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Federal Geothermal Research Program Update Fiscal Year 2000

Prepared for:
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency
and Renewable Energy
Office of Wind
and Geothermal Technologies

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Idaho Operations Office

DISCLAIMER

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INTRODUCTION

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 Wind and 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 of Geothermal and Wind Technologies.

Mission

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

Goal

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

This Federal Geothermal Program Research Update reviews the specific objectives, status, and accomplishments of DOE's Geothermal Program for Federal Fiscal Year (FY) 2000. The information contained in this Research Update illustrates how the mission and goals of the Office of Geothermal and Wind Technologies are reflected in each R&D activity. The Geothermal Program, from its guiding principles to the most detailed research activities, is focussed 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 four categories of work used to distinguish the research activities of the Geothermal Program during FY 2000 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.

Exploration Technology

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 Technology 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.

Reservoir Technology

The geothermal industry has made progress in devising techniques for characterizing and developing hydrothermal reservoirs. Nevertheless, reservoir technology still suffers from several major uncertainties, such as those encountered in assessing reservoir productivity and sustainability, and in assessing the extent of field reserves. These uncertainties may lead to overproduction in a field and premature pressure and production declines. Reservoir Technology research combines laboratory and analytical investigations with equipment development and field testing to establish practical tools for resource development and management for both hydrothermal reservoirs and enhanced geothermal systems. Research in various reservoir analysis techniques is generating a wide range of information that facilitates development of improved reservoir management tools. Improved geothermal tracer chemicals and tracer data interpretation techniques will optimize injection strategies and increase resource longevity. Capabilities for predicting scaling and corrosion have improved markedly with ongoing research in brine chemistry. Improved methods of numerically modeling reservoirs are increasing the understanding of fluid flow in geothermal systems.

Drilling Technology

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

Conversion Technology

The three conversion technologies in current use for electricity generation are: 1) Dry steam conversion, such as used at The Geysers since 1960; 2) Flash steam plants, favored for liquid-dominated or two-phase resources when the resource temperature is over 180°C (360°F); and 3) Binary cycles, favored for moderate resource temperatures in the range of 100°C to 180°C (212°F to 360°F). Dry steam and flashed steam plants are mature technologies generating cost-competitive electricity in some situations. Binary-cycle power plant technology is less mature, only recently coming into general use as an economic conversion alternative. Conversion Technology research focuses on reducing costs and improving binary conversion cycle efficiency, to permit greater use of the more abundant moderate-temperature geothermal resource, and on the development of materials that will improve the operating characteristics of many types of geothermal energy equipment. Increased output and improved performance of binary cycles will result from investigations in heat cycle research. High-temperature, scale-resistant, corrosion-resistant, and thermally-conductive liner materials are being developed for fluid transport systems, heat exchanger applications, and energy conversion processes. CO2-resistant well cements able to withstand the aggressive chemistry of certain geothermal fluids are also under development. Biotechnology research focuses on solutions that characterize microbiological growth and changes with various processes and environments encountered in the geothermal settings, as well as methods to prevent and repair damage to equipment and facilities from microbiological attack.

EXPLORATION TECHNOLOGY

Project Title:
Data Collection of Geothermal and Market and Infrastructure Related to Electrical Use

<table>
<tr><td>Contract/Grant #: F99-181037</td><td colspan="2">Contract/Grant Period: FY 2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Organization Type: IN</td><td>Congressional District:
Virginia 11th</td></tr>
<tr><td>Directing Organization:
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<tr><td>DOE Funding Allocation:
$13,465</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Conduct geothermal research which includes assisting the US geothermal industry with the collection of geothermal data and market and infrastructure data related to electrical use in E. Africa including Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Mozambique, Rwanda, Tanzania and Uganda.

Approach/Background:

Idaho National Engineering and Environmental Laboratory (INEEL) was tasked with conducting geothermal research, which included assisting the U.S. geothermal industry with the collection of geothermal data, and market and infrastructure data related to electrical use in East Africa, including Djibouti, Eritrea, Ethiopia, Kenya, Tanzania, and Uganda. In conjunction with this research, INEEL required the assistance of a subcontractor in the performance of this work, which was expected to last approximately three years.

The approach was to use consultant experience and data collected both in the field and in the US to identify and develop opportunities for the participation of US industry in the use of geothermal resources in the Rift Valley region of E. Africa.

Status/Accomplishments:

During FY 2000, accomplishments include the following:

(1) Preparation of a report on the geothermal resources and energy sector in Tanzania.

(2) Identification and tracking of World Bank(WB)/Uganda project with provision for support to private sector-based geothermal development in Uganda.

(3) Update reports prepared on geothermal development in Kenya and Ethiopia.

(4) Articles written on geothermal development in Africa for GEA newsletter.

(5) Proposal and budget prepared for White House Energy Initiative.

Planned FY 2001 Milestones:

(1) Planned and implemented a seminar on March 1, 2001 at GEA's offices with eight Geothermal Energy Association/Geothermal Resources Council (GEA/GRC) members participating in person and on a conference call phone line. World Bank Representative Ted G. Kennedy was the invited guest. Prepared summary report on the meeting and assisted with distribution to GEA/GRC members.

(2) Prepared draft "White Paper" report on background and issues related to geothermal development in developing countries for GEA and WB/International Finance Corp. (IFC)/Global Environmental Fund (GEF)/International Energy Agency (IEA) Geothermal Initiative for Developing Countries. Expect to continue to participate in and monitor WB/IFC/GEF/IEA Geothermal Initiative for Developing Countries in collaboration with GEA and GRC member countries.

(3) In collaboration with GEA, planning follow on meeting on May 25 for larger group of GEA/GRC members and WB/IFC representatives to further discuss WB/IFC/GEF/IEA Geothermal Initiative for Developing Countries.

Major Reports Published in FY 2000:

(1) "Tanzania's Energy Sector and Geothermal Resources", November, 1999.

Major Articles Published in FY 2000:

(1) Articles published in GEA newsletter on geothermal development in Kenya, Tanzania and Uganda.

Project Title:
Collection and Assembly of Published Data on Geothermal Resources

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October 1999-September 2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Directing Organization:
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All Travel Expenses to Conferences</td></tr>
<tr><td>DOE Funding Allocation:
$187,703.74</td><td>Cost Share Funding:
$5,153.85</td></tr>
</table>

Project Objective:

Bob Lawrence & Associates, Inc. (BL&A) will create searchable, user-friendly databases in Microsoft Access® of geothermal resources in 14 Central/Eastern European countries -- Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Former Yugoslav Republic of Macedonia (FYR Macedonia), Hungary, Romania, Slovakia, Slovenia, and Yugoslavia (Serbia and Montenegro) -- China, Russia, and Ukraine. The firm will incorporate data from published literature and, to the extent it exists, from a database and reports previously done for Sandia National Laboratory. Various sources of information, both U.S. and in-country, will be used. In addition to site-specific information, e.g., site name, location, development status, temperatures, potential (MWe and MWt), chronology, and general notes, BL&A will also include in the final reports information which U.S. project developers require to perform pre-feasiblity studies, e.g., the country's current power situation, economic data, electricity prices, growth in energy demand, a power profile, geothermal power generation and direct use potential, and relevant legislation.

Approach/Background:

BL&A will create five searchable, user-friendly databases in Microsoft Access® of geothermal resources in 14 countries -- Albania, Bosnia-Herzegovina, Bulgaria, China, Croatia, Czech Republic, FYR Macedonia, Hungary, Romania, Russia, Slovakia, Slovenia, Ukraine, and Yugoslavia (Serbia and Montenegro). The completed databases, along with a copy of the reports in PDF format for easy distribution to the U.S. geothermal industry, will be delivered on CD-ROM to INEEL.

Status/Accomplishments:

All program deadlines were met on schedule. In FY 2000, "Geothermal Resources in China" was delivered to INEEL 30 April 2000, "Geothermal Resources in Hungary" was delivered 31 July, and "Geothermal Resources in Russia" was delivered 30 November. In FY 2001, two databases and reports will be created. "Geothermal Resources in the Balkans" (Albania, Bosnia-Herzegovina, Croatia, FYR Macedonia, Slovenia, and Yugoslavia) will be delivered 30 April 2001. "Geothermal Resources in Bulgaria, the Czech Republic, Romania, Slovakia, and Ukraine" will be delivered 29 December.

Planned FY 2001 Milestones:

(1) In FY 2001, "Geothermal Resources in the Balkans" (Albania, Bosnia-Herzegovina, Croatia, FYR Macedonia, Slovenia, and Yugoslavia) will be delivered 30 April 2001. "Geothermal Resources in Bulgaria, the Czech Republic, Romania, Slovakia, and Ukraine" will be delivered 29 December.

Major Reports Published in FY 2000:

(1) "Geothermal Resources in China"

(2) "Geothermal Resources in Hungary"

(3) "Geothermal Resources in Russia."

Major Articles Published in FY 2000:

None

Project Title:
Funding Sources for Small Geothermal Projects

<table>
<tr><td>Contract/Grant #: K99-18108</td><td colspan="2">Contract/Grant Period:
October 1999-September 2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Organization Type: IN</td><td>Congressional District:
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<tr><td>Directing Organization:
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All Travel Expenses</td></tr>
<tr><td>DOE Funding Allocation:
$42,821.48</td><td>Cost Share Funding:
$0.00</td></tr>
</table>

Project Objective:

Bob Lawrence & Associates, Inc. (BL&A) will collect and update information on financing sources for small geothermal projects. The firm will provide this information to the U.S. geothermal industry by updating the "Geothermal Financing Workbook" and creating and distributing "Green Green," an electronic newsletter.

Approach/Background:

BL&A will (1) create a second edition of the highly successful "Geothermal Financing Workbook," adding additional financing sources, and (2) create, edit, and distribute via email "Green Green," a bimonthly electronic newsletter created in HTML which provides financing information to the U.S. geothermal industry. "Green Green" will report on international geothermal power projects, focusing on project financing and upcoming events, track international geothermal power projects, and feature other items of interest and relevance to the U.S. geothermal industry.

Status/Accomplishments:

All program deadlines were met on schedule. The second edition of the "Geothermal Financing Workbook" was delivered to INEEL 30 November 1999. Four issues of "Green Green" were created and distributed to the U.S. geothermal industry in FY 2000 -- 31 March, 31 May, 31 July, and 30 September.

Six issues of "Green Green" will be distributed in FY 2001. The newsletter was distributed 31 December 2000 and 28 February 2001. Additional issues are planned for 30 April, 30 June, 31 August, and 31 October.

Planned FY 2001 Milestones:

(1) "Green Green" will be published six times in FY 2001. It will be sent via email to the U.S. geothermal industry every other month, beginning 31 December 2000.

Major Reports Published in FY 2000:

(1) "Geothermal Financing Workbook," 2nd edition, was published 30 November 1999.

(2) "Green Green" was published and sent via email to the U.S. geothermal industry 31 March, 31 May, 31 July, and 30 September.

Major Articles Published in FY 2000:

(1) "Financing Small-Scale Geothermal Power Plants," Small-Scale Electric Power Generation & Geothermal Heat Pumps. Klamath Falls, Oregon: Geo-Heat Center, Oregon Institute of Technology, International Summer School, October 1999.

Project Title:
Geothermal Resource Analysis and Structure of Basin and Range Systems, Especially Dixie Valley Geothermal Field, NV

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13886</td><td colspan="2">Contract/Grant Period: 01/01/00-9/30/00</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Directing Organization:
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N/A</td></tr>
<tr><td>DOE Funding Allocation:
$102,326</td><td>Cost Share Funding:
$0</td></tr>
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Project Objective:

There are two main objectives to this contract. 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.

Approach/Background:

Recently released information dealing with the Dixie Valley geothermal system indicates a greater potential for geothermal systems in the Basin and Range in terms of reservoir size and reservoir temperature than has been anticipated based on historical results. This data suggests new directions in exploration and evaluation. This new information has been described to the geothermal community in the papers cited below. 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 US was compiled and put into the public domain on our website. We will continue to add additional wells to the data base 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 database 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 the period of the contract in fiscal year 2000 (1/1/00-9/30/00) a number of tasks were accomplished. We gave papers at the World Geothermal Congress in Japan and at the Geothermal Resources Council (GRC) Meeting in San Francisco on the thermal regime in Dixie Valley to introduce the new information the the geothermal community. We gave a poster paper at the GRC meeting with the results of the regional geothermal data base compilation 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 the field aspects of the gravity survey (collecting about 300 new stations), digitized the seismic sections started preliminary analysis, and wrote a paper on a natural state model of the system that will be submitted to the Journal of Geophysical Research.

We added a total of over 500 points to the regional thermal well data base including the assimilation of the extensive Phillips data base that John Sass made available in late 1999. We extensively modified the Web Page to make it more user friendly and to simplify access to the data by interested users. We began the processs of calculating heat flow and overall system heat loss for the geothermal systems with sufficient data. We started to determine lithology, thermal conductivity and heat flow for those sites which did not already have that information. This task will be complete in the first half of FY 2001. 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).

Planned FY 2000 Milestones:

(1) The planned milestones for FY 2001 are developing the detailed Dixie Valley/Fairview Peak area geothermal model, including complete interpretation of the gravity survey completed in the summer of 2000, building a new natural state thermal model of the Dixie Valley area, and initiating application of the results from Dixie Valley to the areas outlined by the regional data compilation. We will add heat flow values to all of the sites in the regional geothermal data base and use these heat flow values to determine heat loss for as many systems as possible. We will complete initail compilation of the data bases for the new Geothermal Map of North America.

Major Reports Published in FY:

(1) Blackwell, D.D., K.W. Wisian, M.C. Richards, and J.L. Steele, Geothermal Reservoir Investigations Based on Heat Flow and Thermal Gradiant Data for the United States, Final Report DOE Contract DE-FE07-97ID13504, 47 pp., April, 2000.

Major Articles Published in FY:

(1) Blackwell, D.D., B. Gollan, and D. Beniot, Thermal Regime in the Dixie Valley, Nevada geothermal system, ed. E. Iglesias, D. Blackwell, T. Hunt, J. Lund, S. Tamanyu, and K. Kimbara, Trans. World Geothermal Congress 2000, 991-996, 2000

(2) Blackwell, D.D., B. Gollan, and D. Beniot, Temperatures in the Dixie Valley, Nevada geothermal system, Trans. Geothermal Resources Council, v. 24, p. 223-228, 2000.

Project Title:
Field Studies

<table>
<tr><td>Contract/Grant #: DE-AC07-99ID13727</td><td colspan="2">Contract/Grant Period: 2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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Idaho 2nd</td></tr>
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<tr><td>DOE Funding Allocation:</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The Cove Fort-Sulphurdale geothermal field is unique because production comes from both a naturally developed parasitic vapor cap and the underlying liquid-dominated reservoir. Other geothermal systems are either liquid or vapor-dominated and produce solely from the predominant phase. The return curves from the tracer test reflect this uniqueness. They have been rising for nearly a year and have not yet reached their peak. The objectives of this project are to develop better understanding of Cove Fort-Sulphurdale geothermal resource, in particular, and the behavior of geothermal systems with vapor-dominated caps in general. An improved understanding of reservoir boundaries, communication between injector and production wells, and interaction between the liquid zone and steam cap must be developed before resource expansion can be considered.

Approach/Background:

The Cove Fort-Sulphurdale geothermal system produces both dry steam from a shallow parasitic vapor cap and liquid from the underlying liquid-dominated resource. Samples of the steam and liquid indicate that their compositions have remained stable since production began in 1985 but that the field experienced a transient pulse of increased gas shortly after injection was initiated. A preliminary numerical model for the Cove Fort-Sulphurdale geothermal system was constructed to help design a tracer test. Liquid and vapor-phase tracers were injected into the reservoir in January 1999. Steam containing the refrigerant R-134a, which was used to trace the movement of the vapor phase, was observed in the production wells after 2 weeks. However, as of December 2000, tracer concentrations

were still increasing. The cumulative tracer returns suggest that the steam cap taps a small fraction of the injectate plume near the injection well. The calibration of the numerical model to match the tracer return curves suggest that recharge is related to deep circulation of ground waters. Fluorescein was used to trace the liquid that was injected. To date, no fluorescein has been observed in samples from the well that discharges liquid water.

Status/Accomplishments:

Investigations of the Cove Fort-Sulphurdale geothermal system are providing a unique opportunity to analyze reservoir and tracer behavior in a moderate-temperature field producing dry steam from a parasitic vapor cap and liquid water from the underlying liquid reservoir. Analyses of the steam and liquid indicate that their compositions have remained relatively stable since production began in 1985. A tracer test was conducted in January, 1999, to evaluate the movement of steam and liquid and the effects of injection. Liquid (fluorescein) and vapor-phase (R-134a) tracers were injected at a depth below the producing horizons. R-134a was detected in all of the steam wells two weeks after injection. Methods of simulating the thermodynamic behavior were incoporated in the numerical simulator. Simulation studies indicate that recharge to the geothermal system is deep circulation of ground water near the steam producers Linda and Olga. Less than 1% of the R-134a and no fluorescein have been recovered to date. These results suggest that the early tracer returns have come from a location where the reservoir taps a small fraction of the slowly-moving, liquid injection flow close to the injection well, and that the rest of the tracer may arrive later, and by a different route.

Planned FY 2000 Milestones:

(1) Incorporate thermodynamic behavior of tracers into the numerical simulator

(2) Sensitivity studies of conceptual model to match the observed tracer returns.

Major Reports Published in FY:

None

Major Articles Published in FY:

(1) Moore, J.N., Adams, M.C., Sperry, T.L., Bloomfield, K.K., Kunzman, R., (2000) Preliminary Results of Geochemical Monitoring and Tracer Tests at the Cove Fort-Sulphurdale Geothermal System, Utah Procedings of the Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University.

Project Title:
Seismic Mapping of the Subsurface Structure at the Rye Patch Geothermal Reservoir

<table>
<tr><td>Contract/Grant #:</td><td colspan="2">Contract/Grant Period:</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization</td></tr>
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<tr><td>DOE Funding Allocation:
$125K</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

In 1998 a 3-D surface seismic survey was conducted to explore the structure of the Rye Patch geothermal reservoir (Nevada) to determine if modern seismic techniques could be successfully applied in geothermal environments. Furthermore, it was intended to map the structural features which may control geothermal production in the reservoir. The results suggested the presence of at least one dominant fault responsible for the migration of fluids in the reservoir (Feighner et al., 1999). In addition to the surface receivers, a 3-component seismometer was deployed in a borehole at a depth of 3900 ft within the basement below the reservoir, which recorded the waves generated by all surface sources. The objective of the current report is to use this dataset to determine the subsurface structure and to delineate the existence of possible faults within the the Rye Patch reservoir.

Approach/Background:

The Rye Patch Geothermal Survey covered an area of 3.03 square miles and was designed with 12 north-south receiver lines and 25 east-west source lines. The source interval was 100 feet while the source line spacing was 400 feet. A high temperature, wall-locking, 3-component geophone was installed in well 46-28 at a depth of 3,900 ft. The borehole geophone recorded all shots throughout the survey area, amounting to a total of 2,134 traces.

A total of 2,005 first arrival travel times were determined out of the 2,134 possible traces. 2-D 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 a velocity profile calculated from a Vertical Seismic Profile (VSP) recorded in the same well (Feighner et al., 1998). This VSP represents the best estimate for the distribution of velocities in the subsurface around the well and is the only in situ velocity measurement available. It was assumed that differences in travel time between the observed and modeled data are caused by structural deviations from a homogeneously layered model as determined by the VSP, and thus were mapped into topographic changes at depth. The topographic changes were assumed to be changes in basement elevation caused by faulting cutting through the basement including the reservoir structure above.

Status/Accomplishments:

The results of the present study suggest an east-west-trending structure (possibly a horst) with boundaries that match the location of faults found in the analysis of the 3-D seismic surface data. These faults are separated by about 5,000 ft. The throw on these faults cannot be exactly determined but values in excess of 200 ft can be excluded. The northern boundary lies north of well 42-28, while the southern boundary is located between wells 44-28 and 46-28. The structure seems to be manifested throughout the survey area in east-west direction extending more than 5,000 ft to the east and west of the wells.

In 1999, an integrated study based on various geophysical data was conducted by Teplow (Teplow, 1999). This study included, among other results, gravity, magnetic, and self potential data, that was collected over the Rye Patch geothermal area. The gravity data reveal a Bouguer residual indicating a broad region of constant values bounded by steep negative gravity gradients to the north-west and south-east. The results support the interpretation of higher density or excess mass in the central region around the wells, surrounded by less dense material (e.g. an elevated high density basement may represent a fitting model). The contour lines of the total magnetic field reveal an east-west trending feature with a low in the central part between the boreholes. A possible explanation may be the presence of hydrothermal mineralization in the alluvial deposits of the area. The self potential data support the trend of the magnetic and gravity surveys. Again, the data reveal a low in east-west direction around well 44-28 bounded by gradients to the North and South.

Overall, it can be stated that the self potential, magnetic and gravity data support the interpretation of an east-west feature in the central region around the boreholes and therefore corroborates the results of the seismic mapping in the present study.

References:

(1) Feighner, M., Daley, T.M., Majer, E.L., 1998, Results of Vertical Seismic Profiling at Well 46-28, Rye Patch Geothermal Field, Pershing County, Nevada, Lawrence Berkeley National Laboratory Report LBNL-41800.

(2) Feighner, M., Gritto, R., Daley, T.M., Keers, H., Majer, E.L., 1999, Three-Dimensional Seismic Imaging of the Ryepatch Geothermal Reservoir, Lawrence Berkeley National Laboratory Report LBNL-44119.

(3) Teplow, B., 1999, Integrated Geophysical Exploration Program at the Rye Patch Geothermal Field, Pershing County, Nevada - Final Report.

Planned FY 2001 Milestones:

None

Major Reports Published in FY 2000:

(1) Gritto, R.; Daley, T.M.; Majer, E.L. (2000): Seismic Mapping of the Subsurface Structure at the Ryepatch Geothermal Reservoir, Earth Sciences Division, Lawrence

(2) Berkeley National Laboratory Report LBNL-47032, pp. 1-25.

Major Articles Published in FY 2000:

(1) Gritto, R.; Majer, E.L.; Daley, T.M. (2000): Development and Application of 3-D Seismic Imaging Methods for Geothermal Environments, Geothermal Resources Council Transactions, Vol. 24, LBNL-46032 pp. 235-238.

(2) Gritto, R.; Daley, T.M.; Majer, E.L. (2000): Seismic Mapping of the Subsurface Structure at the Rye Patch Geothermal Reservoir, Nevada, EOS, Vol. 81, 48, LBNL-46834, pp. 1199.s

Project Title:
Refined Conceptual Models for Deep-Circulation and Magmatically-Heated High-Temperature Hydrothermal Systems in the Great Basin and Cordilleran United States

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13891</td><td colspan="2">Contract/Grant Period: 10/01/00-09/30/04</td></tr>
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<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Organization Type: CU</td><td>Congressional District:
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<tr><td>DOE Funding Allocation:
$260,000 (FY 2000)
$370,347 (FY 2001)</td><td>Cost Share Funding:</td></tr>
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Project Objective:

(1) Develop and refine new geological, geochemical, and numerical models for the two major types of high-temperature convective hydrothermal systems in the Western U.S., including those systems presently cryptic but certain to be found: (a) in association with young andesitic volcanoes of the Cascade Range; and (b) beneath tightly capped Cenozoic valley-fill sequences throughout the Basin and Range physiographic province.

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

Approach/Background:

In close cooperation with our long-time industry partners (Calpine Corporation, CalEnergy Corporation, and Caithness Energy), we are conducting an ambitious, multidisciplinary research program aimed at better understanding the intricate and interlinked geological and geochemical controls governing the

inception, evolution, configuration, and permeability structure of the two distinct types of high-temperature (>150 degrees Celsius) hydrothermal systems in the American West -- those demonstrably driven by shallow, cooling igneous intrusions (e.g., The Geysers, Medicine Lake, and Salton Sea systems, California); and those heated in response to circulation along deeply-penetrating faults and fractures in regions of anomalously high heat flow (e.g., Dixie Valley, Nevada). Building upon a quarter-century experience base in the Western U.S., we are working with newly available subsurface samples and corresponding databases to complete four-dimensional analysis and characterization of each of the above-named exemplary systems with formerly impossible levels of detail. The results of these studies are yielding individual and aggregate conceptual models of the critical controls on fluid and heat transfer through finite rock volumes (three dimensions) with time (the fourth). The models will be immediately useful to the geothermal industry not only for more efficient development and expansion of existing resources, but also for more cost-effective exploration for the many profitable systems still to be found in the region. The research program is being implemented utilizing a balanced mix of traditional and novel technologies, including, but not necessarily limited to: (1) Surface and subsurface mapping of geology, fracture geometry and extent, and hydrothermal alteration; (2) Integrated petrologic studies comprising petrographic characterization, geoehemical analysis, electron-microprobe microchemical analysis, scanning-electron microscopy, X-ray diffraction, and fluid-inclusion microthermometry and gas analysis; (3) organic geochemistry; (4) hyperspectral image analysis; (5) radiometric age-spectrum dating and cooling-history modeling; (6) numerical simulation of pluton cooling and thermal energy and mass transport, with particular attention to permeability prediction. System-specific models arising from this work are being synthesized with the benefit of pertinent information from analogous systems worldwide, and integrated into hydrothermal-system conceptual models that will materially aid geothermal exploration and development programs throughout the Western U.S.

Status/Accomplishments:

(1) Determined the sealing mechanism and mineralogy inhibiting thermal-fluid escape as well as cool-groundwater incursion at the andesitic Medicine Lake volcano geothermal system on the eastern flank of the Cascade Range in northern California.

(2) Worked with Denis L. Norton (separately funded by DOE-ID) to complete numerical igneous-intrusion and thermal-history models for the north-central Geysers steam field, California. The model clearly shows that peak paleotemperatures recorded in rocks penetrated by scientific corehole SB-15-D would have been reached within a maximum of 55,000 years following intrusion; the heating mechanism is constrained to have been convective thermal-fluid flow. The model also predicts the geometry and permeability of fracture networks created by borad-scale, magmatic-heating-induced hydrothermal fracturing.

(3) Examined the role of strike-slip fault tectonics in guiding emplacement of The Geysers plutonic heat source. Proved that space for accommodation of this >300 cubic kilometer pluton must have been created by local extension in a dominantly compressive structural regime. This mechanism was determined to be analogous to that which creates space for sedimentation in deep "pull-apart" basins like the nearby Little Sulphur Creek basins.

(4) Completed preliminary work on the use of indigenous bituments as thermal-history indicators in high-temperature geothermal systems.

(5) With CalEnergy Operating Company (CEOC), characterized scaling mechanisms and scale compositions for selected production and injection wells at the Salton Sea geothermal field.

(6) Also with CalEnergy, discovered and made initial descriptions of an ancient, buried, rhyolite flow-dome complex at the Salton Sea field; developed a workiing model for the influence of this igneous body on past, present, and future geothermal-reservoir behavior.

(7) Developed a new hypothesis for the evolution of fracture porosity and permeability at shallow levels in a portion of the Yellowstone (Wyoming) hydrothermal system.

(8) Completed editing of a special issue of the international journal Geothermics dedicated to The Geysers Coring Project and the Geysers-Clear Lake igneous-geothermal regime (to be published in March 2001).

(9) Publication of "Volcanoes, Crucibles of Change" (Princeton University Press, 1997) in a Chinese translation. The book, by Fisher, Heiken, and Hulen, includes several chapters prominently featuring volcanic-geothermal systems and their evolution.

Planned FY 2000 Milestones:

(1) Develop a three-dimensional geologic model for the northern Dixie Valley geothermal field, Nevada (in cooperation with Caithness Energy geologist Stuart Johnson). We believe it possible that such a model could benefit from information gained through Hulen's experience with gravity-slide tectonics in analogous, oil-rich, Railroad Valley in eastern Nevada.

