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# *Federal Geothermal Research Program Update Fiscal Year 1999*

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# EXECUTIVE SUMMARY

## 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 Geothermal and Wind 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

This Federal Geothermal Program Research Update reviews the specific objectives, status, and accomplishments of DOE's Geothermal Program for Federal Fiscal Year (FY) 1999. 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 five categories of work used to distinguish the research activities of the Geothermal Program during FY 1999 reflect the main components of real-world geothermal projects (Figure 1). These categories are described briefly here and form the main sections of the project descriptions in this Research Update.

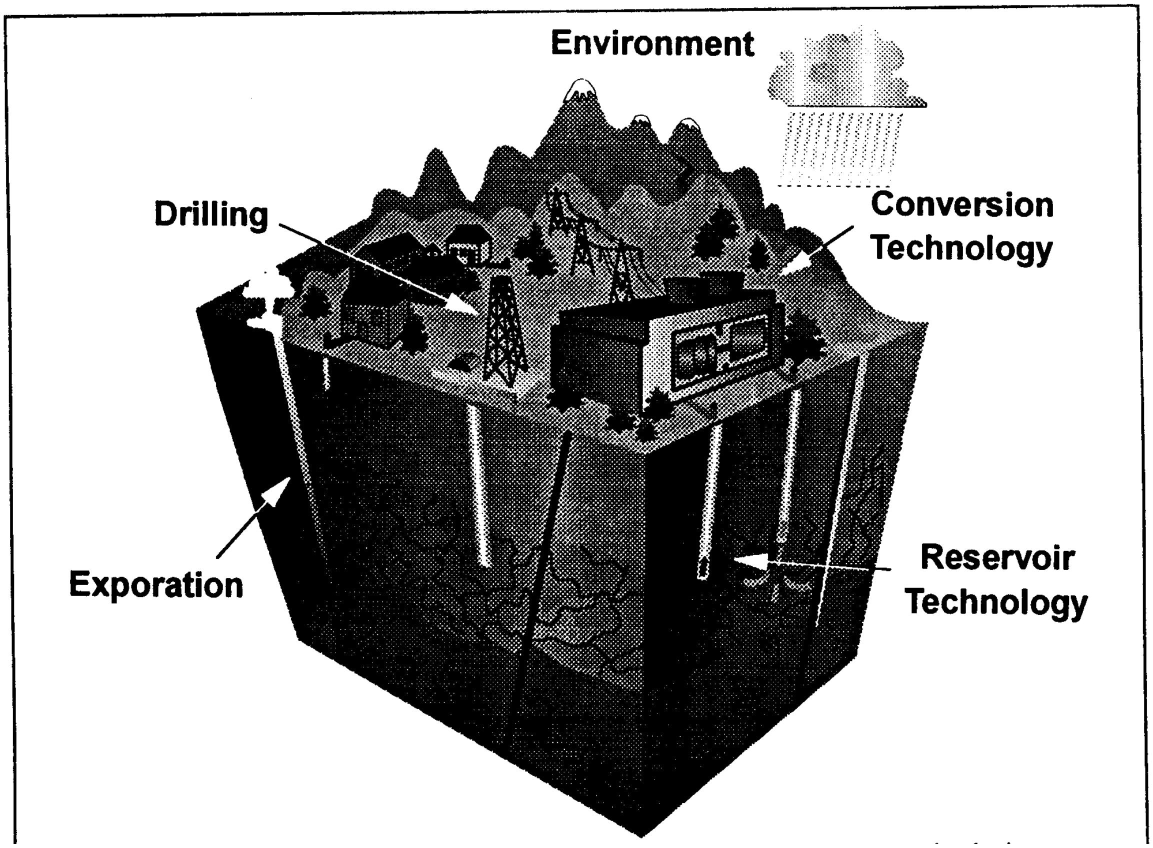


**Figure 1.** Schematic Diagram of a Geothermal System and its Component Technologies.

### 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. $CO_2$-resistant well cements able to withstand the aggressive chemistry of certain geothermal fluids are also under development. Biotechnology solutions for geothermal waste disposal are being refined,

