay the initial polymerization of monomeric silica in a supersaturated brine, and dispersive agents inhibit agglomeration of silica colloids.

In this project, we 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 are developing a relatively rapid, reliable and robust sampling and experimental protocol for evaluating inhibitor formulations. We are obtaining a basic understanding of the effect of the inhibitors and, by on-site sampling and analysis techniques, better defining the initial chemical and physical state of the brine at the point of inhibitor addition to better select appropriate inhibitors.

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 have a mobile test facility containing required analytical equipment for on-site testing. 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 allows 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: We conducted laboratory screening of additional inhibitors for the Coso geothermal field. Of the inhibitors tested using inhibitor concentrations up to 50 ppm at a pH of 6 to 7, four antiscalants effectively inhibited polymerization of silica for 45 minutes to an hour. Of the antiscalants tested so far, one product in particular is the most effective at inhibiting the polymerization of silica in Coso-type brine.

Additional consideration was given to scale inhibition in geothermal waters from the Mammoth geothermal field. Mammoth Pacific LP plans to use spent geothermal brine as make-up water for their cooling systems in order to minimize the use of tertiary water purchased from a local utility. Silica scaling is not a problem in this binary system until the geothermal fluids are cycled through the cooling system and concentrated.

We outfitted our mobile test facility with the analytical equipment required for on-site field testing. Our analytical equipment includes 20- and 5-liter computer-controlled stirred reactors, associated heating and cooling units to control fluid temperature, a dynamic light scattering (DLS) instrument for particle size analysis, a visible spectrometer for monomeric silica analyses, water quality instruments for measuring fluid pH, conductivity, and turbidity, and a wet chemical laboratory for preparation of chemical additives used in the silica precipitation tests. Field tests are conducted jointly with the ESR&T LLNL task "Co-production of silica and other commodities from geothermal fluids."

Additional potential industrial collaborators for future on-site and laboratory testing were identified. Planned field work sites will depend on the status of their development plans and the potential to conduct joint field campaigns with the ESR&T LLNL task "Co-production of silica and other commodities from geothermal fluids."

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: Conduct field and laboratory tests to support silica scale inhibition at an additional geothermal field

POWER PLANT COSTING METHODOLOGY

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	AC07-99ID13727
Performing Organization:	Idaho National Engineering and Environmental Laboratory Renewable Energy & Power Technologies 2525 North Fremont Drive P.O. Box 1625 Idaho Falls, ID 83415-3830
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DOE Funding Allocation:	$49K
Cost Share Funding:	None

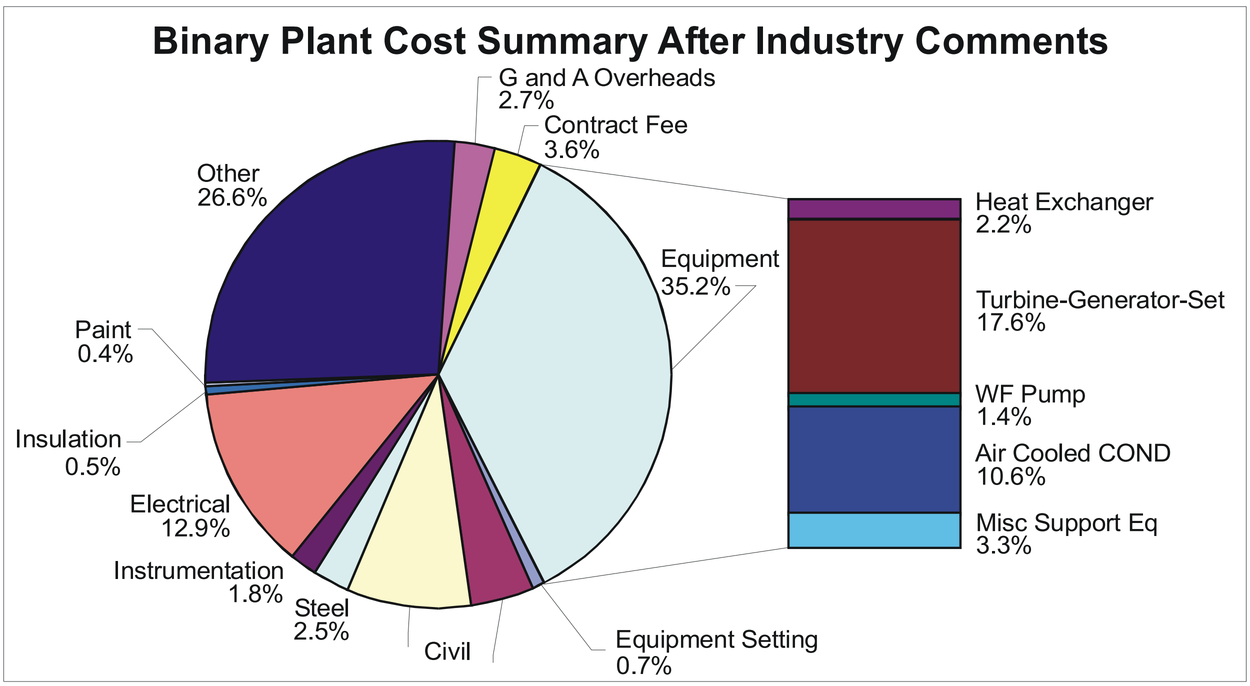
Project Objective: The goals of DOE's Geothermal Program include increasing the supply of electrical power produced by geothermal energy by reducing the levelized cost of power to 3–5 cents per KWh. In this task, methodologies are being developed to provide representative capital costs for conventional types of power plants used with liquid-dominated, hydrothermal resources (binary and flash steam). The methodologies developed will provide a means for evaluating how technology advancements for geothermal energy conversion systems impact the cost of power, and as such contribute to the goal of reducing the cost of electrical power from geothermal resources.

Background / Approach: The viability and future growth of the domestic geothermal industry is contingent upon reducing both operating and capital costs. In order to assess whether advances in technologies for energy conversion systems are reducing these costs, it is necessary that costs for components and activities related to the production of electrical power are adequately defined. Historical costs, in terms of $/KW installed, provide a valuable perspective on the costs of geothermal plants, but are not adequately for assessing the impact of improvements to specific components or systems. In this task, methods are being developed that will allow power plant costs to be determined in detail sufficient to assess the large cost items and the impact of technology improvements on the cost of these plant components/systems.

The primary issues associated with the task are the availability of data (both cost and performance) from existing geothermal plants, and the lack of current cost data (most "new" plant were built in the early

1990s). These issues have been addressed using a process where commercially available software is first used to model and size energy conversion system components (a commercial plant serving as the design basis). This modeling activity establishes the input to a costing software package that is then used to derive component, system and plant costs. Where possible, plant simulations utilize equipment specifications from commercial plants to assure that component sizes and materials are typical of those used in geothermal facilities. This methodology is then "calibrated" by providing the resulting cost estimates to industry for comments. During this process, the cost estimates may be further refined if industry is willing to provide confidential cost information for the specific plant type. This process has been applied to air-cooled binary plants and is being applied to flash-steam plants.

Status / Accomplishments: The process of using commercially available software to first model and then estimate the cost of a binary power plant was initiated in FY 2001 and completed in FY 2002. The ASPEN Plus software was used to size the plant, and the ICARUS Process Evaluator (IPE) was utilized to derive plant capital costs. A 15 MWe air-cooled binary power plant was sized and a cost estimate prepared which was subsequently reviewed by industry. Comments received on the costs were used to make appropriate adjustments of the cost model that had been developed. The resulting cost distribution for the binary plant is shown in the following figure.



Once this calibration was completed, the methodology was used to estimate costs for the 15MWe plant at different resource conditions. The subsequent results indicated the plant costs did not vary significantly (about 7%) between resource temperatures of 300˚F and 350˚F. This cost evaluation did not include the costs of the wells or the surface gathering and injection systems. These costs must be included to accurately reflect the impact of resource temperature on total project cost (and the cost of power); the brine requirement for the 300˚F resource was 68% greater than that for the 350˚F resource.

Efforts were initiated to develop methods of evaluating the capital costs of flash steam plants and to include the costs of the surface gathering and injection systems associated with each plant type. Data and equipment specifications were obtained from two operating flash plants, which were used to develop the plant model used to size components and systems. It was found that there were issues associated with modeling both cooling towers and steam ejectors with the ASPEN Plus simulator. As a result, the plant sizing activity was accomplished using EXCEL spreadsheet models developed for individual components. This subsequent sizing information is then used as input to the IPE cost model to predict flash plant costs. Cost estimates from the EPRI's *Next Generation Geothermal Power Plants* are being used to perform the initial calibration of the flash plant cost estimates. In FY 2003, estimates will be prepared for specific plants and industry input used to complete the calibration of the technique.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: Provide correlations to predict capital costs of binary plant components.