(2) Investigate our hypothesis that the deep, high-temperature, Aidlin portion of The Geysers, California, may be a microcosm for evolution of the entire, but perhaps older portion of this vapor-dominated geothermal system. Will employ vitrinite-reflectance, fluid-inclusion microthermometry, X-ray diffraction, petrographic analysis, numerical thermal-history modeling, and other techniques toward this end.

(3) Complete, with Denis Norton, a new model for magmatically-induced fracture propagation at The Geysers. This model will assist steam-field operators in optimizing production and injection strategies.

(4) Approach finalization of a field-wide, three-dimensional map of The Geysers felsite, working in collaboration with geochronologists from the University of California at Los Angeles.

(5) Determine the geometry and influence of young igneous intrusions on fracture evolution and geometry at the Medicine Lake volcano geothermal system in the Cascade Range of northern California.

(6) Revise the Office of Wind and Geothermal Technologies' popular brochure "Geothermal Energy", by mid-May 2001

(7) Write an article on volcanoes and geothermal energy for the new environmental magazine "Living Planet" (affiliated with the World Wildlife Fund).

Major Reports Published in FY:

None

Major Articles Published in FY: 2000

(1) Fisher, R.V., Heiken, G., and Hulen, J.B., 2000, Volcanoes -- Crucibles of Change (Chinese Translation): Bardon-Chinese Media Agency, International Publishing Company, 365 p.

(2) Hulen, J.B. (Guest Editor), 2000, The Geysers Coring Project and The Geysers/Clear Lake igneous-geothermal regime: Geothermics (Special Issue), v. 30, numbers 2 and 3, p. 165-394 in press.

(3) Persoff, P., and Hulen, J.B., 2000, Hydrologic characterization of reservoir metagraywacke from shallow and deep levels of The Geysers vapor-dominated geothermal system, California in The Geysers Coring Project and the Geysers/Clear Lake igneous-geothermal domain (J.B. Hulen, ed.): Geothermics, v. 30, p. 169-192, in press.

(4) Norton, D.L., and Hulen, J.B., 2000, Preliminary numerical analysis of the magma-hydrothermal history of The Geysers geothermal system, California, USA in The Geysers Coring Project and the Geysers/Clear Lake igneous-geothermal domain (J.B. Hulen, ed.): Geothermics, v. 30, p. 211-234, in press

(5) Gruszkiewicz, M.S., Horita, J., Simonson, J.M., Mesmer, R.E., and Hulen, J.B., 2000, Water adsorption at high temperature on core samples from The Geysers geothermal field, California, USA in The Geysers Coring Project and the Geysers/Clear Lake igneous-geothermal domain (J.B. Hulen, ed.): Geothermics, v. 30, p. 269-302, in press

(6) Hulen, J.B., and Collister, J.W., 1999, The oil-bearing, Carlin-type gold deposits of Yankee basin, Alligator Ridge, Nevada: Economic Geology, v. 94, p. 1029-1049.

(7) Hulen, J.B., and Lutz, S.J., 1999, Altered volcanic rocks as hydrologic seals on the geothermal system of Medicine Lake volcano, California: Geothermal Resources Council Bulletin (October, 1999).

(8) Hulen, J.B., and Norton, D.L., 2000, Wrench-fault tectonics and emplacement of The Geysers felsite: Geothermal Resources Council Transactions, v. 24, 8 p.

(9) Moore, J.N., Adams, M.C., and Anderson, A.J., 2000, The fluid-inclusion and mineralogic record of the transition from liquid- to vapor-dominated conditions in The Geysers geothermal systems, California: Economic Geology.

(10) Lutz, S.J., Hulen, J.B., and Schriener, A., Jr., 2000, Alteration, geothermometry, and granitoid intrusions in well GMF 31-17, Medicine Lake Volcano geothermal system, California: Stanford University, 25th Workshop on Geothermal Reservoir Engineering, Proceedings, 7 p.

(11) Moore, J.N., Adams, M.C., Sperry, T.L., Bloomfield, K.K., and Kunzman, R., 2000, Preliminary results of geochemical monitoring and tracer tests at the Cove Fort-Sulphurdale geohtemral system, Utah: Stanford University, 25th Workshop on Geothermal Reservoir Engineering, Proceedings, 6 p.

Project Title:
Noble Gas Isotope Geochemistry in Geothermal Systems

<table>
<tr><td>Contract/Grant #:</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Organization Type: FF</td><td>Congressional District:
California 9th</td></tr>
<tr><td>Directing Organization:
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$140K</td><td>Cost Share Funding:</td></tr>
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Project Objective:

In general, this project is aimed at critically assessing the value of isotope ratio measurements for characterizing geothermal reservoirs. Our objective is to develop a set of isotopic parameters, based on measurements of fluids, fluid inclusions, and rocks and minerals, that will help to identify past and present fluid sources in geothermal systems and to estimate their extent, heat content, and lifetime.

Specific objectives include:

(1) Natural Injectate Tracers: Develop noble gas compositions and concentrations as reliable natural tracers for monitoring the breakthrough of re-injected fluids.

(2) Helium and Heat: Develop a better understanding of the coherence between helium isotopic composition and the heat sources driving geothermal systems. Identify processes responsible for heat-helium fractionation. Explore heat-helium coherence as a potential new geothermal exploration tool.

(3) Flow in Fractured Reservoirs: Expand models describing the flow and fate of phase partitioning tracers in fractured reservoirs.

(4) Acid Fluids: Develop a better understanding of the origin and fate of acid fluids.

Approach/Background:

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

(1) Natural Injectate Tracers: Injection of spent production fluids back into the geothermal reservoirs from which they are produced is now widely recognized as the single most important factor in conserving reservoir pressure and extending the productive lives of geothermal systems. Growing environmental awareness throughout the world also generally require that spent geothermal fluids be returned to the reservoir to protect surface and subsurface waters. Injectate is always colder than reservoir fluids, so eventually returning injectate will cool individual wells and entire reservoirs. Because of the inherent properties of fluid flow and water-rock interaction, the chemical breakthrough of injectate will precede thermal breakthrough. To accurately predict the onset of cooling, it is necessary to develop sensitive, reliable, quantitative, and inexpensive chemical tracers to identify and monitor injectate return. The ultimate goal is to use injectate tracers to model the where and when of thermal breakthrough.

The low solubility of noble gases in water make them very sensitive natural tracers for monitoring the return of injectate in geothermal reservoirs. Initially geothermal reservoirs recharged by natural meteoric waters will have noble gas concentrations and relative abundances equivalent to air-saturated water (ASW). Flashed brines used for re-injection can be easily identified by noble gas concentrations up to ~100 times lower than the natural recharge waters.

(2) Helium and Heat: The helium isotopic composition of fluids from geothermal systems within continental terranes varies from ~9 Ra to ~0.02 Ra. The high values are indicative of a pure magmatic helium signature and the low values are indistinguishable from the value predicted for radiogenic helium production in the crust. In the Earth, helium and heat are uniquely coupled because the natural radioactivity of U and Th is responsible for ~75% of the heat production and all of the 4He production. The coherence suggests that helium isotopic variations can be used to quantify the proportion of heat supplied by either magmatic input or deep crustal fluid circulation. Deviations from helium-heat coherence may be used to evaluate the process and relative efficiency of heat and volatile extraction.

(3) Flow in Fractured Reservoirs: There is growing interest in developing tracers that partition between liquid and gas phases in order to evaluate the fate and transport of liquids injected into two-phase and vapor dominated reservoirs. In favorable cases, such tracers can be used to identify fast paths for vapor transport, to monitor reservoir processes, and to evaluate the degree of initial water saturation and the amount of injected liquid converted to vapor. In collaboration with Karsten Pruess (LBNL), noble gases, which have very low solubility in water, are being incorporated into models of phase-partitioning tracers to study their behavior when injected into fractured vapor dominated reservoirs.

(4) Acid Fluids: An important factor in reservoir management and development is the origin, evolution, and distribution of corrosive acid fluids in geothermal systems. The problem of potentially acid reservoir fluids is common to most geothermal fields associated with recent andesitic volcanoes and it is greatly in the interests of the world geothermal community as well as the U.S. government to understand and anticipate the occurrence of these fluids.

Status/Accomplishments:

(1) Natural Injectate Tracers: The Dixie Valley geothermal field has been in operation for more than 11 years and during this time an aggressive injection policy has been in effect. The production and injectate fluids have been thoroughly documented with quarterly brine analyses, annual non-condensable gas samples, and intermittent stable isotope analyses. Analyses of noble gases and their isotopes have been obtained to give a complete evaluation of the available natural chemical tracers for injectate fluids in a well documented geothermal field.

These data have provided:

(1) An evaluation of the reliability and limitations of the various natural chemical tracers

(2) A quantitative assessment of the volume of injectate co-produced with indigenous reservoir fluid

(3) The rate at which injected fluids are replacing indigenous reservoir fluids

(4) An estimate of the reservoir volume (Kennedy et al., 1999; Kennedy and Shuster, 2000).

In collaboration with CalEnergy, we have begun a program to analyze production fluids from the Salton Sea Geothermal Field. Our role in this project is to identify and map fluid sources and most importantly use noble gas abundances to trace and monitor re-injected fluids.

(2) Helium and Heat: Because ~75% of the Earth's heat budget and all of the 4He is produced from natural U and Th radioactivity, theoretically there should be a well-defined 4He to heat production ratio (4He/Q) of ~3.7 x 10-8 cm3STP/Joule. In volcanic terranes, mass and heat are supplied to the crust by mantle partial melting which drives magma genesis. The Earth's upper mantle has a relatively constant 3He/4He ratio of 8-9 Ra. Therefore, the mass and heat flux associated with magma genesis should be characterized by a relatively constant 3He/Q ratio of ~0.5 x 10-12 cm3STP/Joule. It has been demonstrated by others that the 3He/Q ratios in fluids circulating through mid-ocean ridge spreading centers vary from ~0.1-1 x 10-12 cm3STP/Joule, remarkably similar to the predicted value and confirming the inherent coherence between helium and heat. The observed range in values, however, implies mass-heat fractionation. We are investigating various mass-heat fractionation processes, such as magma degassing, magma aging with preferential loss of 3He, boiling of geothermal reservoir fluids, and conductive heat loss.

In crustal regimes, far removed from volcanic processes, helium in fluids is dominated by radiogenic 4He and characterized by 3He/4He ratios of ~0.02 Ra. This corresponds to a 3He/Q ratio of ~1 x 10-15 cm3STP/Joule, almost three orders of magnitude smaller than the mantle value. The large difference in the helium/heat ratio between volcanic and non-volcanic terranes suggests that the helium isotope composition, when coupled with 3He/Q ratios, can readily differentiate the relative proportions of mantle and crustal heat driving continental geothermal systems. This large difference will be useful as an exploration tool and in developing a better understanding of the present state of a geothermal system by modeling deviations from simple crust-mantle mixing in terms of mass-heat fractionation. See Kennedy et al. (2000).

(3) Flow in Fractured Reservoirs: This project exploits the phase-partitioning properties of artificial and natural (noble gas) tracers in two-phase and vapor dominated reservoirs to identify preferential flow paths and to monitor in place water saturation and the vaporization of injected water. The transport processes are modeled using the TOUGH2 geothermal reservoir simulator (Pruess et al., 1999). The migration of the phase partitioning tracers has been simulated for injection of liquids into a vapor-dominated reservoir. The simulations indicate a complex interplay of different reservoir processes that compare favorably with observations at The Geysers. These processes include (1) advective flow dominates tracer transport between wells, (2) diffusive exchange with matrix rocks strongly affects tracer returns in fractured reservoirs, and (3) fast paths and boiling of the injected liquid can be identified. The preliminary results of this project were presented at the 25th Stanford Workshop on Geothermal Reservoir Engineering (Pruess et al., 2000).

(4) Acid Fluids: The goal of this project is to develop a better understanding of the origin and fate of acid fluids common to most geothermal fields associated with recent andesitic volcanoes. We have established a joint LBNL-Philippine National Oil Company (PNOC) research project to characterize deep geothermal fluids using isotope and geochemical techniques. For the initial survey of Philippine geothermal systems, two fields were selected for study: the Mahanagdong and Tongonan fields in Leyte and the Mt. Apo field, Mindanao. These fields are jointly developed by the Philippine National Oil Company (in charge of the steam fields) and, in part by U.S. companies (CalEnergy Co. Inc. and Ormat Int'l. Inc., operating power plants under BOT contracts). In collaboration with scientists from the PNOC, we have been evaluating a correlation between the helium isotope compositions and fluid chemistry, specifically changes in fluid acidity, cation concentrations, and the invasion of re-injected brine. We have also found that co-variations between helium isotopic composition and calculated Heat/Helium ratios for the individual production fluids suggests mixing between geothermal fluids with constant Heat/Helium and cooler waters similar to that expected for re-injected brine. We will pursue these co-variation and their significance pending receipt of funds from the International Atomic Energy Association, Vienna, Austria in support of this collaborative research project.

We also have a collaborative project (with Dr. B. Christensen, Wairaki Research Centre, New Zealand) to identify the source and fate of volcanic fluids in the Ohaaki geothermal field lying along the eastern margin of the Taupo Volcanic Zone, New Zealand. Within the field, we have identified two thermal upwellings, each emanting from fault structures in the Mesozoic basement graywackes. Fluids associated with the eastern upflow zone carry geochemical and isotopic signatures suggesting the presence of a relatively young and shallowly seated (~4 km) degassing intrusive (Christensen et al., 2000; Christensen et al, 2001, submitted).

Planned FY 2001 Milestones:

(1) Conduct feasibility study for new exploration techniques, identify field area to initiate project, and begin field test study at selected site. Sep 01

(2) Finalize noble gas study of injectate return at Dixie Valley incorporating the extensive gas and chemical data set for Dixie Valley production fluids. Apr 01

(3) Salton Sea Geothermal Field: conduct two sampling campaigns, analyze samples, and identify fluid sources including re-injected brines (completion date: 8/30/01); prepare preliminary report. Sep 01

Major Reports Published in FY 2000:

(1) Kennedy, B.M., Fischer, T., and Shuster, D. (2000), Heat and helium in geothermal systems. Proc. 25th Workshop on Geothermal Reservoir Engineering, January 24-26, 2000, Stanford, CA.

(2) Pruess, K., O'Sullivan, M.J., and Kennedy, B.M. (2000), Modeling of phase-partitioning tracers in fractured reservoirs. Proc. 25th Workshop on Geothermal Reservoir Engineering, January 24-26, 2000, Stanford, CA.

(3) Kennedy, B.M. and Shuster, D.L. (2000), Noble gases: sensitive natural tracers for detection and monitoring injectate returns to geothermal reservoirs. Geothermal Resources Council Transactions, 24, 247-252.

(4) Christensen, B.W., Mroczek, E.K., Stewart, M.K., Lyon, G. and Kennedy, B.M. (2000), Ohaaki reservoir chemistry: insights into the nature and location of the heat source(s). Proc. World Geothermal Congress 2000, Japan, 1059-1064.

Major Articles Published in FY 2000:

(1) Moore, J.N., Norman, D.I., and Kennedy, B.M. (2001). Fluid-inclusion gas composition from an active magmatic-hydrothermal system: a case study of The Geysers, California geothermal field. Chemical Geology, v173, 3-30.

Project Title:
Electromagnetic Methods for Geothermal Exploration

<table>
<tr><td>Contract/Grant #:</td><td colspan="2">Contract/Grant Period:</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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EMI provided data</td></tr>
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$60K</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The objective of the proposed research is to develop efficient numerical codes for in-field data quality checks and on-site interpretation of data from single-hole electromagnetic (EM) surveys. These codes are simple in nature and may be implemented on portable computers situated in the field. Specifically, we proposed to develop a fracture inversion code, and a nonlinear 2D inversion code for investigating conductivity structures of cylindrical symmetry.

Approach/Background:

The most likely conduit of geothermal fluids is either through fractures or zones of highly permeable formation. To map and characterize a fracture we proposed, as a first task, to develop a fracture-imaging algorithm. A fracture may be described by its location, dipping angle, size, and electrical property of fluids in it. The final product should be efficient and simple to use, so it can be easily implemented and operated on portable computers situated in the field. The second task consists of development of an efficient 2D inversion, specifically designed for analyzing data obtained in single borehole configuration. The medium of interest is assumed cylindrically symmetric. A 2D integral equation formulated in cylindrical coordinate has been considered for this purpose. Ultimately, the inversion algorithm should be simple enough to be implemented on PCs operated in the field. The 2D inversion is useful for correctly estimating electrical structures in the vicinity of the borehole.

Inductive resistivity logging has long been an important tool because of the sensitivity of electrical resistivity to variations in reservoir properties. Electromagnetic Instruments Inc. (EMI) has been

developing new type of such a tool for geothermal exploration. It is anticipated that the new device, termed GEO-BILT (Geothermal Borehole Induction Logging Tool), will provide high-quality EM data in a single borehole, high-temperature environment. Development of imaging methods is an integral part of the overall goal of the borehole EM technology for geothermal explorations. Initially, the computer codes developed in this project will be tested for interpreting EM data to be acquired by the GEO-BILT to be developed by EMI.

Status/Accomplishments:

Development of the fracture-imaging code in uniform half space has been completed, and the results have been presented in the World Geothermal Congress (WGC) 2000 Symposium. The 2D inversion code for analyzing single-hole EM data has also been developed and is undergoing further development for field deployment in FY 2001.

Planned FY 2001 Milestones:

(1) Demonstration of 2D inversion on PC at EMI November 00

(2) Completion of the of user friendly 2D inversion code March 01

(3) Field test and final report on the 2D inversion code August 01

Major Reports Published in FY 2000:

(1) Seol, S.J., Song, Y., and Lee, K.H., 1999, Fracture characterization using single-hole EM data, Report LBNL-43941, Ernest Orlando Lawrence Berkeley National Laboratory.

(2) Smith, T., and Lee, K.H., Controlled-source magnetotellurics: Source effects, Report LBNL-43121, Ernest Orlando Lawrence Berkeley National Laboratory, 1999.

Major Articles Published in FY 2000:

(1) Seol, S.J., Song, Y., and Lee, K.H., 1999, Fracture characterization using single-hole EM data, Report LBNL-43941, Ernest Orlando Lawrence Berkeley National Laboratory.

(2) Smith, T., and Lee, K.H., Controlled-source magnetotellurics: Source effects, Report LBNL-43121, Ernest Orlando Lawrence Berkeley National Laboratory, 1999.

Project Title:
"Cutting Costs by Locating High Production Wells:
A Test of the Volcanoseismic Approach to Finding `Blind` Resources"

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13863</td><td colspan="2">Contract/Grant Period: 10/99-9/01</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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KenGen</td></tr>
<tr><td>DOE Funding Allocation:
Year 1: $286,211
Year 2: $285,725</td><td>Cost Share Funding:
$4,271,346</td></tr>
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Project Objective:

Test the use of microearthquakes in locating blind geothermal resources in the Kenyan Rift. Use S-wave splitting tomography as applicable to map subsurface fracture density.

Approach/Background:

Deploy a 60 station seismographic network around the Longonot Geothermal prospect near Olkaria, Kenya. Cooperate with KenGen to target a drill site based on microearthquake studies.

Status/Accomplishments:

We collected 9 months of field data. We have analyzed these data and presented 2 American Geophysical Union papers based on them. We also presented 2 AGU talks/posters. We have found that the near surface materials of Longonot grossly distort seismic waves. We have also suggested that Longonot is not an appropriate target for significant geothermal expansion.

Planned FY 2001 Milestones:

(1) 12/2000 Received the last tapes of data from Kenya.

(2) 3/2001 Finished inspecting the data from Suswa and Menengai, talk to KenGen about our finding.

(3) 6/2001 Finish work on site effects and source mechanism.

(4) 9/2001 Publish work on site effects and sources in the Longonot area

Major Reports Published in FY 2000:

see below

Major Articles Published in FY 2000:

(1) 2000 McCausland, W., A.F. Stroujkova, E. Shalev, P.E. Malin, & S.M. Simiyu. Descrimination between site effect and source processes for Mt. Longonot, Kenya. American Geophysical Union Fall00 meeting, San Francisco, CA, Dec, 2000. In December 2000 EOS.

(2) 2000 Stroujkova, A.F. & P.E. Malin. Multiple ruptures for Long Valley microearthquakes: A link to volcanic tremor? American Geophysical Union Fall00 meeting, San Francisco, CA, Dec, 2000. In December 2000 EOS.

(3) 2000 Shalev, E., P.E. Malin, S.M. Simiyu, & W. A. McCausland. The CIGAR 2000 earthquake monitoring study of Longonot Volcano, Kenya. American Geophysical Union Fall00 meeting, San Francisco, CA, Dec, 2000. In December 2000 EOS.

(4) 2000 Malin, P.E., & A.F. Stroujkova. Viewing the (microearthquake) roots of the Casa Diablo hydrothermal system. 6th Annual Geothermal Program Office Technical Symposium, May 2000, China Lake NAWS, CA.

(5) 2001 McCausland, W., The dominance of site effects in the Kenyan Rift microearthquake recording at Mt. Longonot. Master thesis Duke University, Durham NC.

Project Title:
Improving Exploration Models of Andesite-Hosted Geothermal Systems

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13891</td><td colspan="2">Contract/Grant Period: 10/01/00-9/30/04</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$275,000 (FY2000);
$346,609 (FY 2001)</td><td>Cost Share Funding:</td></tr>
</table>

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.

Approach/Background:

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 Geothermal and the Karaha Bodas Co. LLC (an affiliate of Caithness Energy) have made extensive suites of well data, core and cuttings samples, and the results of geophysical studies available for study from Tiwi, 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:

There have been several significant accomplishments on the investigation of the Karaha Telaga Bodas system. Integration of the downhole temperature and pressure data has led to the formulation of a new conceptual model of the thermal system. We have shown that the system consists of an upper condensate layer, a underlying vapor-dominated zone, and a deep liquid-dominated region with measured temperatures up to 350 degrees C and salinities of <1 wt %. Pressures within the vapor zone range from 30-60 bars. Vapor-dominated conditions extend laterally for at least 10 km.

Mineralogic and fluid-inclusion studies of two coreholes have been completed. These data provide a record of the time-temperature-composition history of the system. Mineral relationships indicate that the system was originally a high-temperature liquid-dominated system. The transition to a vapor-dominated regime, at temperatures >300 degrees C is represented by the deposition quartz and chalcedony. The boiling off of the early liquids may have coincided with a major volcanic eruption.

As the vapor-dominated regime developed, downward percolating condensate deposited anhydrite, pyrite, calcite and fluorite. Halite and precipitates of Fe, Na, K, Ti, and Cl represent the youngest stage of hydrothermal alteration. These precipitates formed as the descending fluids boiled-off.

Comparison with the other volcanic-hosted geothermal systems being studied suggests that they evolve through a series of five stages. Stage 1 represents the initial conditions that develop soon after magmatic intrusion. At this time, the system is characterized by an over-pressured liquid-dominated geothermal system. Stage 2 marks the formation of a magmatic vapor chimney at 350 degrees C and ~140 bars surrounded by a condensate curtain. In Stage 3, the vapor zone extends downward below sea level. The relatively low pressure near the base of the chimney causes liquid inflow adjacent to the intru-sion and development of a secondary marginal vapor-dominated zone. In Stage 4, the magmatic vapor discharge from the intrusion becomes small, vapor pressure declines, and the secondary vapor zone expands above the intrusion. In Stage 5, the vapors zone floods because heat is insufficient to boil all liquid inflow and a more common, liquid-dominated system develops.

Planned FY 2001 Milestones:

(1) During FY 2001, mineralogic and fluid inclusion studies will be conducted on additional wells from Karaha Telaga Bodas, interpretation of existing geochemical analyses of springs and downhole samples will be initiated, and structural studies of the coreholes and image logs will be performed. The results will be presented at the GRC and Stanford meetings.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) Allis, R. and Moore, J., 2000, Evolution of volcano-hosted vapor-dominated geothermal systems: GRC Transactions, v. 23, p. 211-216.

(2) Allis, R., Moore, J., McCulloch, J., Petty, S., and DeRocher, T., 2000, Karaha-Telaga Bodas, Indonesia: a partially vapor-dominated geothermal system: GRC Transactions, v. 23, p. 217-222.

(3) Klusman, R.W., Moore, J.N., and LeRoy, M.P., Potential for surface gas flux measurements in exploration and surface evaluation of geothermal resources. Geothermics, v. 29, p. 637-670.

(4) Moore, J.N., Adams, M.C., Sperry, T.L., Bloomfield, K.K., and Kunzman, R. Preliminary results of geochemical monitoring and tracer tests at the Cove Fort-Sulphurdale geothermal system, Utah. 25th Workshop on Geothermal Reservoir Engineering, Stanford University.

(5) Moore, J., Lutz, S., Renner, J., McCulloch, J., and Petty, S., 2000, Evolution of a volcanic-hosted vapor-dominated system: petrologic and geochemical data from corehole T-8, Karaha-Telaga Bodas, Indonesia: GRC Transactions, v. 23, p. 259-263.

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

Project Title:
Improved Technologies for Geothermal Resource Evaluation (Remote Sensing and GIS/Technology Transfer Tasks)

<table>
<tr><td>Contract/Grant #: D E-FG07-00ID13891</td><td colspan="2">Contract/Grant Period: 2/1/2000 - 8/30/2004</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Organization Type: CU</td><td>Congressional District:
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<tr><td>DOE Funding Allocation:
FY:$200 K*
FY2001:$324,258.00*
*Includes Gravimetry Task</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

(1) To use a suite of remote sensing data, at various spectral and spatial resolutions, to map surficial features, such as vegetation and soil anomalies, faults/lineaments, and hydrothermal alteration mineralogy, that can lead to the detection of hidden geothermal resources and help develop a better understanding of the characteristics of known geothermal systems

(2) To integrate GIS and the web as a technology transfer tool for superior dissemination of the results of this project.

Approach/Background:

Remote sensing technology has evolved from simple aerial photography to advanced hyperspectral imagery capture. Multispectral imagery has been proven useful for mapping structural features, hydrotheramally altered rock, lithology on a regional scale, and thermal anomalies. Recently, hyperspectral data, with greatly increased spectral resolution, has become available from airborne platforms, and will soon be available from the first satellite mounted instrument -- NASA's Hyperion.

This data is useful for mapping the mineralogy of hydrothermally altered rock and soil, and for the detection of vegetation anomalies that can be found in association with hydrothermal convection systems. It also holds promise for enhanced structural mapping.

It is the intent of this project to use a suite of remote sensing data, coupled with cutting-edge processing techniques to facilitate their analysis, to fulfil the above stated objective. Past experience indicates that a high degree of success can be met, with the most formidable problem being a lack of hyperspectral data over areas of interest. This problem should, however, be minimized as a commercial and NASA hyperspectral instruments are slated to be launched sometime in 2001. While waiting for these data, Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper (ETM) data are being used for structural interpretation and vegetation anomaly detection with excellent results. Work is also being facilitated at Dixie Valley, Nevada, with AVIRIS airborne hyperspectral data.

Additionally, work being done in this task is readily transferable to industry. Therefore, it is being carefully documented for technology transfer, which will be facilitated by a combination of GIS and web technologies. This will allow easy access to data, simplified step-by-step instructions, articles, and other information by geographic location as well as author name.

Status/Accomplishments:

(1) Data acquisition, for the Salton Sea and Medicine Lake, California areas and the Karaha-Telaga Bodas region, Indonesia, was accomplished.

(2) Analysis for potential hydrothermal convection related vegetation anomalies in the Cove Fort-Sulphurdale, Utah region, using seasonal change detection processing on multitemporal TM data was completed. Field spectra analysis underway.