### Direct Use and Geothermal Heat Pumps

This category covers the direct use of geothermal energy sources for applications in other than electrical production. The Department of Energy and other partners initiated the Geothermal Heat Pump Consortium (GHPC) in late 1994. The GHPC is a partnership of utilities, geothermal manufacturers, HVAC vendors, and public agencies whose objective is to overcome market barriers to the widespread deployment of geothermal heat pumps. In addition, the Geo-Heat Center at the Oregon Institute of Technology (OIT) provides technical assistance and conducts research for direct use applications. This work stimulates the utilization of the nation's low-to-moderate geothermal resources.

***** In late 1999, the Geothermal Program became part of the Office of Geothermal and Wind Technologies within the Office of Power Technologies at the Department of Energy.

# EXPLORATION TECHNOLOGY

# GEOTHERMAL RESOURCE/RESERVOIR INVESTIGATIONS BASED ON HEAT FLOW AND THERMAL GRADIENT DATA FOR THE UNITED STATES

David D. Blackwell, Kenneth W. Wisian, Maria C. Richards, and John L. Steele
Department of Geological Sciences, Southern Methodist Univ., Dallas, TX 75275-0395
http:\\www.smu.edu/~geothermal

## KEY WORDS

Eastern US, Western US, Geothermal Potential, Temperature, Heat Flow, Thermal Conductivity, Geothermal Gradient, Western Geothermal Database, Heat Mining.

## PROJECT BACKGROUND AND STATUS

This project extends the early geothermal resource evaluations of Muffler (1979) and Reed (1985). The detailed geothermal data base developed for the Geological Society of America Decade of North American Geology (DNAG) *Geothermal Map of North America* (Blackwell and Steele, 1992; Blackwell et al., 1989, 1991) was expanded and updated in previous projects. Reference to publications about the previous project are contained in Blackwell et al. (1995). This project was initiated in January 20, 1997 and terminated January 20, 2000. This project's focus is on specific area heat flow and geothermal data sets in the western United States. The change in emphasize from previous projects is due to the different nature of the geothermal resource in the high heat flow areas of the western US. This report deals with the final year of the project.

## PROJECT OBJECTIVES

### *Technical Objectives*

The generalized technical objectives of this project are to:

- increase the precision and accuracy of geothermal resource estimates and assessments;
- regionally characterize geothermal resources in the United States.

These objectives are met by the specific technical objectives:

- data base made available for the process of resource evaluation, site specific heat flow, geothermal gradient, and thermal conductivity information for western United States;
- resources available for aiding in the determination of future exploration sites for geothermal energy;
- generalized models for the site specific evaluation of resource potential;
- updated heat flow, geothermal gradient and ancillary (thermal conductivity, sediment thickness, surface temperature, etc.) data bases and maps for the US as new thermal data are published;
- development and operation of an Internet web page with results of the project available in the form of downloadable data and examples of mapping using the results.

***Expected Outcome***

- First, develop the specifications and data for a site specific heat flow and geothermal gradient data base for the western US;
- Second, exploration and evaluation models for Basin and Range geothermal systems;
- Third, a digital representation of where the heat flow data is for the western US;
- Fourth, an updated heat flow data base and a series of digital data bases designed to estimate temperature in the depth range 3 to 5 km at a horizontal resolution of about 5 km over the US;
- Fifth, an Internet home page: the address is http://www.smu.edu/~geothermal.

## APPROACH

The focus of this project expands to more complex geothermal conditions in the western Cordillera. As a consequence the types of information for individual wells and thus geothermal systems are greatly expanded. The data for the resource analysis in the western US have been collected from a variety of published and unpublished sources. A large number of formerly unavailable company temperature gradient and heat flow exploration data, along with the public domain data openly available in papers and open-file reports were collected, compiled and synthesized. For increased reliability of the data set, a separate verification of the data base was completed using original sources such as well logs and reports.