PROCESSES FOR GEOTHERMAL BRINES & RESIDUES MULTIPLE RESOURCES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: EST-174-NEDA

Performing Organization: Brookhaven National Laboratory

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DOE HQ Program Manager: Allan Jelacic
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DOE Funding Allocation: $100K

Cost Share Funding: $50K "in kind" contribution of part time personnel, well facilities and samples from Caithness Operating Company, LLC, Reno, NV and Coso Operating Company, Coso, CA

Project Objective: Modify the pilot tests of amorphous silica production process at Caithness Dixie Valley for different chemistries of geothermal brines at Steamboat Springs sites (Nevada) and the Coso site (California). Also provide data on the factors such as temperature controlled kinetics of silica production; the task will prove the concept of recovering silica from low-salinity geothermal brines. The results will be used to design and test pilot plants in out year experiments leading to commercialization of the technology.

Background / Approach: Geothermal brines and precipitates contain silica, which has a significant commercial potential. However, the quantity, quality and chemical properties of the silica vary with different geothermal sources. The properties of these silicas will determine which recovery processes are needed so that the recovered materials meet market requirements. FY 1999 studies showed that the amorphous silica isolated from Caithness Dixie Valley LLC (Nevada) sources has unique chemical and physical properties. Further, in FY 2001, BNL has worked with Caithness Operating Company in a preliminary demonstration of recovery of high-grade silica via a pilot facility at Dixie Valley, NV. In FY 2002, it is intended to study a much larger area in the Dixie Valley, Steamboat Springs, and Beowawe sites (Nevada) and the Coso site (California) for high quality silica resources. The varieties of amorphous silica materials from different geothermal resources may have multiple applications. It is to be understood that each application requires an intense study of the feedstock properties both in terms of direct and modified applications. The approach is to modify the studies that lead to pilot tests of amorphous silica production process at Caithness Dixie Valley, for different chemistries of geothermal brines.

Status / Accomplishments:

Obtain samples from Steamboat, Beowawe and Coso sites, test silica nucleation process with group 1 ions such as Na^+ and H^+ at 180–200 °F and the tests with Group 2 ions such as Ca^{+2} and Mg^{+2}. The results showed using Ca^{+2} and Mg^{+2}, high quality silica can be produced at very fast reaction rate conditions at 180–200 °F.

Initiated bonding of surface-active agents on the silica products. The study is progressing in enhancing the value of geothermal silica.

Annual Report to DOE.

Reports & Articles Published in FY 2002:

Lin, M. S., E. T. Premuzic, W. M. Zhou, Bin Dong, Ted DeRocher and S. D. Johnson, "Silica Recovery: A Promising Option to Reduce Geothermal Power Production Costs," *Geothermal Resources Council Transactions*, Vol. 24, September 22–25, 2002, p. 149–152.

Presentations Made in FY 2002:

Lin, M. S., E. T. Premuzic, W. M. Zhou, Bin Dong, Ted DeRocher and S.D. Johnson, "Silica Recovery," Presented to the Geothermal Resources Council's Annual National Meeting at Reno, NV on September 22–25, 2002.

Planned FY 2003 Milestones:

Obtain samples from Steamboat, Beowawe, and Coso geothermal reservoirs; test the nucleation process with adding group 1-2 ions, flocculent and seed silica at 200°F. The rate of precipitation is needed for selecting isolation methods. Oct.1 2002–June 30 2003.

Optimize the production yield by varying pH, temperature, reaction rates and isolation methods, June 1–Aug. 31, 2003.

Design a process and the pilot plant to test it. Aug. 1, 2003–Sept. 30, 2003.

Continue bonding of surface-active compounds on the silica products. March 1, 2003–Sept. 30, 2003.

HIGH-TEMPERATURE POLYMERIC ELASTOMERS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC02-98CH10866

Performing Organization: Brookhaven National Laboratory
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Collaborating Researchers: Bob Sullivan, Mammoth-Pacific, L.P.

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DOE Funding Allocation: $30K

Cost Share Funding: $30K

Project Objective: The goal of this task is to replace the bronze oil-lubricated bearings in down-hole pumps extracting the geothermal energy resource from hot brine reservoirs (~ 160°C) for the brine-lubricated bearings made of high-temperature stable polymeric elastomers. Success will eliminate the consumption of a substantial amount of oil and save the costs of maintenance brought about by mitigating damage of the shaft components in the pumps. Thus, the objective is focused on finding suitable materials for brine-lubricated elastomeric bearings for lineshaft pumps; i.e., those having a useful service lifetime of at least ten years.

Background / Approach: Ogden Power Corp., owner/operator of three geothermal power plants at Mammoth Lakes, CA, was selected in 1998 to receive financial assistance for R&D of elastomeric, brine-lubricated bearings to replace the bronze oil-lubricated bearings installed on the Johnston lineshaft production pumps there. Brookhaven National Laboratory was brought into the project as a technical consultant on selecting and evaluating suitable elastomers, and has been involved in that capacity ever since. The initial bearings provided by Palmer Products did not perform well because of severe hardening of the bearing material and improper specification of clearances. Among the failed bearings were those made with acrylonitrile/butadiene copolymer (nitrile rubber) and fluorinated ethylene-propylene (fluoroelastomer, Viton®). The nitrile rubber underwent severe degradation shortly after exposure. Compared with that of the nitrile rubber, the Viton elastomer significantly extended its useful lifetime as a bearing. However, the chemical and physical analyses of the 1-year-old Viton bearing revealed that ~ 25 % of them already had been degraded by hydrothermal oxidation. In contrast, the ethylene-propylene-diene-terpolymer (EPDM) bearing had far better resistance to oxidation, with the extent being 3.5 times less than that of Viton.

In FY 2001, an additional problem arose in the field test at Mammoth when elastomers became swollen shortly after their being exposed to oil-contaminated brine. This was confirmed by BNL in a subsequent autoclave test with 160°C brine containing 82 wt% water, 13 wt% NaCl, 5 wt% steam cylinder oil, and 20,000 ppm CO_2, a composition considerably more extreme than that at Mammoth. The polymeric elastomers not only underwent hydrothermal oxidation under attack by the hot CO_2-laden brine, but also reacted with the steam cylinder oil, which caused them to swell.

Status / Accomplishments: In FY 2002, BNL evaluated four commercial products; Kalrez®, Viton®ETP-500, Viton®GF, and EPDM by exposing them for up to five months to simulated oil-contaminated geothermal brine in a 160°C autoclave. The factors evaluated included the changes in weight, the extent of degradation of the exposed elastomers, and thermal stability. To obtain the information on the second parameter, we explored the alterations in microstructure and the changes in elemental distribution in the cross-sectional profiles of the five-mo.-long exposed elastomers by scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectrometry (EDX). Information on thermal stability was obtained by measuring the temperature at the beginning of thermal decomposition of the elastomers before and after five months exposure, using the thermogravimetric analysis (TGA). From the findings, BNL strongly recommended Kalrez® and Viton®ETP perfluorocarbon-related elastomers for use as anti-swelling and anti-oxidation bearing materials in geothermal down-hole pumps. Because they exhibited negligible weight loss (Figure 1), no notable degradation of the superficial layer, no swelling, and an excellent thermal stability of > 350°C (Figure 2).

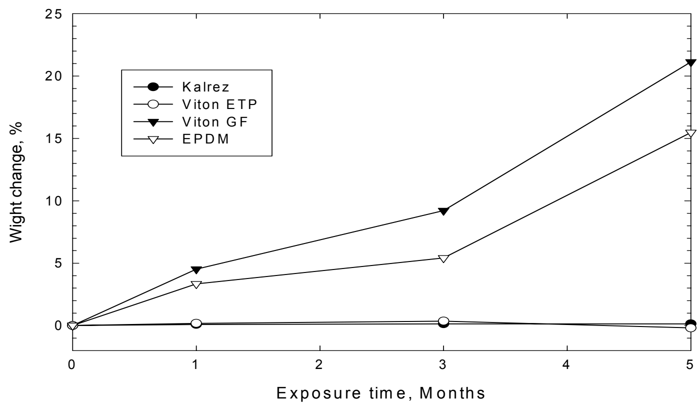

Figure 1. Changes in weight of elastomers as a function of exposure time in 20,000 ppm CO_2-laden 13 wt% Na Cl solution containing 5 wt% steam cylinder oil at 160°C.