(3) Data processing for the Karaha-Telaga Bodas region, Indonesia image was underway with data download and haze reductions being completed.

(4) Web-based GIS for technology transfer was partially completed.

Planned FY 2001 Milestones:

(1) Continue work, and submit a paper to the Geothermal Resources Council 2001 annual meeting, on the structural fabric and kinematics of the Karaha-Telaga Bodas region, Indonesia.

(2) Complete the Dixie Valley, Nevada, hyperspectral hydrothermal alteration mineralogy-soil anomaly survey and prepare a related paper.

(3) Submit a paper to the 2001 Stanford Conference on Geothermal Reservoir Engineering on the above mentioned Cove Fort-Sulphurdale hydrothermal convection related vegetation change study.

(4) Submit a paper on the Cove Fort-Sulphurdale field spectra analysis to Geothermics.

(5) Make arrangements for new hyperspectral data acquisition.

Major Reports Published in FY 2000:

(1) As these tasks started several months later than others under this contract, no reports will be completed until FY 2001.

Major Articles Published in FY 2000:

(1) As these tasks started several months later than others under this contract, no articles will be completed until FY 2001.

Project Title:
CD-ROM Access to the Resources of the Global Volcanism Program

<table>
<tr><td>Contract/Grant #: DE-FG07-95ID13402</td><td colspan="2">Contract/Grant Period: 10/1/00 - 9/30/01</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Organization Type: P</td><td>Congressional District:
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<tr><td>Directing Organization:
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In-kind Smithsonian contributions of staff time</td></tr>
<tr><td>DOE Funding Allocation:
$75,003</td><td>Cost Share Funding:
Estimated as ~$70,000</td></tr>
</table>

Project Objective:

Our short-term objective is to produce an interactive CD-ROM titled Volcanoes of Mexico and Central America, which will contain data, images, and other resources from the Smithsonian's Global Volcanism Program concerning all volcanoes known to have erupted in the region during the last 2 million years. Our long-term objective is to assist in geothermal exploration and to minimize hazards posed to geothermal workers in the field from active volcanoes.

Approach/Background:

This project is being carried out by a combination of Smithsonian employees and DOE-funded contractors. Data and images from the Global Volcanism Program for Mexican and Central American volcanoes are being combined with new petrological and bibliographic databases assembled especially for this project. These components are coordinated through an interactive, map-driven interface constructed with the presentation software Macromedia Director.

Status/Accomplishments:

With DOE support we completed a similar interactive CD-ROM project titled Volcanoes of Indonesia in 1998. We have completed the coding for Mexico as a template that is now ready to apply to the other subregions of Central America.

Planned FY 2001 Milestones:

(1) All databases have been prepared for integration, and nearly 1,000 volcano images have been selected, digitized, and captioned. The Volcanoes of Mexico and Central America CD-ROM is expected to be completed and released at the end of calendar 2001. It will provide a comprehensive view of all volcanism in this complex region during the last 2 million years, and should be of use to both explorationists in the field and managers in the office.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Imaging Tools for Electrical Resistivity in Geothermal Exploration and Reservoir Assessment Task 3

<table>
<tr><td>Contract/Grant #:
DE-FG07-99ID13853/Task 3</td><td colspan="2">Contract/Grant Period: FY 2000, 2001, 2002</td></tr>
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<tr><td>DOE Funding Allocation:</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Provide enhanced modeling capability for Electro Magnetic (EM) borehole investigations

Approach/Background:

Traditional EM needs to be enhanced for geothermal reservoir applications. Present project seeks to enhance techniques using methods from electrical engineering, mathematics and bioengineering.

Status/Accomplishments:

(1) Triaxial EM logging model study

(2) Fractal fracture EM scattering representation.

Planned FY 2000 Milestones:

(1) Complete triaxial modeling and focusing study; 2.) Publish Fractal EM response; 3.) Present enhanced borehole modeling package; 4.) Present technique for enhanced fractuire delineation.

Major Reports Published in FY:

None

Major Articles Published in FY:

(1) Bertete- Aguirre, H., Cherkaev, E., and Tripp, A.C., 2000, Borehole effects in triaxial induction logging: Proceedingsof the Geothermal Resources Council 2000 meeting

Project Title:
Geothermal Prefeasibility Studies in Asia and the Western Pacific

<table>
<tr><td>Contract/Grant #: 1810-38</td><td colspan="2">Contract/Grant Period: 3/99 - 3/02</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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None</td></tr>
<tr><td>DOE Funding Allocation:</td><td>Cost Share Funding:
None</td></tr>
</table>

Project Objective:

Conduct geothermal prefeasibility studies in Asia and the Western Pacific so as to provide critical information to American geothermal firms interested in foreign project development and also to accumulate technical data of possible use to American firms as they develop domestic geothermal projects.

Approach/Background:

Collect and review all available literature and photos prior to travel. Visit selected geothermal sites. Assess geoscientific parameters, environmental matters and obtain non-resource related information from local, regional, federal, private and academic sources.

Status/Accomplishments:

Conducted multiple geothermal site visits in Fiji, Vanuatu and Papua New Guinea between 10/99 and 10/00.

Planned FY 2000 Milestones:

(1) Complete documentation of Fiji, Vanuatu and Papua New Guinea mission; Schedule work with SOPAC (Fiji) to assist in acquisition of funding for a Western Pacific Regional Geothermal Program; Conduct studies on the north coast of New Britain, Papua New Guinea.

Major Reports Published in FY:

(1) "Results of Geothermal Prefeasibility Studies in the Western Pacific Nations of Fiji, Vanuatu and Papua New Guinea" (in last preparation stages).

Major Articles Published in FY:

None

Project Title:
Geothermal Prefeasibility Studies in Latin America

<table>
<tr><td>Contract/Grant #: 1810-40</td><td colspan="2">Contract/Grant Period: 3/99 - 3/02</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Organization Type: IN</td><td>Congressional District:
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<tr><td>Directing Organization:

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None</td></tr>
<tr><td>DOE Funding Allocation:
$</td><td>Cost Share Funding:
None</td></tr>
</table>

Project Objective:

Conduct geothermal prefeasibility studies in Latin America so as to provide critical information to American geothermal firms interested in foreign project development and also to accumulate technical data of possible use to American firms as they develop domestic geothermal projects.

Approach/Background:

Collect and review all available literature and photos prior to travel. Visit selected geothermal sites. Asses geoscientific parameters, environmental matters and obtain non-resource related information from local, regional, federal, private and academic sources.

Status/Accomplishments:

Conducted multiple geothermal site visits in Chile between 10/99 and 10/00.

Planned FY 2000 Milestones:

(1) Complete documentation of Chile mission; Visit Chalapalca region of Southern Peru; Initiate a Honduras prefeasibility study.

Major Reports Published in FY:

(1) "Results of Geothermal Prefeasibility Studies in Chile" (in last preparation stages).

Major Articles Published in FY:

None

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

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13891</td><td colspan="2">Contract/Grant Period: 10/01/00-9/30/04</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Allan Jelacic
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E-mail: allan.jelacic@hq.doe.gov</td><td colspan="2">University of Utah
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<tr><td>Organization Type: CU</td><td>Congressional District:
Utah 2nd</td></tr>
<tr><td>Directing Organization:
DOE-Idaho Field Office
Idaho National Engineering & Environmental Laboratory
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<tr><td rowspan="2">Technical Monitor:
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E-mail: creedrj@id.doe.gov</td><td>B&R Code: EB40</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
$286 K, FY2000;
$273 K, FY2001</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Objectives include development of forward modeling and inversion of 2D and 3D electrical resistivity distributions in the earth to aid in exploration and reservoir assessment for geothermal systems. The inversion approach is intended to improve resolution based on brute-force smoothing constraints. Surface and borehole source-receiver arrays are being considered. Resultant algorithms will be made publically available without the restrictions we are increasingly seeing in privately sponsored research developments. Research magnetotelluric (MT) instrumentation will demonstrate advantage of collection modes not currently in industry, and will implement novel means of removing man-made EM interference common in developed geothermal systems. Capabilities will be tested in a producing geothermal field of the western U.S. (Dixie Valley, NV).

Approach/Background:

Imaging algorithms are based on long-standing, well-tested 2D finite element and 3D integral equations algorithms for simulation developed at Utah. Since the physical process is one of diffusive EM, regularization (constraint) is necessary to avoid model artifacts. We carry this out by damping model departures against a-priori information in a way which exploits natural parameter correlations (e.g., conductivity-thickness product and its higher dimensional analogs). Dense, high-quality data is necessary

for well-resolved images of the subsurface, and our research MT instrumentation increases quality and productivity of MT data through high-bandwidth radio links, simultaneous multi-band acquisition, and 24-bit sampling. However, especially in producing systems, competing EM fields from production or plant maintenance sometimes can greatly overwhelm the low level natural signals in which we are interested. We are implementing a novel model which solves for the desired MT transfer function plus a minimal ensemble of polarized noise sources which may be intermittent in time.

Status/Accomplishments:

FY2000 saw development of a prototype algorithm which performs a-priori inversion of MT responses to yield a two-dimensional resistivity cross-section. This has been tested successfully using existing data sets from Nevada and New Zealand. A beta-version is being used by a major U.S. contractor fielding a new array MT/DC acquisition system with very positive feedback, and it has been incorporated into the industry-standard Geotools® and GOCAD® user interfaces. Overall design of the new MT system is essentially complete and we are dealing currently with the engineering details to implement the system. A set of 900MHz low-power digital spread-spectrum radios were acquired and field-tested locally. Firmware conversion and development for the Xilinx FPGAs, Dallas 80C390 micro-controller and Arcom Elan-104 Single Board Computers (SBC) was advanced.

Planned FY 2001 Milestones:

(1) The algorithmic approach to our MT inversion will be extended to the galvanic dipole-dipole method, also eminent in geothermal surveying. Several basic building blocks for this effort already are in place including an accurate forward problem and efficient parameter sensitivities. Joint inversion of MT and galvanic data sets will be investigated as these methods are complementary in their parameter resolution. Three-dimensional, multi-source efforts will be undertaken in cooperation with Y. Sasaki of Kyushu University in producing a freely-available, staggered-grid finite difference (FD) solution for EM scattering. Our currently proposed instrumentation development should be completed in year 2 and demonstrate the advantage of collection modes not currently in place in industry. The algebraic framework of the joint noise source/plane-wave transfer function development will be finalized in cooperation with J. Larsen. Current coherence-based, noise-rejection schemes will be generalized to include robust outlier removal via jack-knifing.

Major Reports Published in FY 2000:

(1) Wannamaker, P. E., and M. S. Zhdanov, eds., 1999, Three-dimensional electromagnetics, Proc. Second Internat. Symp. in mem. Gerald W. Hohmann, University of Utah, Salt Lake City, 342 pp.

(2) Wannamaker, P. E., 2000, Resolution principles of diffusive EM applied to 2-D MT inversion using a-priori constraints, Proc. Ann. Mtg. Consortium for Electromagnetic Modeling and Inversion, ed. by M. Zhdanov, University of Utah, 253-282.

Major Articles Published in FY 2000:

(1) Wannamaker, P. E., 1999, Affordable magnetotellurics: interpretation in natural environments, in Three-dimensional electromagnetics, ed. by M. Oristaglio and B. Spies, Geophys. Devel. Ser., no. 7, Soc. Explor. Geophys., Tulsa, 349-374.

(2) Wannamaker, P. E., J.B. Hulen, and M.T. Heizler, 2000, Early Miocene lamproite from the Colorado Plateau tectonic province, Utah, J. Volc. Geotherm. Res., 96, 176-191.

(3) Wannamaker, P. E., 2000, Comment on "The petrologic case for a dry lower crust", by B. D. Yardley and J. W. Valley, J. Geophys. Res., 105, 6057-6064.

Project Title:
Behavior of Rare Earth Elements in Geothermal Systems: A New Exploration/Exploitation Tool?

<table>
<tr><td>Contract/Grant #: DE-FG07-98ID13575</td><td colspan="2">Contract/Grant Period:
October 1999 - September 2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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Department of Geological Sciences</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District:
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<tr><td>Directing Organization:
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<tr><td>DOE Funding Allocation:
1/98 - 12/98 $97,614
1/99-12/99 $102,163
1/00-9/30/00 $91,250
10/00-9/01 $92,163.</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Rare earth element (REE) mobility has been studied since the 1950's because REE occur as fission products and have been considered to be chemical analogs of radioactinides. The group behavior of the REE has made them useful as a sensitive probe into igneous petrogenesis and other geological mixing, sorting, and separation processes. The REE are sensitive to ligand activities and redox conditions and have been used as geochemical tracers in groundwater, riverian, lacustrian, and oceanic environments. Under hydrothermal conditions the REE may become more mobile and have been proposed as possible tracers in geothermal fluids. Geothermal energy development in the U.S. has been hindered by a lack of reliable techniques for exploration for and evaluation of new resources, and for reservoir monitoring. The premise of our project is that the behavior of the rare earth elements (REE) in geothermal fluids may yield useful information on the state of the geothermal aquifer. Therefore, a better understanding of the behavior of the REE in geothermal systems may result in the development of additional tools for the exploration for and exploitation of geothermal resources.

Approach/Background:

We have collected REE data from producing geothermal fields in California, Idaho, Oregon, Nevada and New Zealand and will compare the REE concentrations and patterns with those from a wide variety of natural features. We collected as wide a range of geothermal fluid types as possible and we collected from a variety of geothermal heat sources. We intend to determine relationships between REE contents, fluid chemistry, and temperature. We have compared the REE contents with typical host (aquifer) rock compositions. Finally, we have resampled selected locations to determine whether REE contents or patterns have changed within the time frame of this study. Our procedure involves sampling geothermal fluids from developed and natural features. We analyze the fluid samples for major and trace cations, anions and REE. We measure the REE by an iron co-precipitation to preconcentrate the REE followed by analysis by inductively coupled plasma mass spectroscopy. By successive method refinements we have achieved detection limits for individual REE of 10-100 picograms per liter.

Status/Accomplishments:

In spring 2000 we collected waters from New Zealand features a second time as well as a samples from the IGNS sample library for two volcanic features in New Zealand. We obtained a third set of samples from New Zealand in the spring of 2001. We are currently in the process of analyzing these samples for the REE. We have three journal publications in preparation for this summer. The New Zealand data will be published as a paper in the forthcoming Giggenbach volume to be published by the Society of Economic Geologists. A second paper will be published as a book chapter and will cover the analytical methods we have used to acquire our data. The book will be titled Rare Earth Elements in Groundwater Systems edited by K. H. Johannesson. Here is a summary of our finding for New Zealand geothermal fluids to date:

(1) Total REE concentrations in geothermal fluids range from <10E-7 to 10E0 chondrite. pH is the dominant control on REE concentration.

(2) Low-pH geothermal fluids have relatively high REE contents (10E0 to 10E-3 chondrite) with characteristic gull-wing chondrite-normalized patterns. Except for La and Ce, which are depleted, the chondrite-normalized patterns are similar to those of potential reservoir rocks, i.e., with a generally negative slope.

(3) REE concentrations in filtered and unfiltered aliquots of low-pH thermal waters are nearly equal, suggesting that most REE are present as dissolved species.

(4) Near-neutral geothermal fluids can support moderate REE solubility (<10E-6 to 10E-3 times chondrite). As with the Low-pH geothermal fluids, chondrite-normalized patterns are similar to those of potential reservoir rocks, without however the gull-wing shape from depletion of La and Ce. In addition, one area in New Zealand has a distinct positive REE slope.

(5) Geothermal fluids that experienced phase separation, have much lower REE contents than similar unflashed fluids from the same areas. This may indicate that boiling, with concomitant increase in pH, results in the loss of REE to solids precipitated in the well bore.

(6) Speciation calculations indicate that the most important lanthanide species are $LnCO_3^+$ and $LnSO_4^+$, in acid-sulfate and neutral-chloride-bicarbonate waters, respectively.

Planned FY 2001 Milestones:

(1) We have previously sampled natural geothermal features in the Oregon cascades and Southeastern Oregon, producing geothermal fields at Dixie Valley and Beowawe, Nevada, and the Heber and Salton Sea geothermal fields in Southern California. The analysis of all but the Salton Sea samples is complete and we intend to publish the results as one or more papers in refereed journals. FY2001 is the fourth year of a four-year project. We therefore plan to employ most of this year to synthesize all the data gathered thus far and to produce a number of publications. The only remaining analytical milestones are completion of the analysis of the New Zealand samples from FY2000 and FY2001, and the analysis of scale samples from Broadlands to determine whether REE are lost to scale on phase separation.

Major Reports Published in FY 2000:

(1) DOE quarterly reports

Major Articles Published in FY 2000:

(1) Shannon, W.M., Wood, S.A., Brown, K., and Arehart, G. (2001) REE Contents and Speciation in Geothermal Fluids from New Zealand. Accepted: Tenth Internation Symposium on Water-Rock Interaction, Villasimius, Italy, June 10-15, 2001.

(2) Shannon, W.M., Wood, S.A., Brown, K., and Arehart, G. (2000) REE Contents and Speciation in Geothermal Fluids from New Zealand and the Philippines, Annual Meeting, Geological Society of America, Abstracts with Programs, A188.

(3) Shannon, W.M., Wood, S.A., Brown, K., Arehart, G., and Wright, M. (2000) REE Contents of Geothermal Fluids from Selected Geologic Environments. 31st International Geological Congress, Rio de Janeiro, August 6-17, 2000.

(4) Shannon, W.M., Wood, S.A., Brown, K., and Arehart, G., Wright, M. (1999) REE Contents of Geothermal Fluids from Selected Geologic Environments. Annual Meeting, American Geophysical Union, EOS Transactions.

(5) Shannon, W.M., Wood, S.A., Brown, K., and Arehart, G. (1999) REE Contents of Geothermal Fluids from Several Geologic Environments. Annual Meeting, Geological Society of America, Abstracts with Programs, 31 (7), A-351.

(6) Shannon, W.M., Wood, S.A., Brown, K., Arehart, G. (1999) Preliminary measurements of concentrations of lanthanide elements in geothermal fluids from the Taupo Volcanic Zone, New Zealand. Proceedings, Twenty-Fourth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 25-27, 1999 SGP-TR-162, 227-235.

RESERVOIR TECHNOLOGY

Project Title:
Fiber Optic Distributed Temperature Systems

Contract/Grant #: DE-AC04-94AL85000	**Contract/Grant Period:** FY2000	
Sponsoring Office Code: EE-12	**Performing Organization:**	
DOE HQ Program Manager: Allan Jelacic **Phone:** 202-586-6054 **Fax:** 202-586-8185 **E-mail:** allan.jelacic@hq.doe.gov	Sandia National Laboratories PO Box 5800 Albuquerque, NM 87185-1033	
	Organization Type: FF	**Congressional District:** NM District 1
Directing Organization: DOE-Albuquerque Operations Office Sandia National Laboratory P.O. Box 5800 Albuquerque, NM 87185-1033	**Principal Investigator(s):** Randy A. Normann **Phone:** 505-845-9675 **Fax:** 505-844-3952 **E-mail:** ranorma@sandia.gov	
Technical Monitor: Raymond LaSala **Phone:** 202-586-4198 **Fax:** 202-586-8185 **E-mail:** raymond.LaSala@ee.doe.gov	**B&R Code:** EB40	**Cost Share Information:** Pruett Ind
	DOE Funding Allocation: $192K	**Cost Share Funding:** $15K

Project Objective:

Develop the knowledge necessary to reduce fiber degradation to reasonable limits, providing three to five years between re-calibration. Our ultimate objective is to extend fiber life beyond 10 years at 250 °C.

Approach/Background:

Working with SpecTran Specialty Optical Company via a CRADA, Sandia will continue developing a more rigorous geophysical wellbore fiber. This new fiber will have enhanced carbon buffering and a larger cross-sectional area. Both of these modifications will reduce mechanical and chemical fiber degradation. Continued laboratory testing will validate the enhancements while providing opportunities to examine degradation detection methods and correction algorithms. Following validation of fiber enhancements, improved fiber will be deployed within an actual geothermal production well.

Status/Accomplishments:

Completed the CRADA work with SpecTran Specialty Optical Company. We determined that increasing the carbon fiber cross-sectional area did not solve the hydrogen problem at geothermal temperatures. We did discover that removing the phosphorus doping does greatly reduce hydrogen degradation. We did not discover this in time to have significant publications in FY 2000. We did get scheduled for the FY 2001 Stanford Workshop, "Geothermal Reservoir Engineering".

Planned FY 2001 Milestones:

(1) Report on testing new fiber system

(2) Field test improved system at geothermal plant

(3) Conduct logging test to compare the performance of a photosonic tool with PTS.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Liquid Sampler

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Directing Organization:
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Thermochem; Mitco</td></tr>
<tr><td>DOE Funding Allocation:
$43K</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Guide complete commercialization of the steam sampler and design and test a liquid sampler.

Approach/Background:

The Steam/Liquid sampler is used to capture wellbore samples between different downhole production zones. Sampling between zones is used to determine where harmful HCl is entering the well. Sampling can aid in fracture mapping and the characterization of inter-well communication using tracers. The steam sampler tool is mature in design and has been demonstrated to provide quality downhole samples. As such, it is ready to be commercialized. Thermochem is currently seeking funding to build two steam samplers. Sandia will assist Thermochem and Mitco in the fabrication of the tools and provide the necessary electronic and software support to ensure a quality tool. Sandia will modify the existing design to accept a new high-pressure valve for capturing high-pressure reservoir liquid.

Status/Accomplishments:

The Sandia developed steam sampler tool was successfully modified with a newly available high-temperature, high-pressure valve. The basic valve design is currently being manufactured for use in military and aerospace applications. The valve required modification to meet our demanding high-temperature environment. Also, a custom-built valve manifold was designed and fabricated to allow its use in downhole applications. This custom valve and manifold can be purchased through the valve manufacturer and will be available for use in other downhole applications requiring a reliable

high-temperature, high-pressure valve. The valve is capable of continuous operation at 220 C and intermittent use up to 300 C with pressures up to 5000 PSI.

The Sandia fluid sampler was successfully field-tested. The sampler was fielded in a 200 C geothermal well at a depth of approximately 1,100 feet and a 100 C geothermal well at depths of 8,400 and 9,000 feet. The samples were analyzed and the results were quite favorable. Thermochem has several applications for this tool within the US and abroad. Thermochem is in the process of commercializing the Sandia designed steam/liquid sampler tool.

Planned FY 2001 Milestones:

(1) Complete the commercialization of this tool, making the service available for geothermal applications.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Tracing Geothermal Fluids

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13891</td><td colspan="2">Contract/Grant Period: 10/01/00-9/30/04</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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DOE-Idaho Field Office
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P.O. Box 1625
Idaho Falls, Idaho 83415-3830</td><td colspan="2">Principal Investigator(s):
Michael C. Adams .

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<tr><td>DOE Funding Allocation:
$170 K, FY2000;
$221,000, FY2001</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

(1) Develop and test compounds that can be used to trace liquid and steam in vapor-dominated and two-phase geothermal systems. The compounds are tested in the lab as well as in actual geothermal systems.

(2)Transfer the technology to industry through tracer tests and publications.

Approach/Background:

Following exploration, reservoir management is one of the most important functions of the resource owners. Tracers are a prime management tools for this task. At this time, however, the number and diversity of tracers that can be used in geothermal reservoirs is limited. For example, there are no tracers other than radioactive water that can be used to track both liquid water and steam. Geothermal fields frequently produce both of these phases. The number of tracers is also important. It is not uncommon for the operator of a field to want to tag several injection wells at once, requiring one or more different tracers for each well. This is currently impossible for more than a few injection wells because the number of proven tracers is limited, and none of them are known to work in both liquid water and steam. The main thrust of this proposal is a research project that will result in several compounds that can be used to trace both liquid and steam phases.

Our approach is to search the literature for compounds that are nontoxic, highly detectable, likely to be stable at geothermal temperatures, and are expected to have the appropriate solubility in liquid water and steam. Once these are identified, they are screened using short, high temperature runs in a pressurized autoclave. Generalizations taken from the screening tests are used to choose more tracers with a higher probability of success. Once the candidate tracers are chosen, they are tested more extensively for thermal stability and volatility. Finally, they are used in geothermal fields as tracers along with proven tracers to verify their efficacy.

Status/Accomplishments:

(1) Fluorinated alcohols identified as the most likely two-phase geothermal tracer.

(2) Screening tests completed on three fluorinated alcohols.

(3) All of the papers are in and being reviewed for the Special Volume on Geothermal Tracers that will be published in the journal Geothermics. Mike Adams is guest editor for this volume.

Planned FY 2001 Milestones:

(1) Complete and publish a model of the P-1 and DV-11 tracer tests that evaluates the efficacy of vapor-phase tracers.

(2) Test three fluorinated alcohols for thermal stability kinetics.

(3) Complete R-23 thermal decay tests.

(4) Complete the Geothermics Special Volume on Geothermal Tracers.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) Adams, M.C., Beall, J.J., Hirtz, P. Koenig, B.A., and Smith, J.L. Bill, 1999, Tracing effluent injection into the SE Geysers – a progress report: Transactions, Geothermal Resources Council, p. 341-345.

(2) Adams, M.C., and Kilbourn, P.M., 2000, Thermal stability of the vapor-phase tracer R-134a: Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford CA.

(3) Moore, J.N., Adams, M.C., Sperry, T.L., Bloomfield, K.K., and Kunzman, R., 2000, Preliminary results of geochemical monitoring and tracer tests at the Cove Fort-Sulphurdale geothermal system, Utah: Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford CA.

(4) Adams, M.C., Yamada, Y., Yagi, M., Kondo, T., and Wada, T., 2000b, Stability of methanol, propanol, and SF6 as high-temperature tracers: World Geothermal Congress, p. 3015-3019.

Project Title:
Improved Technologies for Geothermal Resource Evaluation (Precision GravityTask)

<table>
<tr><td colspan="2">Contract/Grant #: DE-FG07-00ID13891</td><td colspan="2">Contract/Grant Period: 2/1/2000 - 8/30/2004</td></tr>
<tr><td colspan="2">Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Organization Type: CU</td><td>Congressional District:
Utah 2nd</td></tr>
<tr><td colspan="2">Directing Organization:
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<tr><td>DOE Funding Allocation:
FY:$200 K*
FY2001:$324,258.00*
*Includes Gravimetry Task</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

To establish and test the value of combined modern gravity and GPS campaigns in monitoring the reservoir response to hot fluid extraction and cold water reinjection in geothermal fields.

Approach/Background:

The geothermal industry is interested in reservoir response due to production and injection (i.e. both mass/saturation changes, and contraction/cooling changes). Improvements in the technology of both precision gravimeters and GPS instrumentation now allow 150-benchmark field campaigns over a field, yielding gravity values to 5 ugal and elevations to 1 cm uncertainties in 20 days of field work. This makes annual (or biennial) campaigns over a geothermal field cost-effective. The potential effects of seasonal factors (precipitation) are being carefully evaluated during year 1 of this Task (in particular, at The Geysers). Work over the past 12 months in the Salt Lake Valley has also been looking at the amplitude of

seasonal factors (poster at Fall AGU), including optimizing measurement and interpretation techniques using the electronic precision gravimeter. Results are being compared with water level changes in nearby groundwater wells.

Preliminary interpretation of the changes at The Geysers since the late 1970s confirms gravity decreases, corrected for elevation changes, of up to 700 uGal.

The task will concentrate on using The Geysers and Dixie Valley field for estblishing the value of combined precision gravimetry and GPS technologies for geothermal reservoir management. The opportunity to apply the method at an additional field (e.g. Salton Sea or Roosevelt) will be monitored, and will be attractive if either field expands its production in the next few years. The increase in flux of injection water at The Geysers, and the difficulty of other geophysical and geochemical techiques to track this water, justify the effort in this task. We expect that the techniques will become part of a developer's standard strategy for managing injection and production of a geothermal system to sustain the life of the development.