Geothermal resource estimates and assessments by this and other projects are supported by making available the most up to date heat flow, geothermal gradient, and thermal conductivity information in useful digital formats. Distribution of the results in digital form via the World Wide Web on the Internet is part of the project. Although this is the final year of the project, the web site will continue to be updated. There are already over 1000 additional data points collected for future incorporation in the data base.

## RESEARCH RESULTS

**Geothermal System Heat flow and Thermal Properties Data Base**. This new data base is an extension of Regional Heat flow and Thermal Properties Data Base of heat flow measurements in the (DNAG) 1:5,000,000 G*eothermal Map of North America* (Blackwell et al., 1989, 1992, 1996). That data set has a total of 2191 sites throughout the United States.

One of the main project results is development of a geothermal system specific, thermal well, data base. The ideal set of information for each geothermal gradient/heat flow exploration site includes maximum and bottom hole temperature, depth range(s) of each well, area location (by latitude /longitude and township/range), a thermal gradient(s), heat flow, lithology, and a reference (or references) to any publication of the results as well as the source of the original thermal data. Figure 1 is a map showing all the geothermal system areas corresponding to Table 1. Table 1 shows the well sites location currently available on the web site.

There are 5206 individual well sites in the Western Geothermal database. Each of these has at least one gradient value and latitude/longitude locator; many of the sites have multiple gradient values and lithologies to match. Other related parameters that more than a third of these sites contain are bottom hole temperatures, heat flow and conductivity. There are overview charts of the data listed here on the web site.

**Quantitative analyses made**. Preliminary results of the analysis of the database were described by Wisian et al. (1999). They found that 95% of the geothermal systems with temperatures over 150°C occur in areas where the regional heat flow is greater than 80 $mWm^{-2}$. This result can be attributed to two factors. Young magma chambers will be found in areas with high regional heat flow as high temperature conditions are required at depth to generate magmas. Secondly, for geothermal systems related to deep circulation of water rather than localized magma systems, there seems to be a "maximum" depth of circulation of about 6 km. Thus the higher the heat flow in an area, the higher will be the temperature experienced by the deeply circulated water.

While it has been recognized that there is a frequent association of geothermal systems in the Basin and Range with faulting, the degree of correlation was qualitative. Merging the geothermal well database with a compilation of geologically recent faulting (Raines et al., 1996) shows the degree of correlation between the two. Combining the two databases shows that 90% or more of major known geothermal systems are within 3 km of late Pleistocene or younger faults (Figure 2). This correlation suggests that future exploration in the region should include young faults as a key indicator. One of the better examples of the close association of historic faulting and geothermal systems is Dixie Valley, Nevada where there is geothermal production immediately to the north of a 1954 surface rupture zone (Bell and Katzer, 1987). The close association between recent faulting and the existence of geothermal systems suggests that recent faulting is a requirement for system development (due to the effect of self-sealing) and that future exploration in the region should include young faults as a key indicator.

**Web Page Data.** A major part of the dissemination of the results is the availability of the data in spread sheet form and downloadable from our home page at: http:\\www.smu.edu/~geothermal. This site contains the database, reference lists, and US maps of various kinds. The individual geothermal system analysis results will be available on the site as well. Examples of site specific geothermal anomaly maps generated using the data base are shown for Black Rock Desert, McCoy, Desert Peak, and Grass Valley, Nevada.