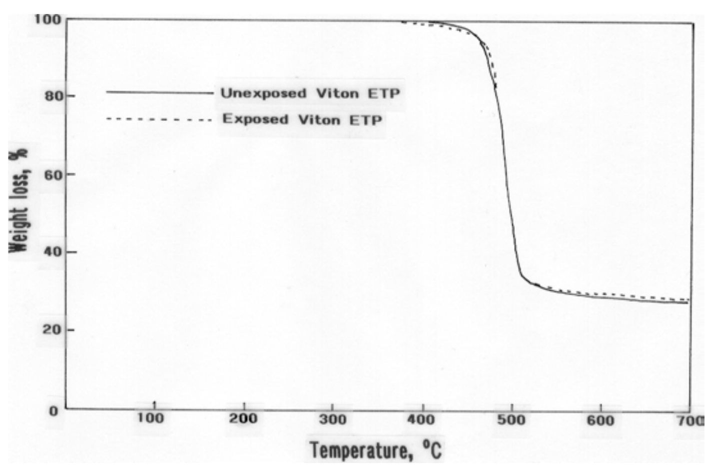

Figure 2. TGA curves for the exposed and unexposed Viton® ETP elastomers.

A six month-long exposure test of Kalrez® and Viton®ETP bearings at the Mammoth Power Plant is being undertaken. Afterward, BNL will conduct post-field analyses of them to evaluate their condition and estimate their useful lifetimes. The analyses will include assessing the changes in chemical composition and states, the rates of hydrothermal oxidation and oil-caused swelling, alterations in microstructure, and thermal and mechanical properties. These data will be obtained from the combined analytical techniques of XPS, FT-IR, SEM-EDX, TGA, and the Instron tensile machine. BNL will integrate the findings to provide information on the changes in physical properties of the elastomers and will develop predictions of their useful lifetimes, which will be documented in a published report and provided to Covanta (successor to Ogden).

Reports & Articles Published in FY 2002:

Sugama, T., “Surface Analyses of Fluoroelastomer Bearings Exposed to Geothermal Environments,” *Materials Letters*, 50, 2001, 66–72.

Sugama, T., and Bob Sullivan, “Hydrothermal Oxidation of Fluoroelastomer Bearings after a Year-long Exposure to Geothermal Environments,” *Journal of Materials Science Letters*, 20, 2001, 1737–1740.

Sugama, T., and Bob Sullivan, “Candidate for Elastomer Bearing in Geothermal Down-hole Pumps,” July 2002.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones:

Complete field validation test	May 03
Complete post-field test analyses	Jul 03
Complete report describing the results of post-test analyses	Sep 03

FIELD DEMONSTRATION AND EVALUATION OF LINED HEAT EXCHANGER

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC02-98CH10866

Performing Organization: Brookhaven National Laboratory
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Ed Curran, Bob Curran & Sons Corp.
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DOE Funding Allocation: $171K

Cost Share Funding: $200K

Project Objective: The objective of this program is to fabricate cost-effective, tough polymer composite liners with excellent thermal conductivity for 20-ft-long carbon steel heat exchanger tubes, and to subject these lined exchanger tubes to a long-term field performance test at geothermal power plant. The program also includes an evaluation of the technical feasibility of using a state-of-the-art lining apparatus, which was installed in a prior year to FY 2002, for 40-ft-long heat exchanger tubes.

The economic utilization of binary working fluids in geothermal energy conversion cycles would dramatically increase the size of the exploitable portion of any hydrothermal resource. A significant cost in a binary plant is the components of the heat exchanger, such as tubes, tube sheets, and shells. The 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 the outermost surface sites of these tubes are detrimental in that the tubes become more susceptible to the deposition of silicate and silica scales, 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 entire cleaning operation, essential for reusing the tubes, is very expensive. An analysis of heat exchanger costs show that a typical titanium heat exchanger would cost about $ 648,000 to purchase and maintain over a 30-year period, a stainless steel heat exchanger would entail a cost of about $ 578,000. 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 cost of the heat exchanger, containing on average 800 tubes, will be markedly reduced. Therefore, the goal of this program is to decrease its capital cost to ~ 100 %, compared to those of the titanium- and stainless steel-based heat exchangers.

Background / Approach: Based upon data obtained before FY 2002, the design criteria for the liner systems being developed in this program are as follows:

- Continuous operating hydrothermal temperature of 240°C.
- Thermal conductivity >1.0 kcal/hr.m°C.
- Cost of liner <$ 1.0/ft.
- Ionic impedance of lining film after 15-day-exposure to 200°C brine: $>1 \times 10^8$ ohm-cm^2.
- Oxidation rate (O/C atomic ratio) of liner surfaces after 15-day-exposure to 200°C brine: < 0.05.
- Abrasive wear rate by SiO_2 grit (particle size of 15 μm) under 150 m/s velocity and 0.6 MPa pressure for liner surfaces after 15-day-exposure to 200°C brine: < 0.1 μm/min.
- Bond strength of liner to tube: >5.0 MPa.
- Tensile strength of lining film before exposure: > 60.0 MPa.
- Low surface energy of liner: contact angle > 80° of water droplet on liner surfaces.

In FY 2000, an evaluation was made of the five-month field performance 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 commercial 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 °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, our plan was to design new thermal conductive PPS/SiC-based material systems possessing excellent abrasive wear and oxidation resistance, and also to develop a lining process technology suitable for the new PPS material systems. These new PPS systems contained two specific additives, Al_2O_3-rich refractory (ARR) to resist abrasive wear, and the anti-oxidant polytetrafluoroethylene (PTFE). Zinc phosphate-primed 20-ft.-long heat exchanger tubes were lined with this new material. An eleven-month-long field test of the performance of these lined tubes was undertaken at the Mammoth Pacific power plant site operating at a brine temperature of 160 °C. After this exposure, the results from the post-field test analyses showed that the anti-oxidation PTFE additive not only minimized the rate of the scale deposition, but also made the liner's surfaces inert to reactions with the scales. Thus, all the deposited scales were easily removed by hydroblasting at only ~ 18.0 MPa pressure. In addition, the PPS liner satisfactory withstood a 160 °C brine temperature and displayed great resistance to the permeation of brine, thereby expressing outstanding performance in protecting the tubes against corrosion. The ARR added for resistance to abrasive wear abated the extent of wear damage during hydroblasting. In contrast, the surfaces of unlined stainless steel tubes were very sensitive to the deposition of calcium silicate hydrate and silica scales, which developed a strong adherence to the tubes. This 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 afterwards, many scales still remained on the oxide layer, forming a ~ 2.0 micron thick layer. The field test also revealed that one shortcoming of the ARR- and SiC-filled PPS/PTFE liners is their brittleness, thereby requiring the development of tough and flexible liners.

Based upon these very promising results, Bob Curran & Son Corp., commercialized this PPS-based lining material system under the trade name "CurraLon".

BNL installed the state-of-the-art apparatus equipped with impedance heater that is used for lining horizontally positioned 40-ft.-long tubes. This apparatus was designed to accomplish quickly and economically the processes of lining the tubes, from primer through to the topcoating layer. It also is intended to serve as a test bed for techniques to line or repair damages on liners incurred in the filed.

Status / Accomplishments: In FY 2002, in efforts to improve toughness-related properties of the liners, BNL succeeded in formulating a carbon microfiber-reinforced PPS/PTFE composite material system and in developing its lining technology. The diameter of the carbon microfiber used was ~ 7.5 μm with a length of 100 to 200 μm. The composite not only significantly improved the toughness of liners, but also raised its thermal conductivity to 1.0 Kcal/hr.m °C. Three 20-ft-long heat exchanger tubes were lined with this composite material, and then were sent to NREL to undergo a year-long field test at the Mammoth power plant.

Using this composite lining system which would meet all the material criteria, the capital costs of the heat exchanger, containing on average 800 tubes, would be strikingly reduced by ~ 83% and ~ 80%, compared to those of the titanium- and stainless steel-based heat exchangers, respectively. Consequently, this high-performance PPS composite lining system was selected for the prestigious "Research and Development (R&D) 100 Award" in 2002.

Of particular concern at the geothermal flash steam power plant in Cove Fort, Utah, is the corrosion of metal pipes caused by their exposure to a highly concentrated solution of dihydrogen sulfide (H_2S). To solve this problem, in collaboration with NREL and INEEL, we assessed the potential of the PPS-based material systems as H_2S corrosion-resistant coatings for the carbon steel piping system in geothermal cooling towers. Although the temperature of the cooling tower basin ranged from 5° to 20°C, at most, bare carbon steel underwent severe corrosion and erosion during only two months of exposure. In contrast, blending the anti-oxidant PTFE into the PPS reduced conspicuously the degree of H_2S-caused oxidation of the coating's surfaces, and also made them hydrophobic, so lowering their susceptibility to moisture. Hence, the PTFE-blended PPS material system has great potential for use as an anti-oxidative and anti-corrosive coating in sulfur- and sulfate-containing geothermal environments.