Because the techniques yield two independent datasets (mass change and benchmark position change), numerical modeling coupling both deformation and fluid flow/saturation changes, has the potential to provide insight on the reservoir cooling mechanisms due to production and injection.

Status/Accomplishments:

(1) A repeat microgravity and precision GPS survey at Dixie Valley, NV, geothermal field was completed in June, 2000, allowing the changes over the past year to be computed.

(2) A field trip to The Geysers geothermal field focussed on re-occupying as many of the USGS precision gravity marks from the late 1970s as possible. About 30% of these marks were located and occupied, giving a reasonable map of net mass changes over the last 25 years. Gravity changes of up to -700 uGals imply the original liquid stration at the Geysers averaged 2% of the rock volume.

(3) Ten bechmark stations in the Salt Lake Valley have been monitored monthly throughout the year in order to optimize precision gravity measurement techniques, to automate data reduction methods, to establish measurement resolution limits under field conditions, and to identify the amplitude of seasonable effects. Systematic variations of up to 40 uGal have been observed.

Planned FY 2001 Milestones:

(1) Complete analysis of benchmark surveys across Salt Lake Valley. Prepare paper(s) describing optimal microgravity survey techniques, seasonal gravity effects, and gravity and surface deformation effects of subsurface fluid withdrawal.

(2) Conduct two repeat gravity and GPS leveling surveys at The Geysers geothermal field.

(3) Submit a paper to the 2001 Stanford Conference on Geothermal Reservoir Engineering on gravity changes at the Geysers geothermal reservoir, 1975-2000.

(4) Submit a paper to the 2001 GRC on gravity changes in geothermal areas.

Major Reports Published in FY 2000:

(1) Precision gravity changes at the Geysers geothermal reservoir, 1975-2000 by Allis, Gettings, Isherwood, and Chapman.

Major Articles Published in FY 2000:

No articles published in FY 2000. Three papers are scheduled for submission in FY 2001.

Project Title:
Effects of Injection and Production on Field Performance

<table>
<tr><td>Contract/Grant #:</td><td colspan="2">Contract/Grant Period:</td></tr>
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field data</td></tr>
<tr><td>DOE Funding Allocation:
$160K</td><td>Cost Share Funding:
none</td></tr>
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Project Objective:

To analyze field data to determine changes in (1) the physical and thermal characteristics of produced geothermal fluids in response to commercial-size production and injection operations, and (2) the recharge characteristics of the field . The results of the project are relevant to other fields, especially those in sedimentary environment like the Imperial Valley of California.

Approach/Background:

The Cerro Prieto geothermal systems in Mexico was the focus of the project. This field, the largest known liquid-dominated geothermal system, has been studied exhaustively since the early 1970s. A wealth of information is available to LBNL scientists by way of information collaborations between the Laboratory and the Comisión Federal de Electricidad, operators of Cerro Prieto. Physical data (i.e., production and injection rates, and temperature/enthalpy of the produced and injected fluids) and chemical data (mainly chloride, fluid isotopic data, and mineralogical data were used to characterize the changes occurring in the reservoir as the commercial exploitation of the field continues (installed electrical capacity in late 2000 was 720 MW).

Status/Accomplishments:

Studies carried out during FY2000 identified areas within the field were reservoir cooling was occurring due to shortcircuiting of the injectate through a fractured zone associated with a major fault in the system (Fault H). Those studies confirmed that regions of the same fault is allowing the downflow of colder

groundwaters into the geothermal reservoir from aquifers located above the producing formation, in effect causing a natural recharge. These regions were identified studying the distribution of produced fluid enthalpies and, later corroborated by mineralogical data collected during the drilling of the wells.

Planned FY 2001 Milestones:

None

Major Reports Published in FY 2000:

(1) Truesdell, A.H., Lippmann, M.J., de León, J. and Rodríguez, M.H. (1999). Cerro Prieto Cold Water Injection: Effects on Nearby Production Wells. Lawrence Berkeley National Laboratory report LBNL-44025.

(2) Lippmann, M.J., Truesdell, A.H. and Pruess, K. (2000). The Control of Fault H on the Hydrology of the Cerro Prieto III Area, Lawrence Berkeley National Laboratory report LBNL-45258.

Major Articles Published in FY 2000:

(1) Truesdell, A.H., Lippmann, M.J., de León, J. and Rodríguez, M.H., (1999). Cerro Prieto Cold Water Injection: Effects on Nearby Production Wells. Geothermal Resources Council Trans., Vol. 23, p. 367-376.

(2) Lippmann, M.J., Truesdell, A.H. and Pruess, K. (2000). The Control of Fault H on the Hydrology of the Cerro Prieto III Area, Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program Report SGP-TR-165, p. 266-274.

Project Title:
Solubility and Phase Equilibria of Fluorocarbon Tracers

<table>
<tr><td>Contract/Grant #: DE-AC07-99-ID 13727</td><td colspan="2">Contract/Grant Period:</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

(1) Evalute candidate compounds for applicability as geothermal tracers.

(2) Measure solubility and phase partitioning of fluorocarbons in high temperature geothermal brine.

(3) Examine thermal breakdown of tracer chemicals.

(4) Publish results in peer reviewed journal.

(5) Complete project report.

Approach/Background:

Tracers can be used to monitor the movement of groundwater and geothermal fluids as well as provide a reference to quantify changes in fluid chemistry. Several materials have been evaluated for application as geothermal tracers. A useful tracer must have several characteristics. Included in these are thermal stability, high detection, and low environmental impact. New tracers are required which meet all of these criteria. One such family of compounds, fluorocarbons, is currently under investigation at the INEEL. Fluorocarbons (FC) are compounds consisting of carbon, fluorine, and hydrogen. Fluorocarbons are

environmentally friendly and exhibit a high degree of stability across a wide range of temperatures and pressures.

Status/Accomplishments:

A corrosion resistant alloy, Hastelloy C-22, has been identified as having the appropriate level of corrosion resistance for long term service in a high temperature halide brine. A two liter Hastelloy C-22 reaction vessel and associated process equipment have been procured and received at the INEEL.

To examine the solubility of various fluorinated tracers in geothermal brine under simulated injection well conditions, the laboratory reaction system has been outfitted with an automated sample collection and injection system. This automated system is configured to minimize void space in the sampling train to reduce the occurrence of sample to sample contamination observed in previous years work. FY2001 work began with a brief investigation of the pure component phase equilibria of fluorocarbon / water system using the automated sampling apparatus. As in previous studies sample cross contamination was evident. Attempts to mitigate the sample retention and cross contamination of samples included materials compatability testing. Test sections of Hastelloy C-22, nickel, 316 stainless steel, silica lined and titanium tubing were exposed to perfluoromethylcyclohexane at temperatures up to 200°C for 24 hours. The desorption of fluorocarbon from these sections was then measured and a comparison was made of the relative mass of analyte retained. The silica lined tubing was found to retain the highest relative amount of fluorocarbon. The relative amount of fluorocarbon retained on the unlined metal test sections was essentially constant. This material study indicates that the fluorocarbon is not significantly retained on the unlined metal tubing.

The findings of the material study indicated that the fluorocarbon may be significantly retained on a silica surface. It is intended to use these fluorocarbon compounds as conservative tracers in a silica containing environment. If the fluorocarbon is significantly retained on solid silica its utility as a conservative tracer is severely compromised. A literature review revealed a study reporting the application of fluorocarbons as conservative tracers for characterization of subsurface DNAPL contamination. This published study indicated that fluorocarbons were minimally retained and performed well as conservative tracers, contrary to observations made at the INEEL.

To further investigate retention of the fluorocarbons on a silica based matrix, the INEEL experimental apparatus was modified to conduct soil column tests. As a result of the moderate temperature and pressure conditions of these tests a large variety of valve rotor materials were available for the automated sampling system. A material is currently in service that does not retain fluorocarbon and eliminates sample cross contamination.

Column tests have been completed investigating perfluoromethylcyclohexane with argon as a conservative tracer. Preliminary results indicate that significant retention of the fluorocarbon occurs in the packed sand column. To date, satisfactory results of the argon have not been obtained due to the low concentrations observed at the column outlet. Future work will employ larger injections of argon to mitigate this affect. Additional studies will be completed using trifluoromethane(R23) and tetrafluoroethane(R134a) in dry and wet sand columns. When these compounds have been proven to be conservative tracers in column tests, testing of the solubility and phase equilibria will be resumed.

Planned FY 2000 Milestones:

(1) Complete upgrade of experimental apparatus with Hastelloy C-22. 12/2000

(2) Complete sand column testing. 6/2001

(3) Complete water / fluorocarbon solubility and phase equilibria testing. 7/2001

(4) Submit article for peer reviewed publication. 9/2001

(5) Final annual report for FY 2001 activities. 9/2001

Major Reports Published in FY:

None

Major Articles Published in FY:

None

Project Title:
A Thermoelastic Hydraulic Fracture Design Tool for Geothermal Reservoir Development

<table>
<tr><td>Contract/Grant #: DE-FG07-99ID13855</td><td colspan="2">Contract/Grant Period: 9-24-99 through 9-24-2001</td></tr>
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<tr><td>DOE Funding Allocation:
$200, 813</td><td>Cost Share Funding:
0</td></tr>
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Project Objective:

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

Approach/Background:

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

Status/Accomplishments:

(1) Development of an efficient numerical procedure for accurate simulation of two-dimensional crack propagation

(2) Investigation of the growth of an arbitrary-oriented fracture from a wellbore; it has been found that a dimensionless parameter defined in terms of the stress state, fracture toughness, and wellbore radius influences the fracture path

(3) Development of a model for heat extraction from a fracture including the influence of leak-off; it has been determined that heat storage and heat dispersion effects can be neglected; the problem of heat flow in the rock mass has been formulated in 2D and will permit determination of thermally-induced stresses on fracture width

(4) Development of a user interface for fracture propagation algorithm

(5) Development of a numerical algorithm for solving thermoelasticity problems by radial basis function approximation and boundary element method

(6) Developmet of a thermoelastic theory for chemically-active porous media useful for modeling rock/fluid interacion in hot environments

(7) Fracture/failure analyses for geothermal wells using a fully-coupled poro-thermoelastic theory.

Planned FY 2001 Milestones:

(1) Quantitative analyses of the role of leak-off on power generation from a fracture in HDR

(2) finalize the development of the 2D fracture propagation code and develop solutions for a number of practical problems

(3) study the influence of heat extraction on stress distribution in a geothermal reservoir as well as on the stability of fractures and faults

(4) develop the solution for the 3D problem of heat extension from a fracture in HDR

(5) inititate work on 3D thermoelastic modeling of a fracture in HDR

(6) develop a dual porosity porothermoelastic model for deformation of chemically-active rocks

(7) finalize the solution for fracture re-orienation resulting from thermally-induced stresses

(8) develop the building blocks for a 2D, fully-coupled porothermoelatic 2D method for modeling fractures in geothermal environments.

Major Reports Published in FY 2000:

Four reports have been published:

(1) NDRM-00-01: Modeling two-dimensional fracture propagation using a complex variable displacemnt discontinuity method

(2) NDRM-00-01: Modeling fracture propagation from a wellbore & heat extraction from a fracture in HDR

(3) NDRM-00-03: Numerical analysis of hydraulic fracture propagation under a thermoelastic perturbation of the state of stress & two-dimensional solution for heat extraction from a fracture in HDR

(4) NDRM-001-04: User interface development and three-dimensional heat extraction from a fracture in HDR.

Major Articles Published in FY 2000:

None, however, three manuscripts have been prepared and submitted for publication.

Project Title:
Core Analysis for the Development and Constraint of Physical Models of Geothermal Reservoirs

<table>
<tr><td>Contract/Grant #: DE-FG07-99ID13761</td><td colspan="2">Contract/Grant Period: May 1, 1999 - May 31, 2004</td></tr>
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<tr><td>DOE Funding Allocation:
FY1999: $ 42,000.
FY2000: $100,000.</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The project focuses on the development and constraint of physical models to improve interpretations of geophysical observations in geothermal reservoirs.

Approach/Background:

The work concentrates on the detailed study of core scale geophysical properties from a variety of reservoirs 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. Areas of technical focus include: shear weakening phenomena (rock water interaction), mineralogic and textural controls, the effects of temperature, brine chemistry, and partial saturation, quantification of core scale heterogeneity, and field scaling of seismic, electrical, and flow properties. The first case study to be addressed is the Awibengkok reservoir in Indonesia.

Status/Accomplishments:

We have found that despite the relatively high porosities of the Awibengkok samples, the effect of pressure on the velocities is weak and the depth dependence is small compared to the variations from core to core. This observation greatly simplifies interpretation of field scale velocity profiles, thus providing an

opportunity to probe and monitor spatial and temporal variations in the processes influencing the fracture system. The results also provide important information concerning interpretation of seismic anomalies. Saturation causes a increase in the Vp/Vs and decrease in Vs (enhanced by shear weakening due to rock-water interactions), with little resulting effect on Vp . This is a similar behavior to that found on core from The Geysers. The net result is that a high Vp/Vs anomaly associated with a low Vs anomaly is indicative of a saturation anomaly while a high Vp/Vs anomaly associated with a high Vp is indicative of another phenomenon (such as lithology or fracture density variations). This is contrary to traditional interpretations of seismic anomalies, which typically look to for high Vp/Vs and high Vp as an indicator of saturation

Electrical impedance is also being measured as a function of pressure, temperature, and brine chemistry in an attempt to better understand the conduction mechanisms operating in these rocks. This information is needed to improve interpretations of electrical logs and electrical resistivity tomography (ERT) which are essential elements for reservoir characterization and monitoring of stimulation. The laboratory data is being used to constrain a physical model which combines the primary surface and ionic conduction mechanisms with the electrochemical interactions of the matrix with sulfides and other electrically conductive minerals. The goal of this work is to build a predictive capability for the effects of temperature and partial saturation on the electrical properties of the matrix. A key aspect of the measurement program is the characterization of spatial heterogeneity of electrical properties. A micro-resistivity mapping apparatus has been developed and the resulting images are rich in information, illustrating a wide variety of "anomalies" ranging from conductive or resistive clasts to fractures and porous veins. Importantly, the results illustrate that the samples commonly have intrinsic variability on the order of a factor of three or more with significant correlations at length scales of a few centimeters. This suggests that core scale heterogeneity (and its structural details) may give rise to significant resistivity signatures, and may explain much of the scatter in the laboratory scale data. Work is in progress to correlate the observed anomalies with detailed petrographic observations. For example, areas of high conductivity and low phase shift may reflect regions dominated by ionic conduction through pores, while regions of high phase shift are believed to be associated with concentrations of electrically conductive minerals such as pyrite and hematite. A better understanding of the electrical heterogeneity should lead to improved interpretations of FMI, induction log, and ERT data.

Planned FY 2001 Milestones:

(1) 2001 GRC Annual Meeting presentation and proceedings article.

(2) Selection and initiation of second case study for the project.

Major Reports Published in FY 2000:

(1) Detailed technical progress reports were submitted to INEEL and posted on the web at http://www.ner.com/geothermal.shtml.

(2) Three progress reports were published during FY2000 detailing the results of laboratory measurements on core from the Awibengkok geothermal field.

Major Articles Published in FY 2000:

(1) A presentation was made and a proceedings paper was published as part of the 1999 GRC Annual Meeting.

(2) A poster presentation without proceedings publication was made at the 2000 GRC Annual meeting.

Project Title:
Geothermal Reservoirs: Products of Cooling Plutons

<table>
<tr><td>Contract/Grant #: DE-FG07-99ID13854</td><td colspan="2">Contract/Grant Period: 9/27/1999- 9/26/2002</td></tr>
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none</td></tr>
<tr><td>DOE Funding Allocation:
$174,050</td><td>Cost Share Funding:
none</td></tr>
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Project Objective:

Three major targets are:

(1) Synthesis of generic models of geothermal reservoirs within the context of the regional magma-hyrothermal activity

(2) Produce a realistic set of dynamical models of the history of magma-hydrothermal activity typical of geothermal environments

(3) Derive new and novel prospecting guides based on patterns derived from (1) and (2).

Approach/Background:

The project goals are to characterize the space and time variations of fracture formation driven by progressive fluid pressure fronts as they propagate outward from a cooling pluton. Norton will analyze the system dynamics as they occur at supercritical conditions, determine the properties of these zones that could be detected remotely. These goals will be achieved by a multidisciplinary approach that combines observations made on high-level plutonic systems that evolved from volatile rich-magmas with an ensemble of numerical models that will display the time-space relations of energy dissipation into the lithocaps of high-level pluton systems.

Status/Accomplishments:

As partial fulfillment of the objectives of the project to describe the complex hydrothermal history of this reservoir, thermal-mechanicalconditions along the carapace of the felsite are being quantified. Specific descriptions of processes responsible for the pore-space transformation have been completed through a set of rate equations that describe extension of fluid filled pore space into slit-like fracture forms in response to an advancing thermal front. Preliminary integration and analysis of these equations reveals several features of reservoir development that are pertinent to cooling-pluton related resources in general as well as to The Geysers.

The consequences of subjecting fluid-filled pore space to thermal conditions typical of those predicted for the early-stages of heating of the Franciscan graywacke host-rocks by the felsite, cf Norton, Hulen, 2001, Geothermics Special Issue, are sequentially: (1) increase pore fluid pressure, (2) pore space altered into fracture forms, (3) fracture extension and alignment in accord with the principal confining stresses at the time, (4) preferential propagation of the longest fractures, (5) exponential fracture extension as temperature increases near the supercritical region of the fluid, and (6) consequent increases in fluid percolation as pore space is altered and concentrated into long-continuous fracture openings. The analysis also affords for quantitative correlation among fracture/vein events and time-space variations in dispersion of thermal energy from the magma. Near vertical, small aperture fractures observed in the deposit, whose form is similar to those modeled probably formed during the first ten's of thousands of years of the thermal history of The Geysers Felsite. This episode would have been long before any manifestations of the embryonic reservoir appeared at the earth's surface.

Supporting field observations, definition of the early hydrothermal history of the felsite, correlation of fluid inclusion, and alteration mineral data bases with time/space in numerical approximation to felsites history have been completed.

Planned FY 2000 Milestones:

(1) aka 2001: Definition of dynamical processes that generated reservoir conditions at the Geysers

Major Reports Published in FY:

(1) Fracture Propagation in Prograde Thermal Fields Theory and Example Integrations. March 8, 2001

(2) Correlation of Time Serial Fluid Inclusion Data with Numerical Analogs to The Geysers Felsite, January 15, 2001

(3) Patterns of Dynamical Hydrothermal Activity in Geothermal Reservoirs: Tourmaline Vein Assemblages from The Geysers Felsite A Record of Complex System Behavior. December 18, 2000

Major Articles Published in FY:

(1) Systematics of Magma-Hydrothermal Processes: Geothermal Resources Near Cooling Plutons GRC-Annual Meeting, 2000

(2) Preliminary numerical analysis of the magma-hydrothermal history of The Geysers Geothermal System, California}. in press Geothermics special issue. by Norton, D. and, Hulen, Jeffery, B. (2001)

Project Title:
Mathematical Modeling of Geothermal Reservoir Processes

<table>
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<tr><td>DOE Funding Allocation:
$175K</td><td>Cost Share Funding:</td></tr>
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Project Objective:

Develop and demonstrate capabilities for more accurate and comprehensive numerical simulation of geothermal reservoirs.

Approach/Background:

Advances in reservoir engineering are key to more economical geothermal field exploration, development, and management. Currently available reservoir simulators include only rudimentary capabilities for chemical transport and rock-fluid interactions. Industry needs more accurate and comprehensive numerical simulation capabilities to develop more reliable reservoir models, and to optimize field development and management.

Status/Accomplishments:

Coding and documentation for a much-enhanced version of the TOUGH2 reservoir simulator was completed and was released to the public. It includes capabilities for transport of phase-partitioning tracers, coupling between reservoir and wellbore flow, a new model for multiphase diffusion, and salt precipitation and dissolution with associated changes in reservoir porosity and permeability.

Methods for simulating tracer transport under multiphase conditions were developed and demonstrated. Applications to The Geysers geothermal field showed vaporization of injectate dependent on previous reservoir depletion, in excellent agreement with field observations.

A new code TOUGHREACT that was developed outside of the geothermal program was successfully applied to studying mineral alteration in the caprock of magmatic hydrothermal systems.

A number of specialized studies provided new insights into geothermal reservoir dynamics.

Review articles on geothermal reservoir simulation were published and presented at conferences.

Planned FY 2001 Milestones:

(1) Report on design and analysis of phase-partitioning tracer tests in boiling geothermal systems.

(2) Report on mineral dissolution and precipitation effects in geothermal reservoirs during the natural evolution and during production and injection operations.

Major Reports Published in FY 2000:

(1) Kiryukhin, A. and K. Pruess, Modeling Studies of Pressure Cycling Associated with Seismicity in Mutnovsky Geothermal Field, Kamchatka, Russia, Proceedings, World Geothermal Congress 2000, Japan, pp. 2659 - 2664, May-June 2000.

(2) Lippmann, M.J., A.H. Truesdell and K. Pruess. The Control of Fault H on the Hydrology of the Cerro Prieto III Area, Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, pp. 266 - 274, January 2000.

(3) O'Sullivan, M.J., K. Pruess and M.J. Lippmann. Geothermal Reservoir Simulation: The State-of-Practice and Emerging Trends, Proceedings, World Geothermal Congress 2000, Japan, pp. 4065 - 4070, May-June 2000.

(4) Pruess, K. and J. Garcia. A Systematic Approach to Local Grid Refinement in Geothermal Reservoir Simulation, Proceedings, World Geothermal Congress 2000, Japan, pp. 2809 - 2814, May-June 2000.

(5) Pruess, K., M.J. O'Sullivan, and B.M. Kennedy. Modeling of Phase-Partitioning Tracers in Fractured Reservoirs, Proceedings, Twenty-Fifth Workshop on Geothermal Reservoir Engineering, pp. 167 - 173, Stanford University, January 2000.

(6) Pruess, K., C. Oldenburg and G. Moridis. TOUGH2 User's Guide, Version 2.0, Lawrence Berkeley National Laboratory Report LBNL-43134, Berkeley, CA, November 1999.

(7) Xu, T. and K. Pruess. Hydrothermal Fluid Flow and Mineral Alteration in a Fractured Rock under Multiphase H2O-CO2 Mixture Conditions, Proceedings, World Geothermal Congress, Japan, pp. 2983 - 2988, May-June 2000.

Major Articles Published in FY 2000:

(1) Oldenburg, C.M. and K. Pruess. Simulation of Propagating Fronts in Geothermal Reservoirs with the Implicit Leonard Total Variation Diminishing Scheme, Geothermics, Vol. 29, pp. 1 - 25, 2000.

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

(3) Wu, Y.S. and K. Pruess. Numerical Simulation of Non-Isothermal Multiphase Tracer Transport in Heterogeneous Fractured Porous Media, Adv. Wat. Resour., Vol. 23, pp. 699 - 723, 2000.

Project Title:
The Development of Tools for Managing Injection in Geothermal Reservoirs

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13894</td><td colspan="2">Contract/Grant Period: Oct. 1, 1999-Sept. 30, 2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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cost share not required</td></tr>
<tr><td>DOE Funding Allocation:
$170,300</td><td>Cost Share Funding:
None</td></tr>
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Project Objective:

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

Approach/Background:

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

During the past few years, the Energy and Geoscience Institute (EGI) Tracer Development Laboratory has conducted research directed at developing fluorescent geothermal tracers. A family of compounds known as polyaromatic sulfonates were tested in the laboratory and found to be suitable for use in high-temperature, liquid-dominated geothermal systems (Rose et al, 2000). The compounds were successfully

tested in tracer tests in geothermal reservoirs in Dixie Valley, Nevada; Steamboat Hills, Nevada; Ohaaki, NewZealand; and Awibengkok, Indonesia.

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

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

Status/Accomplishments:

We identified two new polyaromatic sulfonate tracer candidates, 2-naphthalene sulfonate and 2,7-naphthalene disulfonate; both are affordable and commercially available. In laboratory autoclave studies designed to simulate a geothermal environment, neither compound showed any degradation after one week at 330 C, indicating that these are the most thermally stable polyaromatic sulfonates yet studied and that they are suitable for use in liquid-dominated reservoirs exceeding 350 C. The laboratory studies were verified in a field test at the Dixie Valley, Nevada geothermal reservoir where both tracer candidates were tested and observed in several production wells.

We successfully designed, fabricated and tested a simple absorption detector using a Xenon source, a fiber optic for delivering and collecting the light signal, a long pathlength flow cell, and a charge-coupled-device spectrometer. Using this detector in combination with a liquid chromatograph, we measured a detection limit of approximately 270 ppt for the dye acid orange 10. This is the lowest HPLC-based detection limit for an anionic dye by absorption ever reported in the open literature. This also represents a significant first step towards the design and fabrication of a field-based tracer detector.

We successfully synthesized amino-dendrimer-stabilized CdS nanoparticles in the lab. The nanoparticles were shown to be stable under laboratory autoclave conditions designed to simulate a geothermal system.

Planned FY 2001 Milestones:

(1) In FY2001, we plan to study the decay kinetics of two new polyaromatic sulfonates, 1-naphthalene sulfonate and 2,6-naphthalene disulfonate, which we have found to be available in bulk and quite affordable. We will also test their performance in a tracer test in a geothermal reservoir. We also plan to continue to evaluate the performance of the online absorption detector and to extend its applicability to the detection of fluorescent tracers. We will continue to synthesize and test nanoparticles for use as fluorescent geothermal tracers.

Major Reports Published in FY 2000:

(1) Rose, P.E., Harris, J.M., Kilbourn, P.M., Rivera, D., 2000, The Development of Tools for Managing Injection in Geothermal Reservoirs, Annual Technical Report for DOE Project DE-FG07-00ID13894.

Major Articles Published in FY 2000:

(1) Rose, P.E., Benoit, R.W., Lee, S.G., Tandia, B.K., Kilbourn, P.M., 2000, Testing the Naphthalene Sulfonates as Geothermal Tracers at Dixie Valley, Ohaaki, and Awibengkok: Proceedings, 25th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-165.

Project Title:
Greatly Enhanced Detectability of Geothermal Tracers through Laser-Induced Fluorescence

<table>
<tr><td>Contract/Grant #: DE-FG07-98ID13619</td><td colspan="2">Contract/Grant Period: Aug. 1, 1999 -- July 31, 2000</td></tr>
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cost share not required</td></tr>
<tr><td>DOE Funding Allocation:
$100,542</td><td>Cost Share Funding:
None</td></tr>
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Project Objective:

The primary objective of this project is to demonstrate the greatly enhanced detectability of fluorescent compounds over conventional analytical methods. A secondary objective is to evaluate several derivatives of fluorescein for use as geothermal tracers.

Approach/Background:

Prudent reservoir management strategies invariably require the reinjection of produced fluids into geothermal reservoirs via dedicated injection wells. If the injection wells are located too close to the production wells, there exists a risk of premature thermal breakthrough. If the injectors are placed to far from the producers, then the injectate will not return to the reservoir, and the result will be a drop in reservoir pressure. Thermally stable and detectable organic tracers are needed within the geothermal industry in order to optimize injection well placement.

Whereas fluorescent compounds are among the most detectable tracers used in the geothermal industry, hundreds of kilograms are still typically required for each injection well that is tagged during a tracer test. As detection limits are lowered, however, the amount of tracer required is proportionally reduced, with a concomitant reduction in tracer cost. Likewise, since a chemically distinct tracer is required for each

injector that is tagged, many tracers are required in order to tag simultaneously all of the injectors within a reservoir. And, since most candidate fluorescent tracers are not manufactured in bulk, an increase in detectability results in an expansion of the list of candidate tracers. The objective of this research project is to increase the detectability of fluorescent tracers by a factor of 100. This will result in not only a great reduction in the cost of performing a tracer test, but also a significant increase in the number of candidate tracer compounds available.