## FUTURE PLANS

This year completes the project. There are already more data sites being collected for additional entry to the regional geothermal data base. There is a new project to update the DNAG United States geothermal map and this will also generate new data and use the data from the Western Regional data base. We will continue to keep updated results available by operating the web page and respond to inquiries generated from this site.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

We have had an increasing number of inquires from Internet contacts and conventional contacts for information on temperatures and geothermal gradients. The data set on the web has been used by at least 8 groups that have sent us specific comments. Some specific interests in the results are:

**Organization Type and Extent of Interest**

| | |
|---|---|
| Shell, The Hague, | Dry Hot Rock Resource Potential & Characteristics |
| Shell, Houston, | Temperatures at 1, 2, 4 km Depth, US |
| Exxon Exploration, Houston, | Geothermal Map of North America |
| American Electric Power | Ground Temperatures |
| Geological Survey of Columbia | Thermal Mapping |
| Geoheat Center | Geothermal Gradients in US |
| Energy Laboratory, MIT | Temperature for Heat Mining Economic Analysis |

| | |
|---|---|
| MultiMax | Sediment Thickness and Temperature |
| National Energy Resources Lab | Geothermal Gradients in US |
| K-12 Educators | Classroom project assistance |
| International Universities | Geothermal Gradients and Thermal Mapping |
| USGS, cave divers | Temperatures at specific Depths, |
| Lawrence Livermore Nat. Lab. | Detailed site specific information |
| Small Business/companies | Ground water temperature map |
| Individuals | Home owners and student projects |

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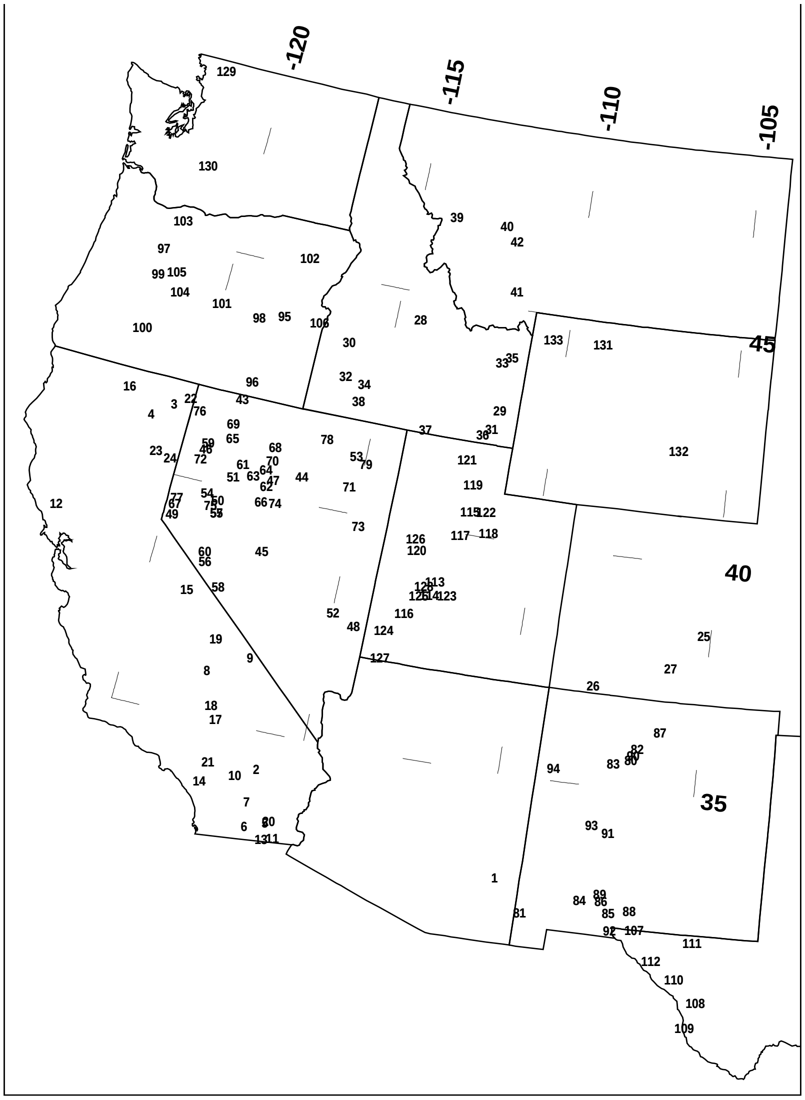


Figure 1. Geothermal areas listed in Table 1. Areas shown have multiple sites within them. Not shown in figure are single well locations.