The post-approval tests were undertaken on the BNL-designed state-of-the-art apparatus that is used for lining the horizontal 40-ft-long tubes to determine its technical feasibility, and also the reproducibility of the liners deposited on these tubes (Figure 1). The factors to be assessed included the liner's thickness, surface roughness and its adherence to underlying tube surfaces. The test results revealed that although a smooth liner adequately adheres to the tube, one drawback was the uneven thickness of the film deposited on internal surfaces. Work is underway to increase the consistency of the PPS slurry to prevent it from dropping from the uper surface of the tube. Once a new formulaton of slurry is established, several 40-ft-long tubes will be lined with it, and then sent to NREL for a field-performance test.

In additon, we are developing an electrostatic powder coating technology, which does not require organic solvents, using the Nordson Sure Coat Spray Gun System

Figure 1. The state-of-the-art apparatus for lining 40-ft.-long heat exchanger tubes using impedance heating system

Reports & Articles Published in FY 2002:

Sugama, T., D. Elling, and K. Gawlik, "Polyphenylenesulfide-based Coatings for Carbon Steel Heat Exchanger Tubes in Geothermal Environments," *Journal of Materials Science*, 37, 2002, 4871–4880.

Sugama, T., K. Gawlik, and P. Pryfogle, "Polytetrafluoroethylene Abates Oxidation of Polyphenylenesulfide Coatings in H_2S-containing Geothermal Basins," *Progress in Organic Coatings*, (in press).

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones:

Develop electrostatic powder coating technology	Apr 03
Prepare two 40-ft-long tubes lined with coating materials	May 03
Delivery two 40-ft-long lined tubes to NREL	Jun 03
Complete validation tests of lined tubes and coated tube/ tubesheet joints	Jul 03
Complete post-test analyses of 1.5-year-long exposure HX liners	Aug 03
Report the results of the laboratory and field test	Sep 03

NON-DESTRUCTIVE TESTING OF CORROSION- AND EROSION-INDUCED DAMAGE IN GEOTHERMAL PIPING

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC02-98CH10886

Performing Organization: Brookhaven National Laboratory

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DOE Funding Allocation: $235K

Cost Share Funding: None

Project Objective: The objective of this project is to evaluate improved methods for non-destructive (NDT) detection of corrosion and erosion-induced damage in geothermal piping systems with emphasis on long range, on-line techniques. The project will identify, validate and support industry-wide implementation of better NDT methods and thereby reduce operating and maintenance costs. In addition, remaining life prediction methodologies that use NDT data are being evaluated. The DOE programmatic goals of reducing the overall cost of generating geothermal electric power are supported by this project.

Background / Approach: Industry responses from our survey of 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. In response to these needs, BNL's research is focusing on better NDT methods and on specific issues related to their applicability in geothermal enviroments. The overall goal of the research is to achieve cost savings and improved reliability for geothermal facilities. Our research involves: (a) investigation of NDT methods as they apply to specific problems encountered in geothermal facilities; (b) field demonstration and evaluation of long range NDT methods; 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.

Status / Accomplishments: Ultrasonic guided wave methods have been identified as having the greatest potential. Currently available guided wave systems for pipe testing use either a ring arrangement of multiple dry coupled piezoelectric transducers clamped to the external pipe surface or a magnetostrictive sensor strip wrapped around the pipe. Piezoelectric transducers in current use have a temperature limitation of approximately 140^{o}C (284^{o}F) and, consequently, their application in geothermal piping is restricted to relatively low temperature conditions (i.e., injection piping or during plant shutdown). The magnetostrictive system has greater range of application owing to its ability to withstand higher temperatures although some insulation may be required in practice. Discussions were held with the developers of both types of guided wave systems and the issues of high temperatures, internal liners and the types of defects encountered in geothermal systems were covered. A demonstration of the magnetostrictive system was provided to us on significant lengths (>100 ft) of large diameter pipes containing known defects. The demonstration and discussions gave great confidence in applying this technology to geothermal piping. Furthermore, modeling studies were conducted to assist in the understanding of guided wave propagation in geothermal piping systems. In these studies SH-waves were considered and dispersion curves were developed. The latter are very useful in the interpretation of test results.

We visited power plants operated by NCPA and CalEnergy to discuss NDT issues and to plan field demonstration of guided wave methods. Both companies indicated strong interest in the project, their need for BNL assistance and willingness to collaborate on field tests. The plant operators communicated the need for global screening NDT methods to monitor pipe condition and to prevent unscheduled maintenance and catastrophic failures, particularly during peak demand periods. The major areas of interest are surface piping, injection piping, production well liners and plant piping. NDT would also be useful at plants for monitoring the performance of corrosion control strategies such as alternative materials, coatings and chemical treatment. Preliminary estimates indicate that guided wave testing will cost one fifth that of manual ultrasonic testing, in addition to the technological advantages.

The program also focused on the integration of results from NDT with remaining strength and life assessment. Specifically, existing methodologies for predicting remaining strength and life of corroded piping using data from NDT were reviewed to assess their applicability to geothermal piping. Results and conclusions from the latter were documented. Deterministic, probabilistic and combined approaches were considered. Several semi-empirical methods that were developed for external corrosion exist but the validity of using them for internally corroded geothermal piping is questionable. If a deterministic approach is chosen then the finite element method is preferable. Probabilistic or reliability methods can take into account inherent uncertainties in parameters such as defect size and material properties and therefore offer a more realistic assessment. The most advantageous approach may be to couple finite element and reliability methods.

In relationship to the subject of remaining life prediction, samples of corroded piping removed from geothermal power plants were analyzed to obtain statistical information on the corrosion process. The samples analyzed had all suffered pitting corrosion. The spatial and depth distributions of the pits were investigated as this is of interest for predicting the probability of failure. It was determined that the pit depths followed a log normal distribution and the maximum pit depths could be described by an extreme value (Gumbel) distribution. The pit spatial distribution was clustered rather than random for the samples tested. This information can be used in more sophisticated life prediction models so that geothermal operators can schedule repair or replacement activities with greater efficiency and reduce the risk of failure. Overconservatism and associated costs in piping replacement can also be reduced.

Reports & Articles Published in FY 2002:

Berndt, M. L., "Applicability of Remaining Strength and Life Prediction Methodologies to Geothermal Piping," BNL 68999, January 2002.

Berndt, M. L., and A. J. Philippacopoulos, "Long Range Non-Destructive Testing for Geothermal Piping," *Geothermal Resources Council Transactions*, Vol. 26, 645–649, 2002.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones:

Complete industry survey on NDT, integrity assessment and repair needs	Mar 03
Complete case study of piping integrity assessment	Aug 03
Document findings and recommendations on NDT and integrity assessment to industry	Sep 03

HIGH-PERFORMANCE COATING MATERIALS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: DE-AC02-98CH10866

Performing Organization: Brookhaven National Laboratory
Upton, NY 11973

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Collaborating Researchers: Keith Gawlik, National Renewable Energy Laboratory
Bob Sullivan, Mammoth Pacific, Inc.
Ed Hallahan, Ticona, Corp.
Paul Hirtz, Thermochem, Inc.

DOE HQ Program Manager: Allan Jelacic
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DOE Funding Allocation: $98K

Cost Share Funding: $50K

Project Objective: Corrosion, erosion, and fouling by scale deposits problems for the carbon steel heat exchangers, piping, aluminum-finned condensers, turbine components, and well-head valves at power plants have increased as steam pressures have declined. These conditions have caused a decrease in electric power generation, increased operating costs, and heightened safety- and environmental-concerns. In resolving these problems, high-performance semi-crystalline polyaryl thermoplastic engineering polymers are very attractive for use as coating materials because of their high-temperature stability of > 200°C. Among the polyaryl family, polyphenylenesulfide (PPS) has a relatively low cost, and excellent adherence to metal surfaces.

The objective of this project is to enhance the thermal conductivity of high-temperature PPS composite coatings and develop technologies that allow the coatings to self-repair and -heal internal and surface cracks. The project also was designed to obtain a fundamental understanding of the characteristics of the coating systems before applying them to full-scale metal substrates.

In collaboration with NREL, Mammoth Pacific Corp., and Thermochem Corp., the goal of this program is to develop highly thermally conductive, anti-corrosion, anti-wear, and anti-fouling PPS polymer composite coatings, which withstand CO_2-laden brine at temperatures up to 200°C, over a pH range of 1 to 14. Coating systems also are required to be very tough to minimize the generation of cracks during the installation and transportation of coated equipment. The success of this composite coating not only will increase electric generation capacities, but also will save substantially on capital costs because it eliminates the need to use expensive stainless steel, titanium alloys, and inconel.