Whereas thermal stability is a desirable quality in a geothermal tracer, it has a drawback. Since geothermal reservoirs in the western U.S. have very little aquifer recharge, tracers that are introduced into a geothermal system remain in that system until they decay thermally. Therefore, if a tracer is too stable its background concentration will increase with every subsequent reuse. If, however, a chemical tracer decays at a reasonable and quantifiable rate, it will gradually be removed from the reservoir, allowing for its subsequent reuse. Fluorescein is an example of a tracer that possesses an intermediate thermal stability; it is sufficiently stable for use in intermediate-temperature (250 C) reservoirs, but sufficiently labile to allow for its slow decay and frequent reuse in those reservoirs.

Our experimental approach has developed therefore along two general pathways. The first pathway was the design, fabrication, and evaluation of extremely sensitive analytical equipment, based upon the technology of laser induced fluorescence. Second has been the selection and evaluation of candidate fluorescent tracer compounds. These compounds are sufficiently similar to fluorescein that they require the same excitation wavelength as fluorescein, serving to greatly simplify the analytical apparatus. They also possess comparable (or poorer) thermal stability, which allows for their use and reuse in intermediate-temperature reservoirs.

Status/Accomplishments:

We have successfully completed the second year and approximately half of the third year of a three-year R&D project to greatly reduce the detection limit of fluorescent tracers through the emerging technologies of laser-excitation, fiber optics, long pathlength flow cells, and charge-coupled-device-spectrometry. Accomplishments include:

(1) The design, fabrication, and testing of a high-sensitivity laser-induced fluorescence (LIF) detector

(2) The demonstration of a detection limit for fluorescein of 40 parts per quadrillion (ppq)

(3) The evaluation of ten fluorescein-derivatives for use as geothermal tracers. Of those ten compounds, four were found to have reasonably good thermal stability relative to fluorescein, whereas one, 5(6)-carboxyfluorescein was shown to be as stable as fluorescein. Fluorescein and 5(6)-carboxyfluorescein will be used in the field tracer tests scheduled for FY 2001.

Planned FY 2001 Milestones:

(1) The major objective of FY2001 is to demonstrate the perfomance of the laser fluorimeter in a field test. At the Dixie Valley, Nevada geothermal reservoir, we will inject 1,000 gm of 5(6)-carboxyfluorescein into the target injection well. This represents a 100-fold decrease in the quantity of tracer fluorescein that would be required using conventional detection methods. In addition, we will conduct a tracer test at the Steamboat Springs, Nevada geothermal reservoir using 1,000 gm of fluorescein in the target injector. Likewise, this represents a 100-fold decrease in the quantity of tracer that would otherwise be required using conventional methods.

Major Reports Published in FY 2000:

(1) Rose, P.E., Harris, J.M., Kleimeyer, J.A., Wong, Y.L., Kilbourn, P.M., Greatly Enhanced Detectability of Geothermal Tracers through Laser-Induced Fluorescence, Annual Technical Report for DOE Project DE-FG07-98ID13619, September 30, 2000.

Major Articles Published in FY 2000:

(1) Wong, Y.L. and Rose, P.E., 2000, The Testing of Fluorescein Derivatives as Candidate Geothermal Tracers: Geothermal Resource Council Transactions, 24, 637-640.

Project Title:
Tracer Matching and Production/Injection Strategies for Fault Dominated Geothermal Reservoirs

<table>
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3/2/1998 to 3/1/2001 (no cost ext. to 9/1/2001)</td></tr>
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University cost share</td></tr>
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3/99 - 3/00 $153,859
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3/98 - 3/99 $6,796
3/99 - 3/00 $6,998
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Project Objective:

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

As part of previous work in support of geothermal technology, Kansas State University developed the Geocrack2D reservoir simulation program (Swenson, 1997). Geocrack2D includes the complex interactions between rock deformation, fluid flow, and heat transfer, where flow paths and reservoir pressures change as a result of heat removal. This project will develop similar capability in three dimensions.

Approach/Background:

In the broadest view, the goal of the project is help move fractured reservoir simulation capability forward in parallel with advances in diagnostic technologies. Significant effort is being applied to borehole imaging, improved tracer data, tomographic imaging, and micro-seismic data analysis. All of these technologies are beginning to make it possible to map major features in a reservoir. When these technologies come to fruition, it will be possible to create a model that incorporates the major features of a reservoir before the reservoir is brought into production. At the same time, future computer power will make it possible to perform complex calculations in a much more routine manner than is now possible. Our goal is to help make future reservoir modeling have the same engineering usefulness that structural analysis has today.

Status/Accomplishments:

In the first year of the project, we completed basic geometry descriptions of fractured reservoirs and flow solutions on fractures. Accomplishments for FY 2000 (October 1999, through September 2000) include:

(1) Implementation of heat transfer in the 3D rock mass and on the planar fractures. The finite element implementation can now solve for flow on the fractures, heat transport on the fractures, and conduction in the solid. Planar triangle and quadrilateral elements are used for the fracture surface and volume tetrahedral elements for heat conduction in the solid.

(2) Development of Logarithmic Well Elements: The solution for flow in the vicinity of a well has a logarithmic pressure distribution. We implemented a new finite element that uses a logarithmic shape function, thus ensuring that the correct analytic solution is obtained near a well. For a single well test case, calculated pressures have an error of less than one tenth of one percent compared to the analytic solution.

(3) Work with Tohoku University: Professor Takatoshi Ito from the Institute of Fluid Science, Tohoku University, spent most of August, 2000, at Kansas State University, working with us on Geocrack2D and Geocrack3D. He used Geocrack2D to simulate the effect of changes in temperature on permeability of rock. Professor Ito also created a Geocrack3D model to examine the effect of thermal cooling on radial fractures extending from a borehole.

(4) Development of Dixie Valley Model: Pete Rose at the Energy & Geoscience Institute University of Utah created a first Geocrack3D model of Dixie Valley. At this stage the model is very simple and needs further development.

Planned FY 2001 Milestones:

(1) Complete implementation of elasticity.

(2) Complete implementation of new cross-platform user interface in Java.

(3) Apply model to Dixie Valley type of geometry (simplified as necessary).

Major Reports Published in FY 2000:

(1) Geocrack3D users manual and example problems, available on the web at www.mne.ksu.edu/~geocrack.

Major Articles Published in FY 2000:

(1) "Design of an Object-Oriented Finite Element Framework for Multi-Physics Problems," B. Hardeman, S. Kulkarni, D. Swenson, and M. James. 5th U.S. National Congress on Computation Mechanics, August 4-6, 1999, University of Colorado, Boulder.

(2) “A 3-D Finite Element Model of Flow in Fractured Reservoirs,” B. Hardeman, S. Kulkarni, and D. Swenson, Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, 2000.

(3) “Initial Calculations of Performance for an Australian Hot Dry Rock Reservoir,” P. Chopra, D. Wyborn, and D. Swenson, Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan, 2000.

(4) “Analysis in Preparation for Hijiori Long Term Circulation Test,” T. Okabe, K. Kirihara, K. Hayashi, K. Karasawa, D. Swenson, R. Schroeder, Proceedings of the World Geothermal Congress, Japan, 2000.

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

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13954</td><td colspan="2">Contract/Grant Period: 08/01/00-07/31/02</td></tr>
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<tr><td>DOE Funding Allocation:
$210,490</td><td>Cost Share Funding:
$0</td></tr>
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Project Objective:

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

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

Approach/Background:

In collaboration with the Geothermal and Power Operations Division of Unocal, we have explored the chemical processes that occur during the coagulation of silica-enriched brines. To this end we have refined a novel method of separating populations of silica polymers on the basis of size using gel filtration chromatography, or GFC. When this method is combined with standard analytical techniques, it is

possible to monitor the evolution of dissolved silica from silicic acid monomers to heavily networked gels in a robust and quantitative fashion.

Status/Accomplishments:

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

In addition, we have tested ultrafiltration (Task 2) and developed other techniques (Task 4) for sizing nanocolloids. In our previous efforts to size silica colloids using calibrated GFC, we observed that the first colloids to appear in solutions containing 500 to 1000 mg/kg silica at pH 7 for both low (0.005 M) and relatively high (0.24 M) ionic strengths measured 20 to 40 kD. We calculated that these weights correspond to sizes of 3 to 4 nm for these incipient colloids, and we confirmed these results by: 1) light scattering; 2) atomic force microscopy (AFM); and 3) transmission electron microscopy (TEM). The light scattering analysis was accomplished with a Microtrac Ultrafine Particle Analyzer utilizing a diode laser (780 nm), and the procedure indicated that the silica colloids have a mean particle diameter of 3.5 nm. For AFM characterization, colloids were deposited on an atomically smooth silicon wafer. Analyses of the particles in the vertical direction yielded diameters of 3.0±0.1 nm. Field emission TEM analysis of the low-density colloids revealed that the smallest particles were 3 nm in diameter, though some particles were clearly aggregates that measured up to 20 nm in size. The identification of these nanocolloids as SiO2 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.

Planned FY 2001 Milestones:

(1) The major goals for the next year are as follows: 1) Long-term analysis of polymer evolution in siliceous brines. Silica solutions with concentrations ranging from 250 to 1250 ppm SiO2 have been prepared from pH 3 to pH 11 and with ionic strengths of 0.015, 0.1, and 0.24, modeled after field sites exploited by Unocal. Investigations of variations in the monomer, polymer, and gel concentrations are in progress and will continue for the next year. These studies will provide kinetic information on the transformation of dissolved silica to gel, and they will serve as a baseline for inhibition studies. 2) Analysis of transition metal complexation to colloidal silica. Silica solutions that have achieved steady state polymerization will be injected with metal chlorides to explore the effects particularly of trivalent Al and Fe on the formation of silica scale. Solutions will be analyzed by GFC, and elution fractions will be monitored for Si, Al, and Fe by ICP-AES. 3) Inhibition of silica polymerization by sulfurous acid and carboxylic acid. Silica solutions with concentrations of 200 to 2000 ppm silica will prepared as standard Unocal brines with sulfurous acid, EDTA, acetic acid, and citric acid. Polymer evolution will be assayed by wet chemical analysis and ICP-AES to ascertain the stages of polymerization that are interrupted by these inhibitors.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) One abstract will be presented at the Goldschmidt Conference in May 2001, and two articles are in preparation.

DRILLING TECHNOLOGY

Project Title:
High-Temperature Unshielded Electronics

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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Pruett Ind; Welaco; Thermochem; various small geothermal companies</td></tr>
<tr><td>DOE Funding Allocation:
$667K</td><td>Cost Share Funding:
$40-75K (estimated).</td></tr>
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Project Objective:

Evaluate and report on commercial activities to produce new high-temperature components, develop Dewarless tool designs deployable within the geothermal wellbore, and transfer this technology to the geothermal industry.

Approach/Background:

(1) Evaluate and report on new commercially available components. This activity is required to provide geothermal companies with important third-party product evaluations. This testing also provides an opportunity for feedback concerning geothermal requirements to the manufacturers of high-temperature electronic components.

(2) Continue circuit design for Dewarless tools. This work moves the new high-temperature components from the lab into complete high-temperature systems. This activity not only provides engineering insight to tackle real-world deployment issues, but also assures effective transfer of the technology to industry. The basic design is universal in nature. The electronics are capable of measuring eight analog channels with 12 bits of accuracy, and include several precision digital counters for measuring frequency-based sensor outputs.

(3) Support DOE's Small Business Innovation Research program to help small companies develop new devices and new high-temperature logging tools. This activity will have direct benefits for the geothermal industry, as the geothermal industry is the ONLY sizeable industry requiring operating temperatures over 225 C.

(4) Transfer high-temperature tool technology. At least one high-temperature workshop will be held with the drilling and logging industry in addition to the normal information passed through HiTED (Consortium on High-Temperature Electronics Downhole) and paper presentations.

Status/Accomplishments:

Completed the ASIC design. Completed the ASIC conversion from low-temperature components to high-temperature 300 C components. Completed development of a new 300 C lead seal for high-temperature electronic packaging. Sent design to Honeywell SSEC for implementation. Held workshop in Albuquerque on high-temperature electronics development with about 80 people in attendance. Overall this project has progressed well, despite a late (first of the calendar year) start.

Planned FY 2001 Milestones:

(1) Receive first SOI ASIC from Honeywell

(2) Conduct SOI wellbore demonstration in a geothermal well

(3) Release SOI data logger documentation.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) Randy Normann and Joseph Henfling, "Elimination of Heat-Shielding for Geothermal Tools Operating Up To 300 Degrees Celsius,"Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28 - June 10, 2000, pp. 2381-2386.

(2) Randy Normann and Joseph Henfling, "Elimination of Heat-Shielding for Geothermal Tools," Transactions Geothermal Resources Council, Vol. 24, September 2000, pp. 697-701.

Project Title:
Advanced Instrumentation for Lost Circulation Detection

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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E-mail: raymond.LaSala@ee.doe.gov</td><td>B&R Code: EB40</td><td>Cost Share Information:
BAE Systems; Epoch; Petron; UniTrak; Sub-Technical; Green Mountain</td></tr>
<tr><td>DOE Funding Allocation:
$268K</td><td>Cost Share Funding:
$47K</td></tr>
</table>

Project Objective:

The objective of the Advanced Instrumentation for Lost Circulation Detection project is to develop and transfer to industry reliable and accurate methods to measure drilling-fluid parameters while drilling. This will be accomplished with an expert circulation monitoring system (CMS), accurate mud inflow and outflow measurement tools, and new instruments to measure mud properties. The expert CMS is a computer-based software approach for analyzing drill-rig data in real time. The CMS will be useful for detecting, characterizing, and quantifying wellbore hydraulics associated with impending and occurring rig and wellbore problems such as loss of circulation, gas/steam kicks, mud-pump degradation, drill-pipe and nozzle washouts, stuck drill pipe, worn or failing drill bits, and improper drilling procedures. Inflow and outflow measurements and mud property information will be used to supply data to the CMS as well as for conventional drilling operations.

Approach/Background:

We will revise the current CMS contract to provide a complete operation manual for the prototype system, and to modify the existing system software to improve playback rates and response time to events. We will complete and document the "smart" rolling float meter (RFM) design package. We will conduct field tests to demonstrate the CMS during both oil and gas and geothermal well drilling

operations. MARCONI (BAE Systems), the CMS contractor, and Sandia will work directly with logging companies to integrate the CMS into their commercial data acquisition systems, and to develop a user-friendly interface that will be readily accepted by the drilling industry.

We will continue to investigate rig instrumentation useful for monitoring the status of the rig and the drilling process. This effort will include commercialization of Sandia-developed technology such as the rolling float meter and evaluation of commercially available flowmeters and sensors for application to geothermal drilling. Continuous improvements will be made to the information management and display system to provide minimum trouble-free interfacing with the Advanced Drilling/Diagnostics-While-Drilling (DWD) system currently under development.

Status/Accomplishments:

The CMS contract was revised to include an operation manual in addition to the revised CMS software and a final project report, with a completion date in early FY01. The CMS was field tested at various drilling sites, in cooperation with several logging companies, to verify compatiable operation with their data aquisition systems. The RFM controller black box for a "smart" RFM was designed, fabricated, and successfully tested. A complete users/operation manual was prepared. Two of these controllers were purchased for field use on the Sandia National Laboratory (SNL) prototype RFM's. The CMS software was also evaluated at Sandia by a university summer student who used the prototype CMS operation manual to set up and test the CMS with data from both geothermal and oil and gas well-drilling operations.

The RFM technology has been successfully transferred and is currently being used by the drilling industry. A fabricator/supplier for the RFM instrument has been identified. Preliminary groundwork has been completed to monitor mud pump parameters in an attempt to determine if changes in pump efficiency during drilling operations can be diagnosed. This capability will allow improved wellbore-hydraulics data feedback for the CMS and other rig data monitoring systems.

Planned FY 2001 Milestones:

(1) During FY01 the CMS contract will be completed and evaluation test results will be documented. We will initiate a cooperative agreement with a well-service company to acquire baseline data from mud-pump operations at selected well sites. We will investigate both mud- pump pressure changes and mud-pump vibrations while drilling. This data will then be analyzed to determine the merit of monitoring mud-pump efficiency on the basis of either of the above parameters.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) A. J. Mansure, G. L. Whitlow, G. P. Corser, J. Harmse, and R. D. Wallace, "A Probabilistic Reasoning Tool for Circulation Monitoring Based on Flow Measurements," SPE 56634, SPE Annual Technical Conference, Houston, TX, October 1999.

Project Title:
Acoustic Telemetry for Measurement-While-Drilling (MWD)

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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Baker Oil Tools; ABB Vetco Gray; PDC; NGOTP</td></tr>
<tr><td>DOE Funding Allocation:
$639K</td><td>Cost Share Funding:
$605K</td></tr>
</table>

Project Objective:

The development of advanced drilling systems hinges upon effective methods for communicating drilling and navigation parameters between the drill bit and the surface, and vice versa. Stress waves can be used to achieve this goal. We are developing a telemetry tool, designed to fit directly behind the drill bit, that will gather information about drilling parameters and formation properties, and will transmit these data to the surface without a hardwired connection. This tool has the potential to operate at higher temperatures and faster transmission rates than conventional telemetry systems. Its design is based on other tools that we have licensed to the oilfield industry.

Approach/Background:

Both high and low-temperature versions of a prototype telemetry tool will be assembled and tested at our surface facility. These tools will be capable of measuring and transmitting values of pressure in the annulus. They will then be field tested, their measurement capabilities will be expanded, and they will be licensed to industry.

Status/Accomplishments:

All components of the low-temperature tool have been built. Final stages of the integration of this tool are in progress, and we will be field testing it in a few months. All mechanical and electrical components of

the high-temperature tool have also been successfully operated to 200 C. We are assembling the high-temperature tool and will field test it after we have successfully field tested the low- temperature tool and incorporated any improvements resulting from this initial field test.

Planned FY 2001 Milestones:

(1) Complete surface testing of high-temperature tool

(2) Field test low-temperature tool

(3) Field test high-temperature tool.

Major Reports Published in FY 2000:

(1) U.S. Patent 6,188,647--Extension Method of Drillstring Component Assembly, D.S. Drumheller.

(2) U.S. Patent 6,147,932--Acoustic Transducer, D.S. Drumheller.

Major Articles Published in FY 2000:

None

Project Title:
Technical Advisory Committee (TAC)

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Organization Type: FF</td><td>Congressional District:
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<tr><td>Directing Organization:
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E-mail: raymond.LaSala@ee.doe.gov</td><td>B&R Code: EB40</td><td>Cost Share Information: TAC members have provided venues and logistical support (lunches, refreshments, etc.) for meetings.</td></tr>
<tr><td>DOE Funding Allocation:
$40K</td><td>Cost Share Funding:
see above</td></tr>
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Project Objective:

A panel of experts from the geothermal, oil & gas, and drilling service, industries has been assembled to advise Sandia on technical aspects of the Diagnostics-While-Drilling (DWD) program. The TAC will assure that the DWD program benefits from past work on high-speed telemetry. Also, it will help maintain focus on practical solutions to technical challenges. The TAC will also help assure that technology developed by the DOE-Geothermal program will be adopted by industry.

Approach/Background:

The TAC will meet at least twice a year and will host a workshop on high-speed data telemetry for drilling applications.

Status/Accomplishments:

TAC met 3 times during FY 2000, receiving valuable input from members in each case. All meetings were documented and reported to TAC members, industry, and DOE.

Planned FY 2001 Milestones:

(1) A meeting was held in February, 2001, another is planned for May, 2001, and other meeting schedules will be determined by project status.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Diagnostics-While-Drilling Program - Proof of Concept Test

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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N/A</td></tr>
<tr><td>DOE Funding Allocation:
$593K</td><td>Cost Share Funding:
N/A</td></tr>
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Project Objective:

The first step toward developing a Diagnostics-While-Drilling (DWD) system must be a convincing demonstration of the need and utility of such a system.

Approach/Background:

During FY00, Sandia, in cooperation with industry, will assemble a prototype closed-loop DWD system. This prototype will be used in proof-of-concept (POC) tests to verify the benefits of DWD and to study how to make DWD practical.

Status/Accomplishments:

A contract was placed for design of a downhole measurement sub; conceptual design of uphole software/hardware; and lab test of wet-connect wireline data link.

Planned FY 2001 Milestones:

(1) Perform benchmark roller cone tests at Catoosa

(2) Conduct and document drilling tests on generic Polycrystalline Diamond Compact (PDC) bits at Catoosa

(3) Complete POC test and begin conceptual definition of field-ready system

(4) Document POC results and development plan

(5) Organize industry cost-share mechanism.

Major Reports Published in FY 2000:

(1) J.T. Finger, A.J. Mansure, M. R. Prairie, and D.A. Glowka, "Development Plan for an Advanced Drilling System with Real-Time Diagnostics (Diagnostics-While-Drilling),"Sandia Report SAND2000-0239, February 2000.

Major Articles Published in FY 2000:

(1) J.T. Finger, A.J. Mansure, and M.R. Prairie, "A Proposal for an Advanced Drilling System with Real-Time Diagnostics (Diagnostics-While-Drilling)," Transactions Geothermal Resources Council, Vol. 23, October 1999, pp. 155-157.

(2) A.J. Mansure, J.T. Finger, M.R. Prairie, D.A. Glowka, and B.J. Livesay, "Advanced Drilling Through Diagnostics-While-Drilling," Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28 - June 10, 2000, pp. 2371-2373.

(3) M.R. Prairie and D.A. Glowka, "Diagnostics-While-Drilling: Reducing the Cost of Geothermal-Produced Electricity," Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28 - June 10, 2000, pp. 2393-2397.

Project Title:
Drag-Cutter Mechanics and Materials

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Allan Jelacic
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<tr><td>Organization Type: FF</td><td>Congressional District:
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<tr><td>Directing Organization:
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N/A</td></tr>
<tr><td>DOE Funding Allocation:
$335K</td><td>Cost Share Funding:
N/A</td></tr>
</table>

Project Objective:

This project is devoted to improvements in drag-cutter penetration of hard rock. The planned investigations involve industry and/or university partners and utilize Sandia's analytical expertise and unique test capabilities to address key technical issues. In particular, the research effort encompasses complementary activities in task areas related to (1) Polycrystalline Diamond Compact (PDC) cutter behavior in hard rock, (2) advanced cutter development and testing, and (3) advanced cutter materials for hard-rock drilling.

Approach/Background:

PDC Cutter Behaviour in Hard Rock

Fundamental studies will be conducted to systematically determine the influence of basic nonproprietary parameter variations on cutter durability and performance. U S Synthetic Corporation and other interested manufacturers will participate by supplying PDC cutters with designated material compositions and geometries. Variables may include the diamond-particle size distribution and concentration, matrix materials, and processing conditions. Geometric variations will involve changes in the diamond-table thickness and chamfer dimensions, alternate diamond-table/substrate interface configurations and bonding techniques, and differences in diamond-table surface finish. Results of this work will have broad impact across the drag bit industry and will be published in the open literature.

Advanced Cutter Development and Testing

Selected industry-supplied cutters will be evaluated and optimized on the basis of laboratory testing and analysis. Work will continue to upgrade PDC claw cutters that are now a standard feature on commercial drag bits such as those manufactured by Security DBS. Sandia will complete optimization analyses, and Dennis Tool Company will fabricate new PDC claw cutters following design guidance derived from Sandia's three-dimensional stress analyses and experimental data regarding wear performance and cutting forces for earlier claw-cutter configurations. The optimized claw cutters will be subjected to wear testing on the Hard Rock Drilling Facility (HRDF).

Advanced Cutter Materials for Hard-Rock Drilling

Sandia will support industry and university efforts to develop advanced ultrahard cutter materials. The wear performance of fracture-resistant TSP (thermally stable polycrystalline) diamond cutters being developed by Technology International in conjunction with NASA's Jet Propulsion Laboratory (JPL) and the Colorado School of Mines (CSM) will be evaluated in the HRDF.

Work on the formulation and processing of novel ultrahard cutter materials will proceed at the New Mexico Institute of Mining and Technology (NM Tech) under contract to Sandia. Cutters composed of these materials will be machined and tested at Sandia. In particular, boron suboxide will be consolidated in a titanium-based matrix that will replace the aluminum infiltrant that was tried previously. Synthetic-diamond cutters with a titanium-based matrix, as well as cubic boron nitride cutters, will be generated via explosive consolidation and hot pressing, then tested.

Status/Accomplishments:

Sandia and U S Synthetic established the test matrix for initial parametric studies on PDC cutters; and U S Synthetic manufactured 120 test cutters. These cutters have six different combinations of geometric and material features. Sandia also generated a detailed matrix of tests to be performed in FY01 to provide definitive data applicable to the optimized design of claw cutters. Technology International achieved performance improvements for TSP cutters using two unique diamond-to-tungsten-carbide brazing methods and a proprietary process for enhancing fracture toughness of the diamond table. NM Tech performed explosive compaction experiments that utilized various concentrations of hydrazine to catalyze the conversion of hexagonal boron nitride to ultrahard cubic boron nitride for drag-cutter applications.

Planned FY 2001 Milestones:

(1) Complete cutter testing for fundamental parameter study

(2) Complete claw cutter optimization testing

(3) Report results on claw cutter optimization project

(4) Document results of fundamental parameter cutter study

(5) Complete testing on improved TSP cutters.

Major Reports Published in FY 2000:

(1) J.L. Wise and J. Combs, "Report on the Sandia-NEDO Geothermal Drilling Workshop May 26-27, 1999," SAND2000-1678, August 2000.

(2) J.A. Hardy, "Processing and Characterization of Metal Infiltrated Boron Suboxide," MS Thesis Proposal, New Mexico Institute of Mining and Technology, September 2000.

Major Articles Published in FY 2000:

(1) Bob Radtke, "Higher Strength and Faster Drilling Thermally Stable Diamond Drill Bit Cutters," presented at INTERTECH 2000 International Technical Conference on Diamond, Cubic Boron Nitride, and Their Applications, Vancouver, BC (Canada), July 17-21, 2000.

Project Title:
Bit Mechanics and Design

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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N/A</td></tr>
<tr><td>DOE Funding Allocation:
$789K</td><td>Cost Share Funding:
N/A</td></tr>
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Project Objective:

This project is intended to foster innovations in the design and utilization of bits and related hardware suited to a hard-rock drilling environment. Industry and university involvement is actively sought and maintained. Sandia in-house resources are employed and supplemented, as appropriate, by arrangements made for outside laboratory and field testing capabilities. Improvements in bit design are derived, in part, by incorporating technical advances made in Sandia's cutter research project. This project is composed of task areas dealing with (1) bit mechanics, (2) Polycrystalline Diamond Compact (PDC) bit development and testing, and (3) novel bits for hard-rock drilling.

Approach/Background:

Bit Mechanics

In FY00, Sandia will continue its collaborative efforts with the University of Louisiana at Lafayette to characterize the mechanisms of self-induced bit vibration, a phenomenon that contributes to reduced penetration rate and causes impact damage to PDC cutters via chatter during hard-rock drilling. The state of the art in controllable damping technology will be investigated, and a controllable damper system will be added to the Hard Rock Drilling Facility (HRDF). This system will be used to analyze the dynamic behavior of drillstrings with damping and demonstrate that the degree of chatter in the system can be reduced by the application of damping. In addition, torsional compliance will be added to the HRDF to approximate rotational conditions that can be expected during actual drilling.

With funding administered by Sandia, efforts will continue at New Mexico Tech to demonstrate the utility of new cutting-force models that are based on the mechanics of the rock fragmentation process and on statistical analyses of force-component measurements obtained from Sandia's Linear Cutter Test Facility (LCTF) database. These models have been incorporated in a Sandia-developed bit simulation code, PDCWEAR, to predict the downhole dynamic behavior of a PDC drag bit. The models will be validated by directly comparing code predictions to actual production drilling results from the field.