**Table 1.** Western United States geothermal area locations.

| Geothermal Locations | LAT | LONG | Map # | Geothermal Locations | LAT | LONG | Map # |
|---|---|---|---|---|---|---|---|
| Safford Basin, Arizona | 32.75 | -109.67 | 1 | Paradise Valley, Nevada | 41.07 | -117.51 | 68 |
| | | | | Pinto Mountain, Nevada | 41.36 | -118.79 | 69 |
| 29 Palms, California | 34.18 | -116.01 | 2 | Pumpernickel Valley, Nevada | 40.77 | -117.49 | 70 |
| Alturas Basin, California | 41.47 | -120.53 | 3 | Ruby, Nevada | 40.55 | -115.28 | 71 |
| Beiber, California | 41.15 | -121.06 | 4 | San Emidio, Nevada | 40.45 | -119.41 | 72 |
| Brawley, California | 33.08 | -115.50 | 5 | Shellbourne, Nevada | 39.76 | -114.81 | 73 |
| Cactus, California | 32.92 | -115.98 | 6 | Shoshone, Nevada | 39.89 | -117.15 | 74 |
| Coachella Valley, California | 33.45 | -116.06 | 7 | Soda Lake - Stillwater, Nevada | 39.54 | -118.83 | 75 |
| Coso Hot Spring, California | 36.04 | -117.82 | 8 | Soldier Meadows, Nevada | 41.46 | -119.79 | 76 |
| Death Valley, California | 36.51 | -116.82 | 9 | Truckee Meadows, Nevada | 39.53 | -119.76 | 77 |
| Desert Hot Springs, California | 33.96 | -116.50 | 10 | Tuscarora, Nevada | 41.47 | -116.17 | 78 |
| East Mesa, California | 32.79 | -115.23 | 11 | Wells, Nevada | 41.11 | -114.97 | 79 |
| Geysers-Clearlake, California | 38.75 | -122.83 | 12 | | | | |
| Heber, California | 32.72 | -115.50 | 13 | Albuquerque, New Mexico | 35.65 | -106.70 | 80 |
| Lake Elsinore, California | 33.68 | -117.33 | 14 | Animas, New Mexico | 32.07 | -108.93 | 81 |
| Long Valley, California | 37.65 | -118.86 | 15 | Baca - Valles Area, New Mexico | 35.89 | -106.57 | 82 |
| Medicine Lake-Glass Mtn., CA | 41.61 | -121.85 | 16 | Cabezon, New Mexico | 35.52 | -107.13 | 83 |
| Mojave Desert, California | 35.05 | -117.30 | 17 | Florida, New Mexico | 32.50 | -107.52 | 84 |
| Randsburg, California | 35.33 | -117.50 | 18 | Las Alturas, New Mexico | 32.29 | -106.78 | 85 |
| Saline Valley, California | 36.75 | -117.80 | 19 | Las Cruces, New Mexico | 32.53 | -107.00 | 86 |
| Salton Sea, California | 33.13 | -115.41 | 20 | Ojo Caliente Warm Springs, NM | 36.30 | -106.04 | 87 |
| San Bernardino-Harlem HS, CA | 34.12 | -117.23 | 21 | Otero County, New Mexico | 32.39 | -106.28 | 88 |
| Surprise, California | 41.67 | -120.12 | 22 | Rio Grande Rift, New Mexico | 32.68 | -107.05 | 89 |
| Susanville, California | 40.41 | -120.65 | 23 | San Diego Grant, New Mexico | 35.75 | -106.66 | 90 |