Background / Approach: In 2001, the focus was upon developing a technology that improves the mechanical behaviors and enhances the thermal conductivity of boehmite ceramic-and SiC grit-incorporated PPS materials. These materials are intended for use as corrosion/wear/fouling resistant coatings with good thermal transfer properties at temperatures up to 200°C. We found that incorporating chopped carbon fibers into the PPS matrix significantly improved these properties. The carbon fiber-reinforced PPS composite coatings exhibited outstanding mechanical properties, such as tensile strength, tensile modulus, and elongation. In addition, the thermal conductivity of the non-reinforced PPS rose ~ 60 % after adding an appropriate amount of fiber. Since the thermal conductivity of carbon fibers depends mainly on their graphite content, adding a highly graphitized carbon fiber should further enhance the thermal transferring efficiency of the composite coatings. Further, advanced milling technology made it possible to produce an extremely short carbon microfiber, while retaining all of these mechanical properties and the filament's shape. The milled fiber is 100–200 μm long with a 7.5 μm diameter. One attraction in using such short fibers is that a substantial amount of it can be incorporated into the PPS. Although the toughness of PPS was improved by carbon fibers, one important question still remained: How to repair any damage caused by micro- and nano-sized cracks generated in the matrix during mechanical loading and service life, and also, how to retard growth of the cracks. Thus, a micro-sized crack might initiate and develop into a serious crack that ultimately leads to the degradation of the coatings and undermines their ability to prevent corrosion.

Status / Accomplishments: In FY 2002, emphasis was directed toward assessing the effectiveness of the short milled carbon microfibers (7.5 μm diam. × 100–200 μm long) in increasing the thermal conductivity and the mechanical properties of the PPS composite coatings. After adding 5 wt% fibers, the thermal conductivity of the PPS coatings rose 2.6 fold to 3.7 kJ/h.m.°C. Furthermore, 3 wt% fiber-reinforced PPS coating films displayed a great tensile strength and elongation of 40.8 MPa and 5.8 %, respectively, corresponding to the improvement of 5.2 times and 2.6 times over those of the non-reinforced coatings. However, increasing the amount of fibers beyond 3 wt%, caused a gradual decline in these mechanical properties. Although we have no experimental evidence, we assumed that such mechanical retrogression is due to the deficient coverage of the fibers' surfaces with PPS, caused by incorporating an excessive amount of fibers into the matrix, reflecting the development of low interfacial shear bond strength at the fiber/PPS joint.

Our concept of developing a self-healing composite coating involved two different procedures: One is to incorporate micro- and nano-sized encapsulated healing agents into the composite; the other is to add hydraulic inorganic fillers, which are capable of crystal growth in hydrothermal environments. For the former technology, we synthesized micro- and nano-encapsulated healing materials consisting of a dicyclopentadiene monomer as the healing agent and ethylene maleic/formaldehyde copolymer as the micro- and nano-capsule shell, and then incorporated into the PPS matrix. However, there was one major drawback to this encapsulated material system; the polymeric shell structure thermally decomposed during the melt-flowing process of PPS at 310°C. Thus, there is needed to improve the thermal stability of the polymeric shell for the PPS. For the latter technology, we incorporated hydraulic monocalcium aluminate ($CaO.Al_2O_3$) and calcium dialuminate ($CaO.2Al_2O_3$) reactants into the PPS matrix. The following interaction pathway of these reactants within the cracks led to the rapid growth of hard, strong boehmite (γ-AlOOH) crystals known as engineering ceramic.

Hydrolysis of reactants;

$CO_2 + H_2O \rightarrow HCO_3^- + H^+$,

$CaO.Al_2O_3 + 4H_2O \rightarrow Ca^+ + 2Al(OH)_4^-$,
$CaO.2Al_2O_3 + 7H_2O + 2OH^- \rightarrow Ca^{2+} + 4Al(OH)_4^-$,

Interactions;

$Ca^{2+} + HCO_3^- \rightarrow CaCO_3 + H^+$,
$Al(OH)_4^- + H^+ \rightarrow AlH(OH)_4 \rightarrow \gamma\text{-}AlOOH + 2H_2O$.

During exposure for 10 hours to 200°C CO_2-laden brine, the block-like boehmite crystals, ~ 4 μm in size, densely filled and sealed the open cracks (Figure 1): this repair process was reflected in an increase in pore resistance by two orders of its magnitude compared with that of cleaved coatings without reactants. Extending the exposure time to 20 days did not change the pore resistance, suggesting that the sealing of the cracks by the boehmite crystals played an essential role in reconstituting and restoring the function of the failed coatings as a corrosion-preventing barrier. Therefore, PPS coating films filled with these reactants are able to self-heal and –repair cracks generated on their surfaces in hydrothermal environments.

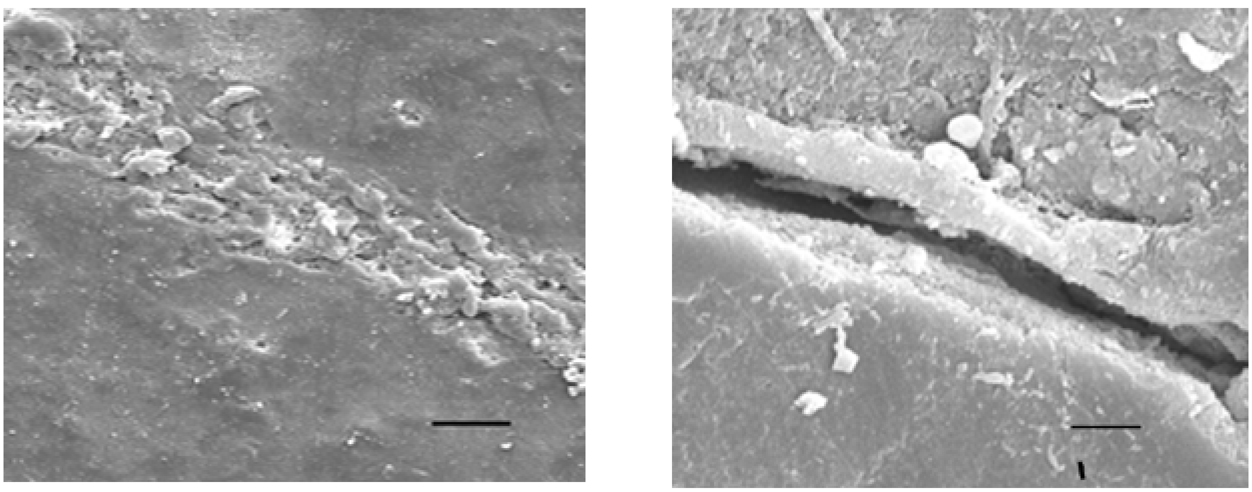

Figure 1. Cracked coating film (left) and coating film (right) healed by crystal growth after exposure in brine at 200°C (—, 1μm)

The smart, multifunctional PPS coating systems described above were designed to withstand the hydrothermal temperatures up to 200°C. One important question remained unanswered. Will this coating adequately protect the underlying steel against a very harsh environment at an upgrade temperature of 300°C? Thus, work is underway to develop 300°C-stable nanocomposite coating systems consisting of the PPS and polybenzimidazole (PBI) as the matrix, and nano-sized boehmite crystals and clay as the nanofillers. PBI is a new type of room temperature curable polymer and its thermal decomposition begins around 630°C.

Another concern facing geothermal binary power plants during the summer, the most profitable period for selling electricity is a decline in the efficiency of the air-cooled condensers, causing ~ 30 % reduction of the plant's net monthly energy delivery compared with that in the winter. In an attempt to augment power output in the summer, relatively clean geothermal brine or treated waste water is directly sprayed over the surfaces of aluminum-finned steel condenser tubes; this technology is becoming increasingly important. In fact, the plant's output of water-sprayed condensers in the summer was almost tantamount to that of wintertime conditions.

However, two intriguing questions remained unanswered: One concerns the susceptibility of the two metal components of the condenser unit, the aluminum fins and the carbon steel tubes, to brine-initiated corrosion; the other concerns the deposition of irremovable scales adhering and clinging to the metal surfaces. In response to these questions, a new polyaminopropylsiloxan (PAPS) polymer developed at BNL is being evaluated for use as a corrosion-and fouling-mitigating coating for the air-cooled condensers.

Reports & Articles Published in FY 2002:

Sugama, T., and K. Gawlik, "Carbon Fiber-reinforced Poly (phenylenesulfide) Composite Coatings," *Polymers & Polymer Composites*, 9, 2001, 377–384.

Sugama, T., 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.

Sugama, T., and K. Gawlik, "Anti-silica Fouling Coatings in Geothermal Environments," *Materials Letters*, 57, 2002, 666–673.

Sugama, T., and K. Gawlik, "Milled Carbon Microfiber-reinforced Poly(phenylenesulfide) Composite Coatings for Abating Corrosion of Carbon Steel at Brine Temperatures up to 250°C," *Polymers & Polymer Composites*, (in press).