PDC Bit Development and Testing

Sandia will work closely this year with prospective manufacturers of demonstration PDC bits for hard-rock drilling. Prototype geothermal bits will ultimately be fabricated, then subjected to laboratory and controlled field testing (e.g., at the GRI/Catoosa Drilling Technology Test Facility). Arrangements will subsequently be established for the purchase of an additional bit from one or more of the companies whose product showed promising results during the first round of tests, and the selected bit(s) will be tested during actual production drilling in a geothermal field.

Novel Bits for Hard-Rock Drilling

Sandia actively promotes the development of innovative bit concepts that show potential for application to the hard-rock drilling environment. This category is not necessarily restricted to drag bits. One or more of these "novel" bit designs may ultimately be selected for demonstration as part of the PDC bit field testing work described above. A cooperative NADET-funded effort is under way between Sandia, Security DBS, Dynaflow, and Terra Tek to develop and demonstrate a PDC bit that employs high-pressure mudjets that are directed at the cutter/rock interface so as to enhance the cutting process. In FY00, laboratory drilling data will be obtained with the prototype mudjet-augmented bit that was designed and built during FY99.

Sandia and Montana Tech are engaged in a joint endeavor to model and develop bi-center PDC bits. A Rate of Penetration (ROP)-dependent dynamic model for bi-center PDC bits will be completed during FY00. This model will relate the resultant bit drilling forces and moments to the bit geometry and wear state. Validation of the model will be accomplished this year.

Status/Accomplishments:

The HRDF was retrofitted with state of the art controllable dampers during FY00. Drilling tests were conducted which demonstrated that the degree of chatter in the system could be effectively reduced resulting in lower cutter failure rates. Rotational compliance was also added to the HRDF and preliminary testing was conducted. Development of the mudjet-augmented PDC bit was completed in FY00. Demonstration testing was delayed to FY01. Sandia hosted an industry/national-laboratory workshop that addressed issues of mutual importance to Diagnostics-while-Drilling (DWD) and hard-rock bit development activities.

Planned FY 2001 Milestones:

(1) Demonstrate torsional damping hardware for HRDF

(2) Determine effects of controlled damping on cutter failure rate

(3) Establish CRADA with bit manufacturers

(4) Upgrade drilling simulator software

(5) Receive best-effort bits

(6) Receive field-validated drilling simulator at SNL

(7) Complete jet-assisted single cutter testing

(8) Complete design of 2nd generation mudjet bit

(9) Complete a dynamic, 3D code for bi-center PDC bits.

Major Reports Published in FY 2000:

(1) M.B. Ziaja, K.W. Johnson, and S. Kadam, "Modeling and Development of a Bi-Center PDC Bit Design," Progress Report, Montana Tech of The University of Montana, May 31, 2000.

Major Articles Published in FY 2000:

(1) M.A. Elsayed and D.W. Raymond, "Measurement and Analysis of Chatter in a Compliant Model of a Drillstring Equipped with a PDC Bit," ASME Petroleum Division, Energy Technology Conference and Exhibition, New Orleans, February 2000.

(2) D.W. Raymond, "PDC Bit Testing at Sandia Reveals Influence of Chatter in Hard-Rock Drilling," Geothermal Resources Council Bulletin, October 1999.

Project Title:
Geothermal Drilling Organization Projects

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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CalEnergy; Caithness; Two- Phase Engineering; Novatek; Smith International; Drill Cool; APS Technologies</td></tr>
<tr><td>DOE Funding Allocation:
$639K</td><td>Cost Share Funding:
50/50 DOE/Industry</td></tr>
</table>

Project Objective:

The Geothermal Drilling Organization (GDO) is a DOE-industry organization formed to reduce geothermal drilling and well-maintenance costs by developing and commercializing new tools, materials, and techniques via cost-shared projects. Sandia National Laboratories administers DOE funds to match industry contributions and also provides technical support for each project. The projects considered by the GDO are those where the basic research and development have already been completed, and all that remains before possible commercialization are applications development and field-testing.

The GDO serves a very useful purpose by encouraging commercialization of emerging technologies and fostering a spirit of cooperation among the various segments of the geothermal industry toward reducing drilling and well-maintenance costs. For Sandia, the GDO also serves as a mechanism for identifying the industry's drilling and well-maintenance problems and provides a forum for technology transfer.

Approach/Background:

Due to changes in policy, new business rules for the GDO were prepared, reviewed and approved in FY99. The GDO now solicits proposals annually on a competitive basis. The GDO program in FY00 will

consist of on-going projects with prior-year funding, and new projects started under a competitive solicitation.

Status/Accomplishments:

The following projects are on-going with prior-year funding: Foam-Cement Logging (CalEnergy; to be completed in FY01); Foam-Cement Retainer/Packer (Caithness; yard tests started, to be completed in FY01); LEAMS (Two-Phase Engineering, Caithness, and Drill Cool; completed with very successful field test in FY00); Geothermal Mud Hammer (Novatek; parts ordered and fabrication nearly complete); Milling Capability on Valve-Changing Tool (Smith International; fabrication complete, waiting on field test); and Scaled Stator Section (CalEnergy and APS Technologies; modeling complete, fabrication under way).

New projects that will be awarded on the basis of the FY00 competitive solicitation include Hybrid Drill Bit (Thermasource, $150K) and Slimhole Well Testing (Trans-Pacific, $50K).

Planned FY 2001 Milestones:

(1) Award contracts from FY00 Operator Solicitation.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) J. Finger, A. Sattler, G. Whitlow, R. Jacobson, D. Jung, W. T. Howard, T. Champness, and P. Spielman, "Field Test of LEAMS Drilling and Well-Test Separator," Transactions Geothermal Resources Council, Vol. 24, October 2000, pp. 67-70.

Project Title:
Underbalanced Drilling Model, GEODRIL

<table>
<tr><td>Contract/Grant #: DE-AC04-94AL85000</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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N/A</td></tr>
<tr><td>DOE Funding Allocation:
$102K</td><td>Cost Share Funding:
N/A</td></tr>
</table>

Project Objective:

Maurer Engineering, Inc. (MEI) has developed a Windows-based software package, called GEODRIL, that calculates drilling fluid pressure, temperature, and velocity at all points in the wellbore (pipe and annulus). At the end of FY99, the code could perform the calculations for drilling ahead with no phase change in the fluid, but there was a temperature discontinuity at the bit and there were operational problems that made the code difficult to use. One of the principal applications for the code will be to calculate the maximum temperatures that downhole components will experience; the temperature discontinuity makes this application unusable.

Approach/Background:

Because the code will be extremely useful for evaluating the downhole environment and for application to underbalanced drilling, where it will enable geothermal production zones to be drilled more safely and with less permeability damage through knowledge of the pressure-balance point, we will contract Maurer Engineering to remedy the problems mentioned above. GEODRIL's ability to calculate a complete temperature profile in the annulus and in the drill pipe will also allow planning for the use of downhole steering and measurement instruments. Accurate definition of the downhole environment will be essential for designing any drilling or logging tools to be used in the geothermal industry.

Status/Accomplishments:

Complete GEODRIL code has been delivered to Sandia. The revised code has eliminated the temperature discontinuity present in earlier versions. This simulator can be distributed to industry as soon as a final Users Manual is on hand.

Planned FY 2001 Milestones:

(1) Complete GEODRIL update.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) Shifeng Tian and John T. Finger, "Advanced Geothermal Wellbore Hydraulics Model," Journal of Energy Resources Technology (published by the American Society of Mechanical Engineers), Vol. 122, September 2000, pp. 142-146.

Project Title:
Numerical Analysis of Three Component Induction Logging in Geothermal Reservoirs

<table>
<tr><td>Contract/Grant #: DE-FG07-00ID13955</td><td colspan="2">Contract/Grant Period: 6/1/00 - 5/31/01</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$47,430</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The purpose of this one year project is to aid DOE and the California Energy Commission in the development of logging technology for three dimensional imaging of the reservoir surrounding a drill hole. This cooperative project with ElectroMagnetic Instruments, Inc., entails design and manufacture of a unique borehole logging tool (the GEO-BILT tool) and the development and testing of new software for data interpretation for this tool.

Approach/Background:

The role of the University of Wisconsin, Madison in this endeavor is in supporting hardware design with numerical sensitivity studies and tool simulations. We will also be taking an active role in data interpretation through the application of numerical inversion schemes and the modification of existing software for field data interpretation. Both tasks will use and modify software that was previously developed at Sandia National Laboratories. The two primary objectives are as follows. (1) Incorporate finite antennas into 3D EM forward modeling code. Currently the scheme supports finite sized loop sources, but not finite length solenoids. These will be employed to simulate the response of the actual transmitter antennas employed with the GEO-BILT system. (2) Numerical modeling of realistic geothermal scenarios. These forward models will simulate surveys with the Geo-BILT tool in several specific geothermal reservoirs. The primary targets for this study are simulating (a) a borehole with an irregular drilling mud invasion zone completed in fracture geology, and (b) the geothermal reservoir

found at Dixie Valley. (3) interpretation of data collected with the GEO-BILT system. For this task the Sandia 3D EM inversion scheme will be employed to produce three-dimensional geoelectric images from data collected with the GEO-BILT tool.

Status/Accomplishments:

Funding was initiated by DOE on June 1, 2000, and was not in place for use at the University of Wisconsin-Madison until mid-July. In addition, students were not available to work on the project until September 1, 2000. Thus the tasks accomplished by the end of FY 2000 were initial training and supervision of the two graduate students performing the research.

Planned FY 2001 Milestones:

(1) Complete forward simulations of three component induction logging tools through geothermal reservoirs/fracture zones assuming point dipole sources (4/31/01)

(2) Complete imaging analysis of synthetic data generated under Task 2 (8/14/01)

(3) Incorporate solenoid source into finite difference code (5/31/01)

(4) Complete forward simulations employing finite rather than dipole sources to determine the effects of boreholes on measurments (6/15/01)

(5) Analysis of field data, if available. (8/1/01)

NOTE: To complete this work we will be asking for a no-cost extension through the end of August 2001.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

CONVERSION TECHNOLOGY

Project Title:
Performance Enhancement for Air-Cooled Condensers

<table>
<tr><td>Contract/Grant #: DE-AC07-99ID13727</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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NEDO, Japan</td></tr>
<tr><td>DOE Funding Allocation:
$155k</td><td>Cost Share Funding:
$127k</td></tr>
</table>

Project Objective:

The objective of this task is to improve the performance (overall heat transfer coefficient) of air-cooled condensers, with a goal of increasing the heat transfer coefficient by 15% without increasing the air-side pressure drop.

Approach/Background:

The geothermal resources utilizing binary power cycles are frequently located in regions lacking a sufficient supply of make-up water for an evaporative heat rejection system, thus requiring that heat be rejected sensibly to the air. Because air is a poor heat transfer medium, the air-cooled condenser tubes are large and expensive. The Next Generation Geothermal Power Plant study by Ben Holt Co. indicates the air-cooled condenser cost is approximately 25% of the total project cost (including well field). Improving the performance of these heat exchangers is expected to have a significant impact on reducing the cost of power generated from these plants. Two concepts have been identified with the potential to improve performance and are subject of on-going bench scale testing. Both the use of winglets on the fin surfaces and an oval tube configuration have the potential to improve heat transfer performance by reducing the stagnant regions in the air flow across the fin and past the tube. Testing is being used in conjunction with Computational Fluid Dynamics (CFD) modeling to identify those configurations that provide the best heat transfer and ease of manufacturing. 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 International Trade and Industry (MITI). The NEDO grant has been awarded to researchers in Japan, India, and at the INEEL for work similar in scope to this task. In addition to funding, the grant is providing investigators with access to the results and progress of the work being done by the other researchers.

Status/Accomplishments:

The major project emphasis during the past year has been the bench scale testing of the different tube-fin configurations and development of models that adequately depict the observed heat transfer performance. Testing of the heat transfer behavior of baseline circular tube and that of an oval tube were completed. Heat transfer measurements were obtained using a transient technique, which allowed very accurate determinations of local heat coefficients on the fin surface. A CFD code (Fluent) was concurrently used to model both the test configuration and test conditions. The numerical results from the modeling effort provided reasonable matches to the observed thermal performance of both the circular and oval tube configurations. The modeling of the tube-fin configuration with the winglets will be considered next. A meeting was held with Hudson Products Corp., Houston, Texas to identify the issues associated with the commercial development and application of the technology being developed and to discuss possible collaborative efforts. These discussions identified better performance, comparable cost of manufacturing, and ease of cleaning as major issues that have to be addressed before the technology could gain commercial acceptance. Subsequent to this meeting, researchers at NREL and INEEL jointly prepared and issued an announcement in the Commerce Business Daily soliciting industry collaboration in the commercial development of the technologies being developed at both labs. McElroy Manufacturing subsequently contacted INEEL investigators and discussions for possible collaborative efforts are planned in early FY2001.

Planned FY 2000 Milestones:

(1) Report bench scale testing with single tube configurations

(2) Work jointly with NREL to present results to industry and solicit industry participation

(3) Test tube bundle with proposed enhancement and report results.

Major Reports Published in FY:

(1) Informal INEEL Reports for NEDO: Application of Vortex Generators and Oval Tubes to Enhance Performance of Air-Cooled Condensers and Other Heat Exchangers - (1) Experimental Research, (2) Modeling Research.

Major Articles Published in FY:

(1) "Local Heat Transfer for Finned-Tube Heat Exchangers using Oval Tubes," Presented at the 34th National Heat Transfer Conference, Pittsburgh, PA, August 2000.

(2) "Heat Transfer Enhancement for Air-Cooled Condensers," GRC Geothermal Bulletin, Vol. 29, No. 1, pp. 4-5, Jan./Feb. 2000.

Project Title: Co-production of Silica and Other Commodities From Geothermal Fluids

<table>
<tr><td>Contract/Grant #: W-7405-ENG-48</td><td colspan="2">Contract/Grant Period:</td></tr>
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<tr><td>DOE Funding Allocation:
$</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Develop commercial technologies for extracting silica and other metal precipitates from geothermal fluids.

Approach/Background:

Produced geothermal brines contain large quantities of dissolved silica which can be extracted and sold to improve the economics of geothermal power generation. Additional benefits can be realized by generating additional energy at lower inlet turbine temperatures, reducing silica scaling, and maintaining permeability during fluid injection.

CalEnergy Minerals is one of the first U.S. geothermal companies to increase the value of their geothermal resource through mineral extraction. They are currently constructing a zinc extraction facility that is expected to produce 30,000 metric tons of zinc annually. Silica is being removed prior to zinc extraction because of its deleterious effects on the ion exchange resins. However, the value of the produced silica is limited because appropriate methods for producing silica with market-specific properties have not yet been identified. The purpose of this task is to determine the factors that control the physical and chemical properties of silica precipitates from geothermal fluids of varying salinity to allow development of commercial silica extraction technologies.

Status/Accomplishments:

Our FY01 work is focused on methodologies for silica extraction from highly saline brines at the Salton Sea and from less saline brines characteristic of other geothermal fields, for rubber additive and other industrial uses. The market for silica as a rubber reinforcement binder (used in products such as tires and shoes) is immense, and large enough not to be impacted negatively by the influx of large amounts of geothermal silica. Tests are being conducted that simulate silica precipitation under various conditions. The precipitates are subjected to a suite of characterization techniques (e.g., SEM, BET surface area, pore size analysis, dispersion in oil after silane coupling) to determine their suitability as rubber additives for comparison to commercial silicas used for the same purpose.

Laboratory precipitates exhibit a minimum in particle size at a pH of around 2.5, with increasing particle size at higher pH values. This suggests that it is possible to adjust pH to control particle size. However, post-processing may be important to get a final texture that is optimum for silica to be used as a rubber additive, even when the requisite particle sizes are attained. Neither the oil dispersion test nor cross polarization magic angle spinning nuclear magnetic resonance spectroscopy (CPMAS-NMR) seems to discriminate between good and bad silica for rubber use. Therefore we are negotiating with rubber and tire manufacturers for testing of geothermal precipitated silicas. With regard to other industrial uses, it was shown that acid-washed silica precipitated from Salton Sea brines performs adequately as thin layer chromatography-grade silica.

To extend our work to geothermal systems characterized by lower ionic strength fluids, silica precipitation experiments are being conducted using water chemistry representative of produced fluids from the Coso geothermal field. Silica is much less prone to precipitate from these fluids, so calcium and magnesium salts and polyelectrolytes are added to enhance precipitation.

Laboratory tests are being carried out aimed at making a “cleaner” silica precipitate from the Salton Sea geothermal fluids. By using sodium carbonate as the base to increase the pH and stimulate silica precipitation instead of NaOH or Ca(OH)2, silica contaminants such as iron, magnesium and calcium should precipitate in a separate carbonate phase which can be easily removed from the silica by acid rinsing or conventional flotation techniques. If successful, this method would produce cleaner (lower iron) silica precipitates and generate a separate metal-rich side stream for additional metals extraction.

To test this concept, we completed a silica precipitation experiment simulating Salton Sea brines with added Fe, Mn, Zn, and Ba and using soda ash (Na2CO3) as the precipitation agent. Precipitation was rapid (a few minutes at 80 degrees C) and formed three precipitates- silica and two separate carbonate phases with different structures (calcite, aragonite).

Planned FY 2001 Milestones:

(1) Identify target metals for extraction from geothermal fluids and their potential economic value (January, 2001)

(2) Provide silica precipitates to B. F. Goodrich (or alternate) for testing for rubber additive suitability (May, 2001)

(3) Complete matrix of bench-top tests to determine optimum residence time, neutralizing base, and agglomeration agent for CalEnergy silica precipitation process (June, 2001)

(4) Issue report to CalEnergy with a recommended process for silica extraction for rubber additive use (September, 2001)

(5) Issue progress report on development of metals extraction technology for geothermal fluids (September, 2001)

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

(1) A paper entitled “Developing a Process for Commercial Silica Production from Geothermal Brines” was accepted and is ready for publication in the 2001 Geothermal Resources Council meeting transactions volume.

Project Title:
Historical Costs

<table>
<tr><td>Contract/Grant #: DE-AC36-99-GO-10337</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$50,000</td><td>Cost Share Funding:</td></tr>
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Project Objective:

Document the historical costs of existing geothermal power plants.

Approach/Background:

Review the existing literature and data base sources on geothermal power costs, access existing securities and regulatory filings, and consult with industry. Use Princeton Economic Research Inc. (PERI) and Global Power Solutions as consultants.

Status/Accomplishments:

A summary report was prepared by PERI that incorporated the findings of Global Power Solutions, NREL and existing databases. NREL prepared an overview presentation of the findings that was given by PERI at the subcontractors' review in Albuquerque in May 2001.

Planned FY 2001 Milestones:

(1) PERI's report on historical costs will be updated with more detail on O&M costs by September 30, 2001

Major Reports Published in FY 2000:

(1) "Estimates of Historical Costs of U.S. Geothermal Electric Systems," Dan Entingh, Technical Report 9846-008-4G, February 22, 2001

Major Articles Published in FY 2000:

None

Project Title:
Geothermal Goals

<table>
<tr><td>Contract/Grant #: DE-AC36-99-GO-10337</td><td colspan="2">Contract/Grant Period:</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$45,000</td><td>Cost Share Funding:</td></tr>
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Project Objective:

Develop pathways to attaining the market goals of the Geothermal Program

Approach/Background:

The Geothermal Program has several market-related goals. These include: Increase the capacity of U.S. geothermal power to 6 GW by 2010 and 20 GW by 2020, and provide the heat and power needs of 5 million homes and businesses by 2010 to 2015. This analysis examines the feasibility of attaining these goals from a market perspective and identifies the most promising sites and approaches along with the potential costs.

Status/Accomplishments:

An initial draft presentation was prepared by March 2001 that focussed on the goals for Geopowering the West. These goals have subsequently been supplanted by national goals for which the analysis is being reconducted. A draft presentation should be delivered to DOE in June 2001.

Planned FY 2001 Milestones:

None

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
High-Performance Polymer Coating Systems for Brine-Dominated Environments

<table>
<tr><td>Contract/Grant #: AS-174-ESTD</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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Heresite Protective Coating Co. and Applied Surface Technology, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
$90,000</td><td>Cost Share Funding:
$120,000</td></tr>
</table>

Project Objective:

The objectives of this task are to develop a wear-resistant polyphenylene sulfide (PPS) coating and to produce an ultrafine zinc phosphate primer which improves the adherence of Saekaphen coating to metal.

Approach/Background:

In FY 1999, emphasis focused on looking for ways to making PPS more resistant to oxidation by hot brine. One strategy was to modify PPS with polytetrafluoroethylene (PTFE) thermoplastic. The other strategy was to modify PPS with high-temperature antioxidants. As a result, PTFE- and antioxidant-modified PPS coating technologies were transferred to the Applied Surface Technology, Inc., in April 1999. After applying these coating systems to the interior surfaces of heat exchanger tubes, field tests results revealed that, although some scales were deposited on the coating's surfaces, they easily flaked off using hydroblasting method at a pressure of > 6000 psi. However, when this scale-removal method was used repeatedly, the abrasive wear resistance of these coating surfaces was lost, causing a topographical transformation from a smooth surface texture into a rough one. Such a transformation led to the deposition of scales.

Hydrothermal stability tests of commercial phenolic resin-based Saekaphen coatings also were conducted in FY99, to evaluate their ability to withstand hydrothermal temperatures of up to 200°C. The test results showed that although the surfaces of phenolic polymer films had appropriate properties, such as a smooth surface, low surface energy, and surface slip, at 130°C, when the temperature was increased to 170°C, the films peeled off from the tube's surfaces.

Status/Accomplishments:

In trying to confer an abrasive wear resistance of PPS and PTFE-blended PPS coatings, the aluminum oxide-rich calcium aluminate (ACA) fillers were incorporated into the PPS. The sulphuric acid in the brine permeated through the coating, and then preferentially reacted with calcium in the ACA to form water-soluble calcium sulphate which leaches out from ACA particles during exposure to hot acid brine. The hydrothermal hydration reactions of calcium-depleted ACA led to the formation of a well-crystallized boehmite coexisting with the PPS. The in-situ growth of boehmite crystals formed in the ~ 65 micron meter-thick surface layer reinforced the oxidation-damaged PPS, and improved the coating's resistance to blasting wear. Also, PPS coatings containing an appropriate amount of ACA showed a better performance in protecting the underlying steels against corrosion, than that of the bulk PPS coatings without ACA.

Brookhaven National Laboratory (BNL) succeeded in develping an ultrafine, (5 to 10 micron meter crystal size) packed zinc phosphate crystal primer coatings which are ductile and flexible, and provide a great adherent to Saekaphen coatings. A short-term autoclave exposure testing for Saekaphen-coated steel samples demonstrated that the primer significanlty contributed to improving the strength and durability of adhesive bonding and corrosion resistance.

Planned FY 2000 Milestones:

(1) Autoclave validation tests of abrasive wear-resistant PPS coating were completed in April 2000.

(2) Development and evaulation of a new zinc phosphate primer were completed in May 2000.

(3) Zinc phosphate-coated test panels for Heresite's independent evaluation were delivered in June 2000.

(4) Corrosion and adhesive bonding tests of autoclaved Saekaphen coating were completed in August 2000.

Major Reports Published in FY:

None

Major Articles Published in FY:

(1) T. Sugama "Antioxidants for retarding hydrothermal oxidation of polyphenylene sulfide coatings in geothermal environments", Materials Letters, 43 (2000) 185.

(2) T. Sugama and P. Hayenga "Boehmite-reinforced Polyphenylene sulfide as wear/corrosion resistant coatings", Polymers & Polymer Composites, 8 (2000) 307.

Project Title:
Thermally Conductive Composites for Heat Exchanger Tubes

<table>
<tr><td>Contract/Grant #: AS-174-ESTD</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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Mammoth Pacific, Inc. and Applied Surface Technology, Inc.</td></tr>
<tr><td>DOE Funding Allocation
$185,000</td><td>Cost Share Funding
$200,000</td></tr>
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Project Objective:

The objectives of this task are to evaluate the performance of thermally conductive polymer composite-lined (TCPC-lined) heat exchanger (HX) tubes and to understand corrosion mechanisms of steel-made HX tubes at Mammoth Pacific power station.

Approach/Background:

Corrosion of the brine side of tubing in shell and tube heat exchangers can be a major problem in binary plants unless very expensive, high alloy steels such as AL6XN are used. Even then, excessive fouling of the tubes often prevents the economic use of binary processes with hypersaline brine reservoirs. Brookhaven National Laboratory (BNL) is currently working, in collaboration with National Renewable Energy Laboratory (NREL) and CalEnergy, to solve both problems with the development of thermally conductive, corrosion and scale resistant liners and coatings for use with low cost steel tubing. Field test data of the latest liner/coating systems under evaluation have shown significant reductions in the fouling rate compared to previous liner/coating formulations. In an effort to commercialize the application of the PPS-based coating systems to HX tubes, BNL and Applied Surface Technology, Inc., (AST) have signed a technology development agreement. In addition, BNL initiated cost-shared work with Mammoth Power Pacific Inc., which focuses on resolving the problems with corrosion and scale deposits of heat exchanger tubes at the Mammoth Pacific Geothermal Power (MPGP) plant.

Status/Accomplishments:

Two high-temperature performance polymer composite material systems, the silicon carbide (SiC)-filled polyphenylenesulfide (PPS)/zinc phosphate and the Cr oxide-filled resole-type phenolic polymer, were used in this work to evaluate their usefulness as blasting wear/corrosion resistant liners of the HX tubes (1-in.-outside diam. x 0.05-in.-wall thickness x 20-ft.-long). The former lining system was designed and made by BNL, and the latter one known as the trade name Saekaphen Si 14E was prepared and supplied by Heresite Protective Coatings Co., for the 5-month field performance tests at CalEnergy. In the field testing, these lined tubes were cleaned by hydroblasting at an interval for two weeks, and then were reinstalled in the test skid to conduct a continuing field evaluation. As a result, the commercial resole-type phenolic (RP) composite liners failed in a short-term field test for only one month, thereby leaking geothermal fluid throughout the whole tube. By contrast, using the PPS composite liners, the useful lifespan of the HX tubes extended more than four times to 5 months, compared with that of the RP composite liners. However, more enhancement of the surface hardness and slipperiness of the PPS liner will be required to further improve its wear and tear resistance by hydroblasting.

To understand corrosion mechanisms of carbon steel being encountered at the MPGP plant where the brine containing a high carbon dioxide content at 163°C, BNL analyzed the corroded steel panels transferred from MPGP. Analytical results revealed that the corrosion of steel is initiated by a weakly ionized carbonic acid derivative formed by reactions between carbon dioxide and water. To solve this problem, the steel test panels were coated with PPS composite systems being developed by BNL and then sent to Mammoth Power Pacific to perform a 5-mo.-exposure field test. The exposed test panels will then be evaluated in the field and at BNL.

Planned FY 2000 Milestones:

(1) Four to eight lined HX tubes for first FY00 field test were delivered to NREL in November 1999.

(2) Evaluation of lined HX tubes from the final FY99 field test was completed in January 2000.

(3) Five PPS-coated test panels for exposure test at MPGP plant were delivered in February 2000.

(4) Last Four lined HX tubes for second FY00 field test were delivered to NREL in February 2000.

(5) Evaluation of lined HX tubes from FY00 field tests were completed in July 2000.

(6) Analysis of corroded steel panels from MPGP plant was completed in August 2000.

Major Reports Published in FY:

(1) K. Gawlik, S. Kelley, T. Sugama, R. Webster, and W. Reams, "Field testing of heat exchanger tube coatings", Geothermal Resources Council Transactions, 23 (1999) 65.

Major Articles Published in FY:

(1) T. Sugama, R. Webster, W. Reams, and K. Gawlik, "High-performance polymer coatings for carbon steel heat exchanger tubes in geothermal environments", Journal of Materials Science. 35 (2000) 1.

Project Title:
Adhesive Sealants for Turbine Rotor with Blade

<table>
<tr><td>Contract/Grant #: AS-174-ESTD</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Directing Organization:
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Material Integrity Solutions, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
$60,000</td><td>Cost Share Funding:
$100,000</td></tr>
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Project Objective:

The objective of this collaborative task with Material Integrity Solutions, Inc., is to develop a sealant that protects the blade-fit area of a turbine rotor against corrosion.

Approach/Background:

The condensation of steam penetrating through an open space between blades and rotor creates a very low pH (< 2.0) environment. Such a strong acidic environment significantly promotes the rate of corrosion of these turbine components, thereby causing a serious corrosion-related damage to the turbine rotor with its blades. In turn, this damage adversely affected operating costs and energy conversion efficiency of a geothermal plant. In FY 1999, Material Integrity Solutions, Inc., (MIS), was awarded financial assistance from DOE to screen potential sealants from among the commercial ones and to test them in accordance with ASTM standards. Future work was planned on optimizing a cost-effective process technology for selected sealants. During this work, it was determined by MIS that the modification of commercial sealants and the synthesis of new ones are needed to meet the following criteria:

(1) Surface tension of < 50 dynes/cm for uncured sealants

(2) Ability to penetrate a open space (0.03 to 0.15 mm) between the turbine rotors and attached blades

(3) Excellent adherence to primed or non-primed rotors and blades

(4) Hydrothermal and chemical stabilities in a highly concentrated CH_4, H_2S, and CO_2-containing steam at temperatures up to 180°C:

(5) Curability in moist surroundings at room temperature

(6) Recovery of < 10 % after joint movement

(7) High glass transition temperature of > 150°C

(8) Shrinkage of < 2%.

Also, there is a need to gain a fundamental understanding of the mechanisms of the adhesive bonding between the sealants and primed or non-primed metals, and of the inhibition of the corrosion by sealants.

Status/Accomplishments:

In stainless steel (SS) bladed turbine rotors, there is an open space (width 0.03 to 0.08 mm) between the blades and the class 8 alloy steel (AS) rotor that often becomes corroded, particularly in geothermal power plants where acidic brine steam penetrates these crevices. BNL assessed the efficacy of the poly(dimethylmethylphenyl-methoxy)siloxane (PDMPMS)-based silicone elastomer as an anti-corrosion adhesive sealant under these conditions. The rate of penetration of the organic solvent-based liquid PDMPMS sealant into this very narrow interstice depended on its surface tension. Liquid sealants with a surface tension of < 25 dynes/cm displayed great wetting and spreading behavior over SS and AS surfaces, thereby wicking easily into the interstice. When the sealant was cured at room temperature and exposed in a low pH (~1.6) brine steam at 180°C, the hydrolysis-polycondensation reaction of the functional Si-joined methoxy groups in the PDMPMS led to the creation of additional crosslinking units attributed to sesquisiloxane, (CH3- or C6H5- SiO1.5). A growing number of these units not only acted to enhance the thermal stability of the sealant, but also improved its water repellency. Further, the chemical affinity of functional methoxy groups with the SS and AS substrate surfaces conferred a good adherence of the sealant to these substrates, and also provided outstanding durability of the interfacial bonds at the interfaces between the sealant and SS or AS during a 22-day exposure. As a result, this sealant was delivered to MIS for their independent evaluation in a mock-up testing facility. Contingent upon the results of evaluation, MIS will attempt to apply them to the prototype turbine rotor with blades.

Planned FY 2000 Milestones:

(1) Autoclave exposure tests of new-type sealant were completed in April 2000.

(2) Sealant samples for field test at MIS were delivered in May 2000.

(3) Report describing results of in-house work was completed in June 2000.

(4) BNL/MIS joint letter report summarizing results of evaluation was completed in September 2000.

Major Reports Published in FY:

None

Major Articles Published in FY:

(1) T. Sugama and M. Shirmohamadi, "Adhesive silicone sealant for mitigating corrosion of turbine components in acidic brine steam", Journal Materials Science (in press).

Project Title:
CaP Cements

<table>
<tr><td>Contract/Grant #: AS-174-ESTD</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Directing Organization:
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Unocal and Halliburton Energy Services</td></tr>
<tr><td>DOE Funding Allocation:
$150,000</td><td>Cost Share Funding:
$500,000</td></tr>
</table>

Project Objective:

The objectives of this research are to develop cost-effective acid-resistant cements at a temperature of 90°C and pH of 1.8, and to improve ductility and reduce shrinkage.

Approach/Background:

In 1996, Brookhaven National Laboratory (BNL) succeeded in developing a new cementitious material, a calcium aluminate phosphate (CaP) cement, that has superior resistance to carbonation-related deterioration in CO2-rich brine at 280°C.It's use was recommended to Unocal and Halliburton Energy Services. Subsequent field testing and further development by these companies led to full-scale tests and a field-workable CaP cement which was first emplaced by Unocal in a geothermal well in northern Sumatra, Indonesia in September 1997. Four wells were subsequently completed using this new system, which has since been commercialized under the trade name "ThermaLock Cement" by Halliburton Energy Services. In August of 1998, this commerciallized cement was used for completing steam injection wells in the Belridge field near Bakersfield, CA, and also was used in April of 1999 to complete geothermal wells on the island of Kyushu, Japan.

Development of calcium aluminate phosphate (CaP) cements now needs to focus on improving its resistance to highly concentrated H_2SO_4 (pH ~ 1.8) environments encountered in well surface ground water at temperatures of up to 90°C. As of June 1999, BNL completed post-test analyses of the 11-month-old downhole cement specimens used for completing Indonesian wells in collaboration with

Unocal and Halliburton. No decomposition of the cements was observed, nor was there any carbonation-caused erosion, suggesting that CaP cements have an excellent durability in a hostile geothermal environment. However, the tests also revealed that the cements had undergone some shrinkage during this long-term eleven-month exposure to CO_2-laden brine at 280°C, and concurrently, the cements had become more brittle and fragile.

Status/Accomplishments:

To develop an acid-inert CaP system, the physico-chemical factors contributing to a lower magnitude of acid erosion of CaP were investigated. This work included phase identification of acid-inert CaP, changes in chemical composition and states of cement surfaces by acid attack, and alterations of microstructure in cement bodies. As a result, the Al_2O_3-rich calcium aluminate cement, supplied from Lafarge Aluminates Co., was identified as most effective reactant in the CaP cement system in generating a large amount of acid-resistant reaction products and in reducing the formation of $CaSO_4 \cdot 2H_2O$. Samples of this new CaP cement system were delivered to Halliburton and Unocal for independent evaluations. The results of their evaluations also showed that this new cement system has a better performance in decreasing the rate of acid erosion, compared with that of originally formulated CaP cement.

BNL investigated ways of preventing development of microcracks generated by the shrinkage and propagation of cracks caused by brittleness. One approach was the incorporation of high-temperature stable fibrous materials into the CaP cements to create a composite structure. In this work, the carbon fiber was used as one of the potential fibrous materials. The three major factors significantly contributed to the high extent of the conversion from brittleness into ductility. These were (1) a good interfacial mechanical bond at the interfaces between them, (2) the formation of strong interfacial chemical bonds, and (3) the incorporation of a proper amount of fibers, so minimizing any increase in the porosity of the fiber-reinforced cement specimens. As a result, the fiber-reinforced cement specimens had a tensile splitting strength of 6.8 MPa and the fracture toughness of 0.053MN/m3/2, corresponding to improvements of ~ 42 % and ~ 135 %, respectively, over that of the non-reinforced specimens.

Planned FY 2000 Milestones:

(1) Autoclave validation tests of acid-resistant cement were completed in April 2000.

(2) New acid-resistant cement for Halliburton's independent evaluation was delivered in May 2000.

(3) ASTM toughness test of fiber-reinforced cement was completed in July 2000.

(4) Report describing results of in-house work at BNL and an evaluation at Halliburton was completed in September 2000.

Major Reports Published in FY:

(1) T. Sugama, L. Weber, and L.E. Brothers "Sodium polyphosphate-modified fly ash/calcium aluminate blended geothermal well cements: Reinforcement with carbon fibers", January 2000.

Major Articles Published in FY:

(1) T. Sugama, L. Weber, and L.E. Brothers, "Hot acid resistance of polymer-modified calcium aluminate/fly ash/polyphosphate cements", Advances in Cement Research, 12 (2000) 181.

Project Title:
Silica Scale Inhibition

<table>
<tr><td>Contract/Grant #: W-7405-ENG-48</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Inhibit the formation of silica scale in geothermal power plants

Approach/Background:

Silica scaling is a common occurrence in geothermal power production facilities worldwide. Silica scaling can be moderate and therefore easily managed by cleaning on a yearly or bi-yearly basis (e.g. Dixie Valley, CA), or so extreme that the production facility must be specially designed to limit scaling (e.g. Salton Sea, CA). Despite the costs associated with preventing scale formation or removing and disposing of scale deposits, the geothermal industry still lacks effective and economical silica scale inhibitors exhibiting widespread applicability. Variable fluid compositions, different plant operating conditions and the complex nature of silica polymerization reactions all contribute to make scale inhibition a challenging problem. The growing use of brine acidification is promising with regard to scale control, but issues remain even with this technology.

The overall goal of this project is to investigate additives for inhibiting scale formation in geothermal power plants. We will determine silica polymerization kinetics, examine how reaction rates are affected by fluid composition, and model the interaction between silica molecules and the impact of background electrolytes on reactions. The effectiveness of scale inhibitors will be evaluated in both the laboratory and in the field. The combined experimental, analytical and modeling efforts may identify critical steps in the overall sequence of reactions that can be controlled to mitigate scale formation. The research has broad

applicability due to the fundamental approach taken to expand the understanding of silica scale formation and can aid in improving the operating characteristics of geothermal power plants.

Status/Accomplishments:

Planned FY01 tasks include the following:

(1) Obtain an understanding of the homogeneous fluid reactions of silica polymerization and precipitation, as it applies to the geothermal industry, through laboratory experiments and molecular modeling.

(2) Identify components in the geothermal fluids primarily responsible for initiating or accelerating the deposition of amorphous silica.

(3) Screen potential silica scale inhibitors by conducting batch laboratory experiments.

(4) Perform experiments to test scale inhibitors in simulated brines using large scale flow-through reactors.

(5) Conduct on-site evaluations of the most promising scale inhibitors at geothermal power plants in collaboration with industry partners.

The laboratory scaling experiments used to evaluate the effectiveness of scale inhibitors are conducted at elevated temperature in batch and stirred flow-through reactors using both simple control solutions and complex simulated geothermal brines. The kinetics of silica polymerization is tracked by measuring monomeric silica using the silicomolybdate method, and total silica is quantified by atomic absorption. The size distribution of amorphous silica particles is measured by dynamic light scattering. Additional analytical measurements, employed as needed, include elemental analysis of scale deposits and 29Si NMR of the solutions and scales.

Our research suggests that anti-scalants originally targeted for low temperature, reverse osmosis and recirculating cooling water applications have the potential for inhibiting silica polymerization, and hence silica scale. An example of this inhibitory effect was observed with a commercially available product (B. F. Goodrich Good-Rite K-XP212 copolymer). This product is currently being tested in the field by the Philippine Natl. Oil Co. based on our experimental results, and their results will be compared with ours.

The polyacrylate class of homopolymers is being studied because these polymers exhibit the thermal stability necessary for higher temperature geothermal applications.

Molecular level calculations will be used to study the solution polymerization reactions in order to aid in the selection of silica scale inhibitors. We plan to extend the reaction pathway modeling of the formation of a silica dimer to include the aqueous reactions that occur throughout the induction period to the beginning of nucleation in order to focus on key steps in the polymerization process that may be susceptible to intervention by an inhibitor. This may allow us to guide the selection of inhibitors that will work best given the specific fluid chemistry of a particular geothermal power plant.

Planned FY 2001 Milestones:

(1) Complete batch and flow-through experiments to evaluate inhibitor effectiveness (April, 2001)

(2) Issue a report summarizing the findings of the scale inhibitor experiments (May, 2001)

(3) Issue a report on molecular modeling results, with implications for silica scale control (July, 2001)

(4) Issue report on on-site pilot-scale evaluation of scale inhibitors (September, 2001)

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Microbiological Research In Geothermal Plants

<table>
<tr><td>Contract/Grant #: DE-AC07-99ID13727</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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NCPA, Calpine, Structural Integrity Associates</td></tr>
<tr><td>DOE Funding Allocation:
$230,000</td><td>Cost Share Funding:
$16,000</td></tr>
</table>

Project Objective:

The goal of this program is to investigate the impacts of microbiological activity upon the efficient operation of geothermal power production facilities and to support the industry in identifying and mitigating these effects.

Approach/Background:

Significant densities of aerobic and anaerobic organisms bacteria are found in cooling systems using geothermal fluids for make-up. These microorganisms may adhere to the surfaces of critical components in geothermal facilities and develop complex structures called biofilms. The form-ation of biofilms can impact the operational efficiency of plants either directly by reducing heat transfer through condenser systems or cooling towers, or indirectly by altering the interfacial chemistry of metallic substrates influencing corrosion. In addition, microbiological activity may reduce the effectiveness of corrosion inhibitors, protective coatings, and/or chemical treatments used in the plants. The economic impact of microbial activity has been estimated to be as high as $500,000 annually for a 100 MWe plant.

In spite of the high costs associated with biofouling, few plants have monitoring programs in place to assess biological activity. Most facilities simply apply treatments either on a pre-defined schedule, or on

an as-needed basis corresponding to the visual evidence of growth, creating the potential that either too much or too little biocide will be added to the process stream. In addition to the inefficient use of expensive chemicals, these treatments may accentuate growth and require more costly countermeasures, such as the application of expensive coatings. In the worst case, the components may have to be replaced.

Scientists at the INEEL are conducting studies to characterize and microbiological growth at various geothermal facilities. The goals of this effort are to establish what levels of activity might be expected for a typical exposure, how the activity changes with environmental and process conditions, and which analytical techniques might be the most useful in the timely identification of the on-set and severity of growth.

Status/Accomplishments:

Prior characterization studies were based upon the current industry practices and included the collection of water quality parameters, metal coupon analyses, measurement of soluble carbon, and the use of selective growth media for the determination of the relative number of various classes of organisms. Data was collected on a seasonal basis at six different facilities at The Geysers' in Northern California. While this data is valuable in establishing biological growth trends, more detailed information about the microorganisms and their interactions in the plant environments is required to determine what is triggering or sustaining growth in these facilities. This data, in turn, is needed in order to develop improved monitoring and treatment techniques. Therefore, the characterization work was expanded to include new biochemical approaches based upon the extraction and analyses of phospholipid fatty acids and DNA recovered from the samples. Samples were collected from Geysers' facilities and analysed using these techniques and compared with results obtained from selective culturing techniques. The biochemical methods indicated similar growth trends, while also providing information on the community structure, dominant species, and the nutritional status of the organisms. The results of this work will be used in the investigation and development of monitoring techniques and control strategies targeting key species and/or nutrient conditions.

In addition, two instruments were deployed at a Northern California Power Agency plant to evaluate their operational feasibility and ability to track microbial growth in the plant. The first instrument, a Bio-scan luminometer, was operated in an off-line sampling mode and used to measure the amount of adeno-sine triphosphate, or ATP, found in the sample. ATP is present in all living cells; and therefore, can be used as an indicator of biomass. The ATP readings correlated favorably with cell counts determined from concurrently-collected water samples. The second instrument, the BioGEORGE, was installed in a cooling water stream and used to continuously monitor the build-up of a biofilm through change in the electrochemical properties of the probe. The BioGEORGE was able to detect the development of a biofilm during its operation at the facility.

Water samples from two Geysers' facilities were used in a study to evaluate if microbial activity is breaking down the chelate catalysts used as an abatement chemical by using the binding compounds, such as ethylenediaminetetraacetic acid (EDTA), as nutrient sources. A correlation between increased biomass and cell numbers were noted with changes in geothermal fluid sulfate levels. However, interferences in the fluids prevented a definite confirmation that chelate degradation was also occurring.

Planned FY 2000 Milestones:

(1) Seasonal Sampling of Geothermal Sites

(2) In-Plant Deployment of Monitoring Techniques

(3) In-Plant Study of Iron Chelate Cycling with Microbial Activity.

Major Reports Published in FY:

(1) P.A. Pryfogle. "Comparison of Selective Culturing and Biochemical Techniques for Measuring Biological Activity in Geothermal Process Fluids", INEEL Report, Sept. 2000.

Major Articles Published in FY:

(1) P.A. Pryfogle, "Evaluation of Biological Measurement Methods Used at the Geysers", Transactions of Geothermal Resources Council, Vol. 24, pp. 311-315.

Project Title:
Removal of Non-condensable Gases in Binary Power Plants

<table>
<tr><td>Contract/Grant #: DE-AC07-99ID13727</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$130K</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Development and deployment of a membrane-based system for continual removal of non-condensable gases from binary power plant condensers.

Approach/Background:

Although not usually associated with binary geothermal power plants, non-condensable gases (NCG) are present in working fluid systems in most plants. NCGs are introduced during recovery of working fluid from the turbine oil lubrication system, during maintenance activities, and during periods when the condenser (or other portion of the working fluid system) is sub-atmospheric. Though the introduction rate is low, the gases are relatively insoluble in the working fluid and the excess pressure due to their presence can be significant. Presently the NCGs are typically removed by periodically venting the vapor region at the condenser outlet. Based upon the NCG partial pressure levels reached before venting, a binary plant output might be increased by 2 to 4% by developing a system that continuously removed the gases. It has been proposed that this could be accomplished by using a continuous separation system based upon selective membranes. Selective membranes have been developed by Membrane Technology and Research, Inc. (Menlo Park, CA) for a variety of organic vapor/air separations, and commercial applications of this system are growing. These membranes are expected to be suited to the target application as well. In addition to the performance gains, this technology is expected to reduce

hydrocarbon working fluid losses relative to the existing systems, leading to reduced costs for working fluid replacement and improved regulatory compliance.

Status/Accomplishments:

Preliminary discussions have been held with binary plant operators to assess industry interest in the concept. (Based upon these discussions there is considerable industry interest.) During the plant visits, operational information and data has been gathered to be used to evaluate potential benefits of the proposed NCG removal system. Gas samples were collected and to identify typical constituents (NCG was found to be primarily air). Operating data (several years) from one facility's condenser was evaluated to attempt to quantify rates of introduction and to quantify the effect of condenser pressure on plant performance. A statistical analysis of the operating data was used to isolate the effects of condenser pressure from other factors (brine conditions). The results were consistent with model projections; plant power output increased nearly 1% for every 1 psi decrease in average condenser pressure. An agreement was subsequently reached with Membrane Technology and Research, Inc. to test their membranes for isopentane/air and isobutane/air separations. This testing started in August 2000, with positive and encouraging results

Planned FY 2000 Milestones:

(1) Complete sampling and analysis of NCG levels in binary plants

(2) Complete testing of membrane separation effectiveness

(3) Complete conceptual design and cost estimate of membrane separation unit for a typical binary power plant.

Major Reports Published in FY:

None

Major Articles Published in FY:

None

Project Title:
National Energy Management System (NEMS) Improvements

<table>
<tr><td>Contract/Grant #: 9846-004-3A</td><td colspan="2">Contract/Grant Period: 12/1999 - 8/2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$55,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Improve the representation of geothermal in Energy Information Agency (EIA)'s NEMS model.

Approach/Background:

NEMS is the pre-eminent source of projections for the U.S. energy system. As such, it influences many funding and policy decisions within Congress and the DOE. Thus it is important that geothermal be well modeled within NEMS. This task accomplished this by having Dan Entingh of Princeton Energy Resources International (PERI) work directly with the EIA to revise their representation of geothermal in NEMS.

Status/Accomplishments:

A revised algorithm was developed for the representation of geothermal in NEMS and implemented by the EIA within NEMS. The principal modifications included revisions of the geothermal resource base estimates, increased capacity factors, and modifications to the capacity expansion algorithms that allow faster deployment of geothermal.

Planned FY 2001 Milestones:

None

Major Reports Published in FY 2000:

(1) "Improvements in Geothermal Electric Modeling in the DOE/EIA National Energy Modeling System" Dan Entingh, Technical Report 9846-004-3A, August 11, 2000

Major Articles Published in FY 2000:

None

Project Title:
Mitigating Effects of Off-Design Operation

<table>
<tr><td>Contract/Grant #: DE-AC07-99ID13727</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$135K</td><td>Cost Share Funding:</td></tr>
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Project Objective:

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

Approach/Background:

Because geothermal binary power plants utilize a relatively low energy source, their performance is significantly impacted by changes either in the heat source (brine) or sink (ambient) conditions. This impact is especially significant in plants using air-cooled condensers where heat is rejected to the ambient dry-bulb temperature. In these plants, the total available energy can decrease by 30 to 40% during a summer day, when typically the demand (and market value) for power is the highest. To minimize the resulting effect on the plant revenues, investigators examined different schemes for increasing power production during these periods. One approach considered was to cycle production from the resource, over-producing during periods of high revenues and cutting production during periods of low demand, allowing the resource to recover. A concurrent approach identified how the plant performance was being limited, and evaluated technologies that could alieviate those limitations. It is envisioned that the techniques and methods that are developed would have application to both exisitng power plants and new plant designs to provide operational flexibility that would increase revenue streams and extend resource life.

Status/Accomplishments:

Investigators identified the use of variable frequency drives (VFD's) as a potential technique for cycling production from pumped wells, and evaluated the potential benefit that this cycling could have on plant revenue streams. This study used historical deregulated power price values obtained from the California Power Exchange (through 1999). Results of this study were presented at the 2000 annual Geothermal Resources Council meeting.

Models of binary plants were developed that are similar to the Ben Holt designed plants at Mammoth and Steamboat. The models have been used to identify those components and plant systems that are affected the most by changes from design conditions. At off-design conditions, modeling results indicated that irreversibilities associated with the turbine and the parastic power requirements ("house loads") had the largest increases relative to the total available energy. Results indicate more effective management of the "house loads" and techniques to improve turbine efficiency, could minimize the adverse impact of operating at off-design conditions. The VFD's represent an effective method of managing the "house loads", as well as providing the operational flexibity to reduce or increase plant output in response to demand. Turbine efficiencies can be increased by modifying operating conditions to approach optimimum ideal enthalpy changes during the turbine expansion. This can be accomplished by modifying the turbine inlet conditions, including those producing a supersaturated vapor expansion, and using VFDs on pump drivers. In addition turibne efficiencies could be increased if there were some mechanism for varying the turbine speed. Investigators continue to examine different potential schemes for accomplishing this variable turbine speed, as well as to evaluate the practicality and economic feasiblity of these schemes.

Planned FY 2000 Milestones:

(1) Identify potential application and benefit of using variable frequency drives in binary plants

(2) Identify components limiting plant performance and initiate study of steps to be taken to improve component and plant performance

(3) Report on concepts identified.

Major Reports Published in FY:

None

Major Articles Published in FY:

(1) K. Bloomfield and G. Mines, "Cycling Geothermal Resources to Increase Revenues", Transactions of Geothermal Resources Council, Vol. 24, pp. 105-108.

(2) G. Mines, "Summary of Investigations of the Use of Modified Turbine Inlet Conditions in a Binary Power Plant", Transactions of Geothermal Resources Council, Vol. 24, pp. 509-512.

Project Title:
Development of Power Plant Cost Database

<table>
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<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$135K</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Develop a data base that would provide DOE researchers (and industry) costs that are representative of different geothermal energy conversion systems

Approach/Background:

The continued viability and future growth of the domestic geothermal industry is contingent upon reducing both operating and capital costs. In order to assess whether research is reducing these costs, it is necessary that costs are adequately defined for those components and activities related to the production of electrical power from a geothermal resource. This task is a costing method to provide information for the energy conversion systems used for the generation of electrical power. The costing methodology developed will be based upon publicly available costing information and commercially available software. The method will be augmented, where possible, using equipment specifications obtained from commercial plants to assure that component sizes and materials are typical of those used in geothermal facilities. Cost estimates will then be refined using confidential, industry supplied cost information. Initial efforts focused on the review of existing, publicly available cost information, and costing methods such as the “value analysis”, which examined the relative affect of plant component and systems costs to the cost of power.

Status/Accomplishments:

A typical commercial binary power plant (15 MW) was modeled using the ASPEN simulator software and equipment/component specifications obtained from plant operators. Publicly available cost information was reviewed and found to be dated, largely due to the lack of new plant construction in recent years. Costing methods evaluated did not provide the detailed desired to evaluate the cost impacts. Rather than attempt to update costs and modify existing costing methods to provide the desired detail, the decision was made to obtain a commercial cost estimating software package and modify it for the geothermal energy conversion systems. A package (ICARUS Process Evaluator) was identified that utilizes the data output from the ASPEN software to prepare detailed cost estimates. Training on the software use and application was completed and the software was purchased. Due to procurement issues and subsequent delays, the software was not received until near the end of the fiscal year. The report summarizing the costing methodology developed for binary geothermal energy conversion systems will be completed in FY-2001.

Planned FY 2000 Milestones:

(1) Develop means of maintaining confidentiality and initiate requests for cost information from industry

(2) Initiate development of methods for predicting the operating costs for the different types of energy conversion systems

(3) Summarize and report costs for a binary energy conversion system.

Major Reports Published in FY:

None

Major Articles Published in FY:

None

Project Title: Communications

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<tr><td>Contract/Grant #: DE-AC36-99-GO-10337</td><td colspan="2">Contract/Grant Period: FY00</td></tr>
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Project Objective:

To support and enhance the DOE Geothermal Energy Program's communications and outreach of program developments, acomplishments, and activities. Obtaining greater visibility for the program and its contributions is important and desirable.

Approach/Background:

Geothermal energy supplies substantial and growing portions of the U.S. and global clean energy needs. This contribution, and the considerable potential of geothermal energy resources, is often overlooked by policy and decision makers, the engineering and scientific community, the power production industry, and the media. Fostering greater recognition of the contributions and potential of geothermal energy technologies is essential for continued growth of the geothermal industry. Well-targeted and appropriately distributed communications products have been used in past years to achieve visibility for the program and its resulting benefits.

Status/Accomplishments:

Four quarterly DOE Geothermal Technologies inserts were placed in the Geothermal Resources Council Bulletin; the book Geothermal Today was published; we were well-represented at the Geothermal Resources Council Annual Meeting/Trade Show; the brochure "Clean Energy for the Earth" was revised and printed; the Geothermal Energy Program and GeoPowering the West Web sites were updated and created, respectively; and the electronic photo library was augmented with additional geothermal photos.

Planned FY 2001 Milestones:

(1) The two Web sites will undergo their annual major revision

(2) Four quarterly GRC Bulletin inserts will be produced

(3) The next issue of Geothermal Today will be produced

(4) Several fact sheets will be developed describing geothermal resources and opportunities in the first several priority western states

(5) The three geothermal exhibits will be refurbished and updated; the GRC Annual Meeting/Trade Show will be attended (with the large exhibit)

(6) Communications and public relations support will be provided to the various state GeoPowering the West initiatives.

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Component Development for Ammonia/Water Power Cycles

<table>
<tr><td>Contract/Grant #: DE-AC36-99-GO-10337</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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<tr><td>DOE Funding Allocation:
$435,000</td><td>Cost Share Funding:
50</td></tr>
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Project Objective:

The objective of this work is to improve the resource utilization and to reduce the cost of electricity generation form medium-temperature geothermal resources.