Presentations Made in FY 2002:

Gawlik, K., T. Sugama, and D. Jung, "Organometallic Polymer Coatings for Geothermal-Fluid-Sprayed Air-Cooled Condensers," *Geothermal Resources Council Transactions*, Vol. 26, pp.657–661, September 22–25, 2002.

Planned FY 2003 Milestones:

Test hydrothermal stability of PS-modified PPS coatings	Feb 03
Complete development of nanocomposite coatings	Apr 03
Define optimized formulation of OMP coatings	May 03
Deliver PBI -and OMP-coated panels to Mammoth for field tests	July 03
Report describing results of in-house work and field-evaluation tests	Aug 03

INTERNAL COATINGS FOR GEOTHERMAL ENVIRONMENT APPLICATIONS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Idaho National Engineering and Environmental Laboratory
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DOE Funding Allocation: $121K

Cost Share Funding: None

Project Objective: This task supports the program goal to promote the economical production of electricity from geothermal resources by improving components, reducing operation and maintenance costs. The objective is to investigate the functionality of thermally sprayed coatings for geothermal applications and validate the technical feasibility and the potential to reduce costs.

Background / Approach: In extreme geothermal operating environments, operators are frequently forced to use exotic materials for piping and components, or to frequently replace these components. The proposed technology of spraying metallic coatings on the inside of pipes and other components has the potential to provide the same corrosion and scaling protection to the internal surfaces of the components as the exotic materials, but at a lower cost. Successful implementation of this technology will reduce the capital and maintenance cost for the geothermal fluid piping systems.

Status / Accomplishments: In FY 2002, the material scoping tests performed in cooperation with CalEnergy at the Salton Sea facilities were completed. Currently, cement linings are used to prevent the silicate in the fluid from bonding with the iron in the carbon steel pipe. Following a 1200 hr exposure period, the initial coupons were removed in February 2002 and examined. Only one set out of the four sets of coupons (Ultimet coating) remained on the coupon tree when it was retrieved. The fate of the other three sets is unknown. The high vibration of the wellhead piping may have caused the nuts or bolts to loosen. Examination of the coupon tree flange ring revealed cracks on the inner diameter of the ring, which could be due to piping vibration (fatigue). The weld that attached the flat plate to the ring was also cracked. Stress corrosion cracking has been found to be possible in these systems. There was a hard, tightly adherent surface deposit on the Ultimet coupons and the corrosion coupon tree. This scale was analyzed and was found to be silicate based with every other element of the liquid phase being present. The deposit was thicker on the corrosion coupons than on the C-276 plate material of the corrosion tree. One possible explanation for this is the coupon tree material has a better initial surface finish than the corrosion coupons, which may affect the scale deposition rate. For the second round of testing, a coated pipe spool was installed downstream from the location of the first corrosion test installation. The location of the pipe is felt to be more representative of the general run of pipe in the facility. The interior of this pipe spool and the flange faces were coated with IN625. The exterior of the four new corrosion coupons were also coated with IN625. This alloy offers the highest bond strength and density of all the coatings tested. It is felt that these characteristics would make an improved coating as compared to the Ultimet coating even though the IN 625 coupons were not retrieved for analysis. The prototype pipe was installed and will tentatively be removed in early 2003. In addition to selecting the materials, the tests provided validation that metallic coatings can be thermally sprayed on the inside surfaces of pipes using INEEL patented technology. Methods for decreasing surface roughness will be incorporated into future pipe sections and coupons.

The capability to thermally spray coatings on the interior surface of piping has just recently been demonstrated. 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 is working to bring the prototype system to the field and to increase the spray system's capacity up to that required for industrial scale fabrication. INEEL will continue to study corrosion issues in geothermal plants for possible applications of thermal spray coatings to protect carbon steel pipe in geothermal environments. A Calpine component will be coated and installed in January 2003. Testing of these coatings will continue in aggressive geothermal environments to evaluate their performance in establishing both appropriate materials and application methods and specifications. The coupon test results suggest that the coating surface finish is an important parameter in geothermal applications in terms of scale formation, as well as pressure drop. These tests will include densification of the coating by glass bead peening or other peening methods, and the use of sealers.

Reports & Articles Published in FY 2002:

ASME International Pipeline Conference Proceedings
GRC Proceeding
National Association Corrosion Engineers Western Regional Conference proceedings

Presentations Made in FY 2002:

International Pipeline Conference, ASME, Calgary, Ontario CA
Geothermal Resources Conference, Reno NV
NACE Western Regional Conference, Palm Springs, CA

Planned FY 2003 Milestones:

Complete evaluation of internally coated piping following extended exposure test (>6 month), and estimate probable duration time	Apr 03
Submit test procedures for spray coating application to ASTM for committee consideration	Aug 03

ENHANCED HEAT REJECTION SYSTEMS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)	
DOE Grant / Contract #:	
Performing Organization:	National Renewable Energy Laboratory
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DOE Funding Allocation:	$344K
Cost Share Funding:	$40K

Project Objective: The project objectives are to identify and develop improvements in geothermal power plant heat rejection systems, including improved air-cooled condenser designs, evaporative pre-cooling of air-cooled condensers, and combinations of air and water-cooled condensers. Our goal is to reduce electricity cost by 0.5-cent per kWh.

Background/Approach: Because of the thermodynamics of operating power cycles at typical geothermal resource temperatures, approximately 85-90% of the heat extracted from the ground must be rejected to the environment. As a result, air-cooled condensers account for as much as 30% of total plant capital cost or 20% of electricity cost. Water-cooled condensers are preferable from a performance standpoint, although air-cooled condensers are widely used in geothermal power plants because of the lack of cooling water. The cost of geothermal electricity can be decreased significantly if performance of the heat rejection systems can be improved. This is especially true for air-cooled plants during summer operation when electric output can drop by more than 50% due to elevated air temperatures.

NREL has developed spreadsheet and other computer-based models to evaluate the impact of improved condenser designs and operation strategies. One result to date has suggested that the use of lower design face velocities in air-cooled condensers (about 2 m/s velocity instead of 3 m/s) 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-and-tube 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 has developed a spreadsheet to compare the cost and performance of various options for using evaporative cooling in conjunction with air cooling. This work has shown that several different evaporative cooling alternatives can significantly improve summer performance. As part of this effort, we have provided analytical and measurement support to the Mammoth Lakes power plant in their efforts to implement evaporative cooling systems. We have also investigated ways to combine water-cooled condensers with air-cooled condensers.

Status/Accomplishments:

Cooperative Research and Development Agreement (CRADA). A CRADA was negotiated and signed (on January 30, 2002) with Super Radiator Coils (SRC), a major heat exchanger coil manufacturer, to collaborate on the development of improved air-cooled condenser concepts. SRC is manufacturing prototypes of NREL designs and reference heat exchangers for testing at an independent laboratory. SRC is contributing 45% of the cost of the prototype development.

Transpired Fin Prototype Test Results. Our CRADA partner, SRC, fabricated two transpired fin prototypes. These were tested at Intertek Testing Services on May 15-23, 2002, along with non-transpired reference heat exchangers: helically wound fins and plate fins. One of the transpired concepts proved to have the highest performance. Its air-side heat transfer coefficient was 35% higher than for the helical fins and 20% higher than the plate fins when compared at the same baseline fan power. Because in hydrocarbon condensers, approximately half the heat transfer resistance is on the hydrocarbon side, the improvement in overall heat transfer would be about half the improvement in air-side coefficient.

Analysis of Tube-Side Enhancement. Recognizing that in air-cooled hydrocarbon condensers thermal resistance on the tube side is significant we analyzed two different means for tube-side enhancement: twisted tape and internal fins. The use of internal fins appears to provide a potentially cost-effective means for boosting heat transfer.

Analysis of a Trim Condenser. We developed a computer model to study the feasibility of using a trim water-cooled condenser downstream of air-cooled condensers to boost the summertime performance of air-cooled binary-cycle geothermal power plants. We concluded that it is not cost-effective to use this approach to maintain summer output at design values, because the water-cooled condenser must be sized to handle almost the entire heat rejection load. However, it may be cost-effective to use a smaller size water-cooled condenser to mitigate the summer drop in performance, and our detailed model allows us to study various combinations of air- and water-cooled heat exchanger sizes. We observed that the use of a mixed working fluid could also allow for the use of a smaller trim condenser by allowing the air-cooled condensers to handle a greater portion of the condensation heat load.

Improved Spreadsheet Model of Evaporative Pre-Cooling Systems. We made a number of improvements in our spreadsheet model of evaporative pre-cooling systems. These include a more user-friendly interface and a more rigorous model for deluge cooling. Use of the improved model revealed that deluge systems could use significantly more water, because they can wind up evaporatively cooling the environment. This problem can be addressed by using deluge cooling of one section of condenser tubing as pre-cooling for another section. We found in the literature that this very type of system is currently being investigated in Japan.