Approach/Background:

This investigation is to reduce low temperature power cycle capital and maintenance costs through development of inexpensive and efficient components such as the heat rejection component for the power cycle. This work targets systems that utilize ammonia/water as the working fluid, such as the Kalina cycle. Some of the work carried out at NREL shows great promise. In some of these cases, brine effectiveness increase is claimed to be as high as 30% which will result in reduced cost of electricity generation. These new power cycles require development of new components (e.g. absorber/cooler for the heat rejection side) and laboratory or field testing for proof of concept.

A state-of-the-art ammonia/water condensation test facility was assembled at NREL in FY99 to provide the capability of testing condensation of ammonia/water vapor mixtures in shell and tube type heat exchangers. This facility is designed to simulate the condensing portion of a plant. During FY99 and FY00, NREL researchers successfully carried out tests during which heat and mass transfer data were collected for condensation of ammonia-water mixtures at various pressures and concentrations. Our approach in this activity will encompass activities as listed:

(1) Test of an absorber/cooler for the heat rejection side and testing of single tubes with finned or rough surfaces: NREL will actively pursue close collaboration with a major U.S. heat exchanger manufacturer for proper technology transfer - a major candidate is EFCO

During FY01, we will test the performance of a plate-fin absorber/cooler fabricated at NREL. This unit is designed and built such that it will enhance the condensation process of ammonia/water vapor mixture exiting the turbine by introducing a lean liquid mixture to the vapor stream, allowing the vapor to be absorbed into the liquid stream rather than direct condensation of the vapor stream. It is important that this technology be transferred to the U.S. industry. NREL will actively seek an industry partner for taking this product to the next stage of mass production.

NREL has completed single tube condenser tests involving a smooth tube over a wide range of flow conditions. NREL will test the performance of a single tube involving finned tubes and for tubes with rough surfaces to enhance flow distribution, and heat and mass transfer. These tests will be performed over a wide range of Reynolds numbers and various pressure and concentration levels. As part of this activity, we will carry out flow visualization tests in which a high-speed camera will be used to observe and record the flow of the condensate and vapor inside the test condenser. We will conduct flow visualization tests to study the impact of the baffles in heat exchangers on the flow of condensate.

(2) Collaboration with Heat Transfer Research Institute (HTRI) for incorporation of single tube in shell data: NREL will work with industrial concerns such as EFCO and Exergy to transfer the technology. NREL data is very valuable for the design of the recuperators used in ammonia/water cycles. Heat exchanger designers use the codes available from HTRI. However, because of the lack of adequate data on condensation of the ammonia/water vapor mixtures, these correlations have not been incorporated into the HTRI codes. NREL's will work with HTRI to provide the fundamental data gathered during NREL tests into the HTRI codes.

Status/Accomplishments:

During the past several months, NREL has completed performance tests on tube and shell configuration with rough surfaced tubes. NREL has also completed a comprehensive set of flow visualization tests on smooth surface tubes. NREL has completed initial design and testing of plate-fin heat exchangers. NREL has manufactured and setup an air-cooled fin-plate heat exchanger consisting of 5 plates. NREL has modified existing water-cooled tube and shell condenser setup to encompass the air-cooled plate-fin heat exchanger. Modifications were made by constructing a separate air-cooled loop. We have completed several set of tests with the plate-fin heat exchanger. A complete performance report is due Sept. 1, 2001.

Planned FY 2000 Milestones:

(1) Complete testing of plate-fin absorber/cooler and prepare a report on performance of the unit under different vapor mixture conditions, including mixture concentration and condensing pressure.

Major Reports Published in FY:

(1) A report will be published on the design and performance of plate-fin heat exchangers on Sept. 2001. A computer model will be developed to model ammonia/water absorption/condensation process in absorber/coolers.

Major Articles Published in FY:

(1) An article will be published on the absorption of ammonia vapor into the lean liquid solution inside the plate-heat exchangers on Sept. 2001.

Project Title:
Remediation of Deformed Well Casing

<table>
<tr><td>Contract/Grant #: DE-AC02-98CH10886</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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Project Objective:

The objectives of this project are:

(1) To develop and analyze optimum cement formulations for geothermal well casing remediation

(2) To perform engineering analysis of the remediation area using the developed cements and detailed modelling of the cement-casing-formation interaction.

Approach/Background:

Deformation surveys conducted in geothermal fields have shown that geothermal wells can experience excessive deformation. Formation movement, which in turn, is associated with the long-term response of the site due to tectonic or other loads such as those related to subsidence are suspected to be among the main causes of casing damage. Remediation of geothermal wells is a cost effective alternative to plugging and abandonment. Briefly, a remediation procedure involves: (a) plugging of the geothermal well temporarily using an isolation packer, (b) milling the deformed area and finally (c) patching the area using a casing patch. There is a need for materials to cement the liner into place and also a need to evaluate the strength of the remediation patch using these materials.

Cement formulations are systematically tested to obtain material properties and their range of applicability. The influence of additives and fiber reinforcement on pertinent properties at elevated temperatures is under investigation. The cements have been tested for compressive properties under

unconfined and triaxial loading, flexural and tensile strength, elastic modulus, Poisson's ratio, thermal conductivity and coefficient of thermal expansion.

Previous efforts were concentrated on (a) geomechanical models and (b) structural analysis of axial/shear modes of well deformation. Currently, numerical modelling is performed to investigate the strength of the patch. The loads under consideration are pressure and temperature. Detailed finite element models are developed which incorporate the major components of the patch: patching liner, the various cement formulations developed under this program and the formation. A series of analysis are performed to take into account parametrically different materials and loading conditions. The project initially utilized two-dimensional models. Subsequently, three-dimensional models were used in order to accertain the validity of the assumptions used in the analysis. Due to the nature of the configuration and loads, tensile stresses are developed in the cements. While the cements deform plastically at higher strains under compression, their tensile capability needs to be increased in order to respond to the demand shown by the anaysis. Furthermore, material modeling will be focused on yield surface characterization of the cement materials and subsequent failure analysis. Laboratory testing and finite element analysis are carried out interactively to achieve optimization.

Status/Accomplishments:

Various cement formulations were developed for use in geothermal well remediation projects. Fundamental material properties needed for thermal and mechanical stress analysis were measured. Systematic evaluation of the stress and deformations in the vicinity of the remediation area were performed using 2D finite element models. These models represent sections of the geothermal well at different depths within the remediation patch as well as the original system. Several parametric studies were carried out by considering a range of parameters. For example, the contrast in compression strength between the patch cement and the surrounding formation was varied such as that the cement could be equally, less or more stiff than the formation. In addition, in order to accertain the magnitude of the variations of the patch response along the well axis, 3D finite element analysis was performed. The results demonstrate the significance of the mechanical properties on the integrity of the remediation patch. Particularly, our results show the industry should consider tensile strength requirements in the design process.

Planned FY 2000 Milestones:

(1) In FY 01 this project will focus on design criteria and structural analysis of conventional rather than remediated geothermal wells.

Major Reports Published in FY:

(1) “Engineering Analysis of Materials for Remediation of Geothermal Wells”, Philippacopoulos, A.J., Berndt, M.L., FY 2000 Final Report, BNL Report, April 2001.

Major Articles Published in FY:

(1) "Characterization and Modeling of Cements for Geothermal Well Casing Remediation”, Philippacopoulos, A.J., Berndt, M.L., GRC Transactions, Vol. 24, pp. 81-86, September 2000.

Project Title:
Corrosion Characteristics of Clad and Thermal Sprayed NiCrMo Alloys

<table>
<tr><td>Contract/Grant #: DE-AC02-98CH10886</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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<tr><td>DOE Funding Allocation:
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Project Objective:

The objectives of this project are to characterize and compare the corrosion characteristics of clad, thermal sprayed and wrought Ni-base materials for corrosion protection in geothermal brine and steam transportation systems.

Approach/Background:

Clad and thermal sprayed corrosion resistant alloys have the potential to provide more economic corrosion protection than wrought materials. As a first step in the evaluation process, clad, thermal sprayed and bulk NiCr base alloys have been subjected to electrochemical tests in geothermal brine to compare corrosion performance. Since pitting corrosion is a major concern in geothermal brines emphasis has been placed on comparison of pitting and repassivation potentials, corrosion current densities and extent of passivity. In addition, the statistical variations in material behavior has been studied as this is important in service life prediction. The influence of temperature is included in the research as is the effect of brine chemistry since this is site-specific and time dependent. Through greater understanding of the fundamental aspects of corrosion mechanisms it will ultimately be possible to better model and predict in-situ behavior for a range of brine chemistries and temperatures.

Status/Accomplishments:

The alloys investigated included Inconel 625, Incoloy 825, and Hastelloy C-276. The clad materials were roll bonded to carbon steel substrates. The thermal sprayed coatings were produced by the HVOF process to reduce porosity and enhance protective properties. Cyclic polarization tests were performed in synthetic hypersaline brine and solutions of different chloride concentrations to investigate corrosion characteristics of the different materials. Critical pitting temperature studies were also performed. The clad versions of Inconel 625 and Incoloy 825 consistently exhibited greater susceptibility to corrosion than the wrought materials under the experimental conditions used. The reasons for the difference in corrosion behavior were investigated using microstructural and EDAX analyses. It was determined that the surface microstructure and chemical composition for the clad materials differs from that of the wrought alloys and this results in increased corrosion rates. Wrought and clad Hastelloy C-276 tended to have similar corrosion characteristics. The thermal sprayed Inconel 625 had the highest corrosion rate of all materials tested due to the coating porosity despite using the HVOF process. Of the materials tested, wrought Inconel 625 and Hastelloy C-276 gave the best performance based on corrosion potential and corrosion current density. Whether the observed differences in behavior of clad and wrought alloys will significantly affect corrosion resistance and mechanisms under operating conditions in a geothermal system needs to be investigated further. The initial laboratory-based investigation is completed and there is no activity in this area in FY 01. However, it is desirable to perform field tests in collaboration with industry to evaluate the clad materials under operating conditions and to perform more detailed analysis of methodologies for predicting service life of corrosion resistant alloys in different available forms.

Planned FY 2000 Milestones:

None

Major Reports Published in FY:

None

Major Articles Published in FY:

(1) M.L. Berndt and D. Otterson, Cyclic Polarization Studies on Clad and Thermal Sprayed Ni-Based Alloys in Synthetic Geothermal Brine, Geothermal Resources Council Transactions, Vol. 24, 649-652, San Francisco, 2000.

Project Title:
Coatings and Concrete Mix Design for Prevention of Microbiologically Influenced Corrosion in Cooling Towers

<table>
<tr><td>Contract/Grant #: DE-AC02-98CH10886</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
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</table>

Project Objective:

The objective of this task is to develop materials for repair and prevention of microbiological attack of concrete in cooling towers and thereby reduce maintenance costs and extend service life.

Approach/Background:

Concrete exposed to cooling water containing certain species of bacteria is at risk of severe degradation. In particular, sulphur oxidizing, nitrifying and heterotrophic bacteria are common causes of microbiologically influenced corrosion (MIC) of concrete. Sulphur oxidizing bacteria such as Thiobacillus thiooxidans, Thiobacillus concretivorous and Thiobacillus ferrooxidans produce sulphuric acid which is aggressive towards concrete. Nitrifying bacteria (e.g., Nitrosomonas and Nitrobacter) can act to cause nitric acid degradation of concrete. Heterotrophic bacteria produce organic acids. Such acids can also attack concrete. MIC can involve a progression of different species according to pH conditions. Initially, new concrete is highly alkaline and this prevents growth of bacteria. Once carbonation of the surface occurs the surface pH decreases and certain bacteria can become established. These bacteria further reduce pH, thereby enabling other bacteria tolerant to more acidic environments to flourish. Systematic reduction of pH occurs with each new species. As a result of acid attack, concrete loses its integrity. Therefore, it is necessary to determine how attack of concrete can be prevented and repaired.

The FY 99 effort on this subject was devoted to evaluation of protective coatings and surface treatments against one species of sulphur oxidizing bacteria, Thiobacillus ferrooxidans, and concentrated sulphuric acid. In FY 00 the impact of concrete mix design and the use of supplementary cementing materials to improve durability were investigated. In addition, mortars based on calcium aluminate cement were evaluated for concrete protection. Laboratory tests were combined with field exposure of different concrete mixes and protective coatings in cooling towers at a geothermal power plant.

Status/Accomplishments:

The resistance of different protective coatings, mortars and concrete mix proportions to sulphur oxidizing bacteria has been investigated. The protective materials included three different epoxy coatings, epoxy-modified cement mortar, latex-modified mortar and calcium aluminate mortar. The influence of cement type, silica fume and blast furnace slag on concrete durability was examined. Laboratory screening tests were followed by field exposure tests in cooling tower basins. The field tests were conducted in collaboration with Unocal Geothermal of Indonesia. It was determined that epoxy coatings and calcium aluminate mortar gave the best overall performance. Partial replacement of cement with 5 to 10% silica fume or 40% blast furnace slag improved concrete resistance to MIC. Based on these findings, it is recommended that consideration be given to the use of supplementary cementing materials in initial concrete mix design for cooling tower structures. Epoxy coatings or calcium aluminate mortar are recommended for protection and repair of existing structures suffering from MIC. The research findings and guidelines for repair of damaged concrete structures were documented. The project is now essentially completed. Continued technology transfer activities will include a conference presentation at the 2001 GRC Annual Meeting and availability of the documents through our web site.

Planned FY 2000 Milestones:

None for FY 01.

Major Reports Published in FY:

(1) M.L. Allan, Evaluation of Coatings and Mortars for Protection of Concrete Cooling Tower Structures from Microbiologically Influenced Corrosion in Geothermal Power Plants, BNL 66980, October 1999.

Major Articles Published in FY:

(1) M.L. Allan, Protection of Concrete Cooling Tower Structures from Sulphur Oxidizing Bacteria in Geothermal Power Plants, submitted to Cement and Concrete Research.

(2) M.L. Berndt, Protection of Concrete in Cooling Towers from Microbiologically Influenced Corrosion, submitted to Geothermal Resources Council Meeting, 2001.

Project Title:
Advanced Processes for Geothermal Brines Multiple Resources

<table>
<tr><td>Contract/Grant #: AS-174-ESTD</td><td colspan="2">Contract/Grant Period: continuing</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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Caithness Operating Co. LLD</td></tr>
<tr><td>DOE Funding Allocation:
$300K</td><td>Cost Share Funding:
$150K.</td></tr>
</table>

Project Objective:

The aim of the project is the development of economic and environmentally acceptable methods for treatment of geothermal by-products and their conversion to commercially viable products.

Approach/Background:

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

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

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

Status/Accomplishments:

(1) The rate of silica nucleation and precipitation were found to be fast, they are all finished in seconds.

(2) The particle sizes are distributed in a narrow range of 10-20 nm.

(3) Vacuum drying yields silica with high surface area and high purity better than 99% pure.

(4) The silica products have been bound with chlorosilane on the surface.

(5) The over all yield was improved to 50% recovery.

Planned FY 2000 Milestones:

(1) Determine the rate of silica nucleation in fresh Dixie Valley brine as a function of temperature change over the range of 230ºF down to 200ºF. Oct. 2000-April 2001

(2) Evaluate the effects of introduction of external chemical species on the rate of silica precipitation in fresh Dixie Valley brine as a function of temperature of the range of 230ºF down to 200ºF. Since fresh brine is required for this task, it will be performed at the DixieValley site rather than at BNL. Suggested species might include magnesium, aluminum, Dadmac, or polymerized silica. Oct. 2000-April 2001

(3) Determine particle size distribution of the primary silica particles produced in Task 1 and establish relationship to product quality. Jan. 2001-May 2001

(4) Determine the rate of growth of the primary silica particles produced in Task 1 and 2 as a function of temperature when the solution is quenched to a specific temperature within the range of 230ºF down to 100ºF. Since fresh brine is required for this task, it will be performed at the Dixie Valley site rather than at BNL. Jan. 2001-May 2001

(5) Determine the crucial effect of drying method on the physical charasteristics of the final silica product. Oct. 2000-Sept. 2001

(6) Determine the purity of the silica products produced in Task 3. This task will be performed at BNL. Oct. 2001-Sept. 2001

(7) Investigate the size distribution, shape of particles, surface properties of silica products produced in Task 3. This task will be performed at BNL. Jan. 2001-Sept. 2001

(8) Investigate the ability to perform surface modifications to select samples identified in Task 5. The focus will include ability of geothermal silica to accept silane-organic attachments or other biocatalysts. This task will be performed at BNL. Mar. 2001-Sept. 2001

(9) Determine ability to predict particle size distribution as a function of process control design. Since processing of fresh brine is required for this task, it will be performed at the Dixie Valley site rather than at BNL. Jan. 2001-Sept. 2001

(10) If funding permits identify the mechanism of silica loss with the objective of improving recovery to better than 50% of the potential 400 ppm (on a mass basis) recovery target. Possible mechanisms include

solubility losses during washing and particle loss due to undersized particle development. Since fresh brine is required for this task, it will be performed at the Dixie Valley site rather than at BNL. April 2001-Aug. 2001

Major Reports Published in FY:

None

Major Articles Published in FY: 2000

(1) Mow S. Lin, Michael Bohenek, Eugene T. Premuzic, and Stuart D. Johnson, "Silica Production from Low-Salinity Geothermal Brines" Geothermal Resources Council Transactions, Vol. 24, Sept. 24-27, 2000, pp. 671-674

Project Title:
Continuous On-line Steam Quality Measurement

<table>
<tr><td>Contract/Grant #: W-7405-ENG-48</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Directing Organization:
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<tr><td>DOE Funding Allocation:</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

Develop continuous on-line steam quality and steam purity measurement system

Approach/Background:

Poor steam quality results in high maintenance costs and reduced power generation, and contributes to premature failure of turbine rotors. A continuous monitor of large amounts of brine carry-over should have a fast response in order to prevent damage to the turbines. A steam purity monitor with high sensitivity is also desirable to monitor steam quality degradation over time. Remote optical or acoustical methods of measuring steam quality are preferred to those that require contact with the corrosive steam environment. LLNL has developed several remote chemical monitoring technologies through the DOE Office of National Defense and Non-proliferation. Among these are aerosol detection by laser light scattering and sensitive chemical vapor detection by Cross-Dispersion Infrared Spectrometry (CDIRS). The DOE investment of over $10 M in the development of a unique capability in hardware and data processing algorithms will be leveraged into this problem.

Status/Accomplishments:

In Phase 1- Concept Definition and Feasibility Assessment, LLNL will explore concepts for both fast and high-sensitivity on-line steam quality sensors. Potential methods that will be assessed for a fast response steam quality monitor include light scattering techniques, acoustical/ultra-sonic sensors, and capacitance monitors. For high-sensitivity steam purity monitors, infrared spectral techniques such as CDIRS will be

examined. A signatures trade-off analysis will be performed to select the most promising method(s). A study will be performed on how to best integrate these sensors into geothermal power plants such that plant downtime and additional infrastructure investment will be minimized.

We will collaborate on this project with Douglas Jung of Two-Phase Technology who will share his industry experience in helping us design and field test the steam quality measurement system.

Phase 2 - Development and Demonstration of a Steam Quality Sensor Prototype - will be pursued in future years depending on the findings of Phase 1.

Planned FY 2001 Milestones:

(1) Complete survey of current steam quality measurement techniques, focusing on performance gaps and operational deficiencies (January, 2001)

(2) Complete identification of alternative and/or enhanced approaches that could result in better performance and operability (June, 2001)

(3) Complete recommendations for techniques deemed to offer greatest promise of near-term performance/operability improvements (August, 2001)

Major Reports Published in FY 2000:

None

Major Articles Published in FY 2000:

None

Project Title:
Air-Cooled Condenser Development

<table>
<tr><td>Contract/Grant #: DE-AC36-99-GO-10337</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>Directing Organization:
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<tr><td>DOE Funding Allocation:
$250K</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The objectives of this task are to develop an air-cooled condenser with a significantly improved heat exchanger performance without incurring a serious penalty in first cost or operating cost. The overall goal is to achieve a 0.5-cent per kWh reduction in the cost of electricity generation.

Approach/Background:

Air-cooled condensers are widely used in geothermal power plants because of the lack of clean water available and to avoid the generation of unsightly vapor plumes. The use of air cooling results in a considerable reduction in plant power output because of: 1) the lower density and heat transfer coefficient associated with air and the resulting greater approach temperature difference and 2) the fact that the air dry bulb temperature is higher than the wet bulb temperature, especially in dry climates. The seasonal variation of net plant power output is higher for an air-cooled plant than for a water-cooled plant. The times of lowest plant output are during the summer months, which are often the periods when power has the most market value.

In FY 1999 NREL developed a computer model of a new air-cooled condenser design. We then designed, built, and tested a prototype. Test results showed that the heat exchanger provided 30% more heat exchange than a conventional unit of the same volume and operating at the same fan power. In FY 2000 NREL developed improved designs using computational fluid dynamics simulations and filed a patent. We also released a Commerce Business Daily announcement seeking industry partners for further development and began discussions with potential partners such as Hudson. The Empire Energy team,

which is designing a new 1 MW plant, has expressed a strong interest in testing our new air-cooled condenser concept side-by-side with conventional units at their plant.

Status/Accomplishments:

NREL built and tested a new 4 fin-per-inch prototype. The information gathered was used to improve our computer model of the pleated fin concept. NREL also conducted detailed FLUENT runs that allowed us to optimize the design of a non-pleated thick-fin concept. A patent application was prepared and submitted.

Planned FY 2001 Milestones:

(1) Review responses to CBD announcement and determine best cooperative agreement mechanism for working with manufacturer (I) Nov 00

(2) Design condenser unit for testing at Empire Energy project (C) May 01

(3) Develop field test plan for condenser (I) Sep 01

(4) Complete report comparing different evaporative cooling methods, including collaborative input from INEEL (C) Sep 01

Major Reports Published in FY 2000:

(1) C. Kutscher and K. Gawlik, Advanced Air-Cooled Condenser Development: FY 2000 Progress Report, October 2000.

Major Articles Published in FY 2000:

(1) C. Kutscher and K. Gawlik, "Development of a Porous-Fin Air-Cooled Condenser," presented at the Geothermal Resources Council Annual Meeting, September 2000.

Project Title:
Small-Scale Power Systems

<table>
<tr><td>Contract/Grant #: DE-AC36-99-GO-10337</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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<tr><td>DOE Funding Allocation:
$150K</td><td>Cost Share Funding:</td></tr>
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Project Objective:

The objectives of this project were 1) to evaluate the feasibility of small-scale (under 5 MW) power plants in the western United States and 2) based on the knowledge gained from the feasibility study, develop and issue a solicitation for the design and construction of small-scale plants.

Approach/Background:

Geothermal power plants generate approximately 2,200 MW of electricity in the United States, most of which is provided by plants over 5 MW in size. There are approximately 50 geothermal power plants in the world at or below 5 MW. However, there are only six plants in the U.S. smaller than 5 MW in size and only a single plant smaller than 1 MW. Small geothermal power plants have the potential for widespread application, but achieving cost-effectiveness in small plant sizes presents a number of challenges. This project is aimed at determining the economic feasibility of small-scale geothermal power plants and verifying their operating characteristics.

Status/Accomplishments:

A study was performed comparing the cost and performance of small geothermal power plants in various western resource locations. It was found that for the best resource sites, costs of electricity generation would range from 7 to 9 cents per kWh and that cost effectiveness could be enhanced by also using the geothermal fluid for a direct heating application. An RFP was prepared and issued that solicited the

design and construction of small plants. An expert panel was assembled to evaluate the proposals, and five projects were selected for funding.

Planned FY 2001 Milestones:

(1) Award up to 5 contracts (C) Dec 00

(2) Assemble advisory team (I) Nov 00

(3) Perform preliminary design reviews on projects that do not require drilling (C) May 01

Major Reports Published in FY 2000:

(1) C. Kutscher and K. Gawlik, Investigation of the Opportunity for Small-Scale Geothermal Power Plants in the Western United States, January 2001

Major Articles Published in FY 2000:

(2) C. Kutscher, "The Status and Future of Geothermal Electric Power," presented at the American Solar Energy Society Conference, June 2000

Project Title:
Geothermal Process Monitors

<table>
<tr><td>Contract/Grant #: DE-AC07-99ID13727</td><td colspan="2">Contract/Grant Period: FY2000</td></tr>
<tr><td>Sponsoring Office Code: EE-12</td><td colspan="2">Performing Organization:</td></tr>
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Unisearch Associates, NCPA</td></tr>
<tr><td>DOE Funding Allocation:
$340,000</td><td>Cost Share Funding:
$5,000</td></tr>
</table>

Project Objective:

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

Approach/Background:

Geothermal steam plants contain gaseous and particulate species in their process streams that require the use of abatement processes to minimize equipment damage, maximize perform-ance 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 such processes include the over-application of iron chelate to ensure that hydrogen sulfide emissions from cooling stacks remain within the regulated limits, or excessive steam washing to reduce hydrogen chloride concentrations to non-corrosive levels prior to contacting critical plant components.

This project is directed at the development of new devices capable of providing reliable, on-line measurements for optimizing these processes; and thereby, reducing production costs. These instruments are based upon new solid-state, diode laser technologies that have evolved as a result of the rapidly

growing telecommunications industry. These systems are compact, relatively inexpensive, require little power and can be designed to perform in a variety of environmental and operational scenarios.

Previous activities have concentrated on the detection of process gas species, such as hydrogen sulfide and chloride, using a near-infrared, frequency-modulated spectroscopy technique. The FY2000 effort included an evaluation of the use of near-infrared diodes in the photoacoustic detection of gaseous species and the expansion of the technology to other uses such as the detection of the physical properties of process streams.

Status/Accomplishments:

The investigation of near-infrared diode photoacoustic spectroscopy for the on-line detection of process gases was continued, incorporating various system improvements suggested by previous work to increase measurement sensitivity. These upgrades included miniaturizing the photo-acoustic cell volume and the use of higher sensitivity microphones for signal improvements. Testing with an 1.793 micron diode, allowing access to an absorption line of hydrogen chloride, produced weak signals, on the order of 2-3%, in response to hydrogen chloride gas concentrations of 500 ppm (v/v). For com-parison, detection limits on the order of 1ppm (v/v) were readily detected in a one-meter pathlength using the previously investigated frequency-modulated absorption technique. The conclusion of this investi-gation is that the photoacoustic technique, using the presently available infrared diode sources, is not sufficiently sensitive for geothermal process gas monitoring applications.

Work also continued on the development of the hydrogen sulfide monitoring system that uses the near-infrared, frequency-modulated spectroscopy technique. The prototype was modified to include an automatic calibration system and the necessary control interfaces for unattended, long-term operation. The system was tested in the laboratory and an extended field trial at the Northern California Power Agency Unit 2 facility was planned for the first quarter of FY-2001.

A task to investigate the feasibility of developing a new generation infrared steam densitometer, incorporating new semiconductor emitter and detector technology, was also initiated. For this effort, a laboratory-scale steam loop was designed using the steam output from a facility steam generator used for autoclaving biological samples. The steam loop had an in-line heater that allowed the moisture content of the "wet" steam from this generator to be adjusted before it was vented through a one-meter optical test cell. A throttling calorimeter was also installed in the loop and used to provide an independent measurement of quality. Five infrared light emitting diode (LED) devices were procured for testing and evaluation. The LEDs were specified to respond to a range of moisture conditions.

Planned FY 2000 Milestones:

(1) Evaluation of Photoacoustic Spectroscopy Gas Monitoring Device

(2) Development of an Automated Calibration System for Plant Gas Monitoring

(3) Investigation of Optical Technologies for Measuring Steam Properties

Major Reports Published in FY:

(1) J.K. Partin, "Laboratory Evaluation of a Hydrogen Chloride Monitor Based Upon Near-Infrared Spectroscopy," INEEL Report, March 2000.

Major Articles Published in FY:

None

AUTHOR INDEX