Field Measurements at Mammoth Power Plant. We took measurements of the evaporative pre-cooling systems at Mammoth Power Plant. We determined cooling effectiveness, pressure drops, and the impact on fan performance and provided a report to Mammoth.

Reports & Articles Published in FY 2002:

Kutscher, C., and K. Gawlik, "Report on Measurements of the Evaporative Pre-Cooling System at Mammoth Lakes Power Plant," NREL report, November 20, 2001.

Kutscher, C., and D. Costenaro, "Assessment of Evaporative Cooling Enhancement Methods for Air-Cooled Geothermal Power Plants," *Geothermal Resources Council Transactions*, Vol. 26, September 22-25, 2002.

Kozubal, E., and C. Kutscher, "Analysis of a Water-Cooled Condenser in Series with an Air-Cooled Condenser for a 1 MW Geothermal Power Plant," NREL progress report, September 5, 2002.

Rotherham, B., "Investigation of Heat Transfer Enhancement Strategies for Air-Cooled Condensers at Geothermal Binary Cycle Plants," NREL progress report, September 13, 2002.

Presentations Made in FY 2002:

Kutscher, C., "Enhanced Heat Rejection Systems," Geothermal Energy Program Peer Review, Golden, CO, March 26, 2002.

Kutscher, C., "Assessment of Evaporative Cooling Enhancement Methods for Air-Cooled Geothermal Power Plants," September 24, 2002.

Planned FY 2003 Milestones:

Computer optimization results for the geometry of pleated transpired fin heat exchanger designs	May 03
Laboratory measurements comparing several advanced fin concepts	May 03
Conference paper on the use of a trim condenser	Sep 03
Conference paper on tube-side enhancement	Sep 03

ENHANCEMENT OF AIR COOLED CONDENSERS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: Idaho National Engineering & Environmental Laboratory
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DOE Funding Allocation: $186K

Cost Share Funding: Direct Funding, $111K, NEDO, Japan

Project Objective: Improve air-cooled condenser heat transfer performance by ~15%, resulting in lowering component cost without increasing pressure drop and fan horsepower.

Background / Approach: 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 using air-cooled condensers. Because air is a poor heat transfer medium, a large surface area of the condenser tubes is required. An EPRI report "Next Generation Geothermal Power Plant" prepared by Ben Holt Co. indicates the air-cooled condenser cost can be up to ~25% of the total plant cost (including well field). Improving the performance of the condensers is expected to have a significant impact on reducing the cost of power generated from these plants. 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 CFD modeling to identify those configurations that provide the best heat transfer. 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 recipients of NEDO grant from Japan and India.

Status / Accomplishments: Completed laboratory scale experiments for measuring heat transfer and pressure drop. Subsequently based on the laboratory experiments, a set of tests were performed in INEEL single blow facility using tube bundles without and with winglets on the tube fins. The addition of winglets on the fins showed about ~20% enhancement in heat transfer and ~15% increase in pressure drop across the tube bundle.

Reports & Articles Published in FY 2002: Two reports were submitted to NEDO, Japan, as a part of the deliverables for the grant obtained during FY 2002 and 1999–2002.

Presentations Made in FY 2002:

O'Brien, J. E., M. S. Sohal, and P. C. Wallstedt, "Local Heat Transfer And Pressure Drop For Finned-Tube Heat Exchangers Using Oval Tubes And Vortex Generators," 2001, ASME International Mechanical Engineering Congress and Exposition, New York, NY, November 11–16, 2001.

O'Brien, J. E., M. S. Sohal, T. D. Foust, and P. C. Wallstedt, "Heat Transfer Enhancement for Finned-Tube Heat Exchangers with Vortex Generators: Experimental and Numerical Results," *Proceedings of 12th International Heat Transfer Conference, Grenoble, France, August 2002.*

O'Brien, J. E., and M. S. Sohal, "Testing of Finned-Tube Bundles for Geothermal Air-Cooled Condensers," Geothermal Resources Council Annual Meeting, Reno, NV, September 2002.

Planned FY 2003 Milestones:

Complete CRADA agreement(s) with one or more manufacturers	(I)	Nov.02
Complete economic analysis	(C)	Jul 03
Select a site for full-size bundle testing	(I)	May 03

COMPONENT DEVELOPMENT FOR AMMONIA/WATER POWER CYCLES

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: National Renewable Energy Laboratory (NREL)
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DOE Funding Allocation: $335K

Cost Share Funding: None

Project Objective: The objective of this work is to improve resource utilization and reduce the cost of electricity generation from low-to-medium temperature geothermal resources. The specific goal is to develop new components to improve the performance and reduce the cost of heat-rejection units in air-cooled binary geothermal power plants. The results of this study will facilitate the designing of efficient heat-rejection units by manufacturers in the United States.

Background / Approach: So far, we have focused on reducing the cost of electricity generation from geothermal resources by reducing the power cycle capital and maintenance costs. This can be accomplished through development of inexpensive and efficient components, such as the heat-rejection component for the power cycle. This work targets binary geothermal plants.

Our future focus at the National Renewable Energy Laboratory (NREL) is to design and test an enhanced air-cooled condenser that has superior performance when compared to the conventional air-cooled heat exchangers. The working fluid of choice for this study is ammonia/water. The work conducted during FY 2002 has led NREL researchers to design a prototype air-cooled fin-on-plate heat exchanger (absorber/cooler) with specific design considerations for mixing of vapor with lean liquid, as well as enhanced air-side heat-transfer coefficient. This work has many potential benefits, for example, reducing the size and expense of the condenser unit by as much as 30%, and reducing the turbine back-pressure (hence, increased power generation).

In FY 2002, NREL recognized that fins on plates could significantly reduce the air-side pressure drop, while making it possible to force air through the heat exchanger at higher velocities. This, in turn, results in higher heat-transfer coefficients. In addition, NREL has identified that highly concentrated vapor exiting the turbine can be readily condensed through a mixed absorption/condensation process. This process is accomplished by mixing lean liquid extracted from the high-pressure side of the cycle with the turbine exhaust. NREL researchers have concluded that the best way to thoroughly mix the liquid and vapor, while removing heat from the mixture, is to use a plate heat exchanger, rather than a tube-fin configuration.

Therefore, our objective is to design, build, and test an air-cooled fin-on-plate heat exchanger as an absorber/cooler for binary geothermal power plants. Currently, all the heat exchangers (condensers) on the market are of the shell-and-tube or tube-fin type. No heat exchanger manufacturer has designed or built an air-cooled condenser of the type we propose. NREL tested several fin-on-plate configurations with very encouraging results. The heat transfer coefficients on the air-side were more that 30% higher than the conventional tube-fin heat exchangers.

NREL's fin-on-plate heat exchanger (Figure 1) has two flat plates placed face-to-face and welded together to form passage for the process fluid. A number of short fins are attached (by welding, brazing, or cementing) in a staggered or offset pattern to each side of a flat plate. The flat plate has multiple short studs or other separators welded to it. The fin-on-plate assemblies are then stacked together to form the heat exchanger. Air flows through the finned passages in countercurrent flow to the process fluid, which is distributed into and flows through the passage between the plates.

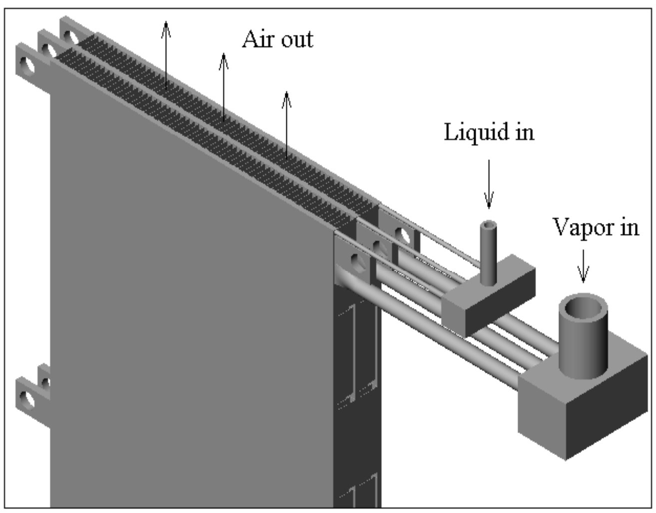

Figure 1. NREL's fin-on-plate heat exchanger.

This configuration has several advantages. For example, the air flow parallel to the fins practically eliminates the form drag that arises in flow across banks of tube. Because the form drag results in a loss of pressure without a commensurate contribution to the heat-transfer process, air velocity can be increased without exceeding the allowed pressure drop. This results in a reduced cross-sectional area required to accommodate the air flow and an increased heat-transfer coefficient.

Further, the countercurrent flow arrangement ensures that the maximum possible temperature difference for heat transfer is realized. The close spacing of the plates ensures that the phases in multi-component condensing situations remain in close contact and, hence, maintain high heat- and mass-transfer rates and near thermodynamic equilibrium between the phase compositions. The downward flow of the condensing vapor results in the two-phase frictional pressure loss being largely offset by the hydrostatic pressure increase. Air blowers or low-pressure compressors may be conveniently used with this configuration if higher pressure drops are required. Because of this design, the fin-on-plate heat exchanger has the potential to be an excellent air-cooled condenser. NREL's effort will significantly benefit the geothermal industry, as well as other industries that use air-cooled heat exchangers.

During FY 2003, NREL will address several manufacturing issues related to the construction and assembly of the fin-on-plate heat exchangers. NREL is in the process of developing a procedure for the design and fabrication of a fin-on-plate heat exchanger that can operate at high pressures. However, this procedure needs to be significantly modified to be cost effective. It is also necessary to develop a commercialization plan for this type of heat exchanger. During this fiscal year, we will address both the R&D and engineering design issues. NREL will carry out the R&D issues such as development of the most effective air-side fin geometry, and development of heat transfer and pressure drop correlations for that fin arrangement. The engineering effort consists of design of a liquid and vapor distribution system, plate and fin manufacturing and bonding techniques, and development of a cost-effective manufacturing procedure. The engineering design effort will be completed in collaboration with an industry partner. One of our major efforts during this year will be to contact several heat-exchanger manufacturers in the United States and sign a collaborative agreement with one.

Status / Accomplishments: During FY 2002, NREL completed testing of several fin-on-plate configurations. NREL made a presentation to Alfa-Laval management. In FY 2003 we will design a vapor distribution system for the fin-on-plate assembly. We have already contacted several manufacturers in the United States (Hudson and GEA Rainey) and will be making presentations to them on the performance of the fin-on-plate heat exchanger.

Reports and Articles-Published in FY 2002: We have written an NREL technical report on the performance of the fin-on-plate heat exchanger.

Presentations Made in FY 2002: A technical presentation was made to Alfa-Laval management.

Planned FY 2003 Milestones:

Complete testing of two sets of fins for high heat-transfer coefficient and low pressure drop	Jan 03
Sign a CRADA with a manufacturer in the United States	Mar 03
Develop heat-transfer correlations for two sets of fins	Apr 03
Complete technology transfer with HTRI (provide the data for fin-on-plate heat exchanger to be included in computer model developed by HTRI)	Sep 03
Complete report on final design and test results for the fin-on-plate heat exchanger	Sep 03

CONTINUAL REMOVAL OF NON-CONDENSABLE GASES FOR BINARY POWER PLANT CONDENSERS

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #: AC07-99ID13727

Performing Organization: Idaho National Engineering and Environmental Laboratory
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DOE Funding Allocation: $176K

Cost Share Funding: None

Project Objective: The objective of this project is to increase the generating capacity of binary power systems used in geothermal generating plants by developing a cost-effective, improved technology for removing non-condensable gases from condenser vapors. This technology will allow continual NCG removal, resulting in continual operation of low levels of NCG in the plant condensers. In addition, the technology will remove NCGs with very little loss of organic working fluid, in contrast with current methods of NCG removal.

Background / Approach: The working fluid in binary geothermal power plants circulates in a continuous loop between the thermal energy source and a turbine. The loop includes evaporation and a condensation step. The efficiency of the condensation step decreases over time because of a build up of inert gases (primarily air) in the working fluid. This leads to a decrease in the overall power generation efficiency of the power plant. It is estimated that power generation decreases by 1% for every psi of inert gas pressure in the condenser overhead. Current practice is to periodically vent the condenser vapor through a refrigeration system to purge the non-condensable gases and recover the working fluid. This leads to loss of the working fluid and means that the power plant operates at a reduced efficiency between purges. Development of a separation system that maintains a low fraction of non-condensable gases in the system is estimated to increase the average output of a binary geothermal plant by three to five percent. Permselective membranes have been developed that are suitable for this application. This technology will be developed by testing the separating and permeation properties of several membranes, designing and sizing a prototype unit for testing at commercial binary geothermal system, testing the prototype, refining the prototype unit, and seeking further industrial applications. The benefits of the technology will be analyzed by comparing plant operating data before and during prototype use. Performance will be measured using on-site chromatographic measurement of condenser vapor and prototype-unit exhaust compositions combined with plant operating data.

Status / Accomplishments: The unit was constructed by MTR from 10/01 thru 2/02 and delivered/installed on a modified Ormat unit at the Steamboat geothermal plant (Reno, NV) in April. The first test was conducted from June to December 2002. Startup problems resulted from control errors and some piping misalignment that disrupted liquid return to the condenser and caused the unit to trip off frequently. This was corrected by rerouting a few piping runs, installing different level sensors, and modifying the automated control software. The plant ran for 4 months with occasional shutdowns caused by high liquid inventory when the liquid return pump cavitated and did not pump as designed. The last month of this period, it ran unattended continuously, except for times when the generating unit to which it was attached was shut down for maintenance. If a liquid level trip occurred, the plant operator would drain the unit and restart. Immediately prior to the GRC meeting in Reno in September, the unit was used to reduce the condenser non-condensable gas content from about 6% to less than 1% over a 2-day period of increased throughput. The plant operator reported an increase in unit output (compared to a similar Ormat unit) when the low condenser NCG level was reached. These results were presented two days later in a paper at the GRC meeting. Following the presentation, two firms involved in geothermal plant design and construction (Ben Holt and Ormat) contacted the presenter and requested further information. Ormat has since indicated that it wants to purchase a unit for testing in another plant near Reno.

The prototype unit has demonstrated the capability to remove air continually from condenser vapor that is 99% organic working fluid, by volume. The removal rate is approximately 20 gm/hr, and, under these conditions, the unit produces a vent gas that is 1% (or less) organic working fluid. During the short period in September ’02, when large amounts of air were being removed (six to eight times the normal vent flow), the amount of organic working fluid in the vent gas increased to about 6%. Even at this rate of organic loss, the system conserves working fluid when compared to the industry practice of venting the condenser directly to remove non-condensable gases.

Reports & Articles Published in FY 2002: None.

Presentations Made in FY 2002:

“*Continual removal of non-condensable gases from binary power plant condensers,”* Geothermal Resources Council Annual Meeting (Reno, NV, September, 2002).

Planned FY 2003 Milestones:

Complete test at Mammoth and issue test report	Jun 1
Present paper at GRC on results of short and long term testing	Sep 03

PLANT PERFORMANCE ENHANCEMENT AND OPTIMIZATION

Reporting Period: FY 2002 (October 1, 2001 to September 30, 2002)

DOE Grant / Contract #:

Performing Organization: National Renewable Energy Laboratory
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DOE Funding Allocation: $70K

Cost Share Funding: None

Project Objective: The objective of this work is to reduce the cost of consumable chemicals currently used in hydrogen sulfide (H_2S) abatement processes in geothermal power plants. Specifically, the use of iron chelate catalyst at Unit 11 at the Geysers, owned and operated by Calpine, Inc. is addressed. Improved methods to make additional dissolved oxygen available in the cooling water stream are looked into through the use of computational fluid dynamics (CFD) models.

Background / Approach: Geothermal steam often contains a large fraction of non-condensable gases, with hydrogen sulfide as one of the components. The emission of sulfur from power plants is regulated because of a disagreeable odor from H_2S and the potential for acid rain from its emission. Current regulations call for a limit of 50 lb/hr released to the atmosphere from a power plant of nominal 100 MW electric generation capacity. Such a plant may handle geothermal steam containing as much as 1,000 lb/hr of H_2S in it. The plant is, therefore, required to dispose the remaining 950 lb/hr in an environmentally acceptable manner. The thiosulfate process requires continuous addition of caustic soda to maintain a proper pH and iron chelate for the oxidation in the cooling water stream. The purpose of this study is to investigate improvements in the process to reduce the use of the chelate catalyst.

Status / Accomplishments: A modified air injection system has been installed in Unit 11. However, the system is not yet operational and is scheduled to come on line soon. Upon successful implementation, these modifications are expected to result in a 30% to 50% reduction in the use of iron chelate used for abatement. When the results of this investigation become available, they will be summarized in a technical report provided there is adequate funding for this activity.

Reports & Articles Published in FY 2002:

Bharathan, D., K. Gawlik, "Investigation of methods to reduce chemical costs related to H_2S abatement in geothermal power systems," NREL submitted milestone, Sept. 2002.

Presentations Made in FY 2002: None.

Planned FY 2003 Milestones: None.

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