| Wendel-Amedee- Honey Lake, CA | 40.32 | -120.23 | 24 | Socorro, New Mexico | 34.02 | -107.04 | 91 |
| | | | | Strauss, New Mexico | 31.92 | -106.70 | 92 |
| Canon City, Colorado | 38.48 | -105.19 | 25 | Tres Montosas, New Mexico | 34.15 | -107.48 | 93 |
| Durango, Colorado | 37.15 | -107.92 | 26 | Zuni , New Mexico | 35.27 | -108.63 | 94 |
| San Luis Valley, Colorado | 37.70 | -105.96 | 27 | | | | |
| | | | | Beulah, Oregon | 43.88 | -118.17 | 95 |
| Bayhorse, Idaho | 44.40 | -114.32 | 28 | Borax Lake - Alvord Valley, Oregon | 42.33 | -118.58 | 96 |
| Blackfoot, Idaho | 42.75 | -111.60 | 29 | Breitenbush, Oregon | 44.67 | -122.67 | 97 |
| Boise, Idaho | 43.62 | -116.18 | 30 | Burns, Oregon | 43.72 | -118.86 | 98 |
| Franklin County - Maple Grove, Idaho | 42.33 | -111.73 | 31 | Cascades, Oregon | 44.10 | -122.00 | 99 |
| Grandview, Idaho | 42.88 | -116.06 | 32 | Crater Lake, Oregon | 42.90 | -121.99 | 100 |
| Madison County, Idaho | 43.79 | -111.78 | 33 | Glass Butte, Oregon | 43.83 | -120.00 | 101 |
| Magic Reservoir - Snake Rv. Plains, ID | 42.80 | -115.50 | 34 | La Grande, Oregon | 45.22 | -117.87 | 102 |
| Newdale, Idaho | 43.94 | -111.53 | 35 | Mount Hood, Oregon | 45.35 | -121.75 | 103 |
| Preston - Bear River Prospect, Idaho | 42.17 | -111.95 | 36 | Newberry , Oregon | 43.85 | -121.25 | 104 |
| Raft River, Idaho | 42.08 | -113.55 | 37 | Santiam Pass, Oregon | 44.25 | -121.50 | 105 |
| Twin Falls and Jerome Counties, Idaho | 42.41 | -115.55 | 38 | Vale, Oregon | 43.90 | -117.14 | 106 |
| | | | | | | | |
| Deer Lodge, Montana | 46.75 | -113.90 | 39 | Hueco Tanks, Trans-Pecos, Texas | 31.99 | -106.10 | 107 |
| Marysville, Montana | 46.75 | -112.37 | 40 | Marfa, Texas | 30.54 | -104.44 | 108 |
| Texton - Ennis Geothermal Area, MT | 45.37 | -111.73 | 41 | Presidio Bolsum, Texas | 29.97 | -104.65 | 109 |
| White Sulfur Springs, Montana | 46.45 | -111.99 | 42 | Rio Grande Valley, Texas | 31.00 | -105.02 | 110 |
| | | | | Salt Basin, Texas | 31.83 | -104.66 | 111 |
| Baltazor and McGee, Nevada | 41.92 | -118.73 | 43 | Van Horn, Texas | 31.36 | -105.62 | 112 |
| Beowawe, Nevada | 40.56 | -116.60 | 44 | | | | |
| Big Smokey Valley Area, Nevada | 38.81 | -117.19 | 45 | Best, Utah | 38.88 | -112.49 | 113 |
| Black Rock Desert, Nevada | 40.70 | -119.35 | 46 | Cove Fort Sulphurdale, Utah | 38.57 | -112.57 | 114 |
| Buena Vista Valley, Nevada | 40.36 | -117.35 | 47 | Crystal Hot Springs, Utah | 40.49 | -111.91 | 115 |
| Caliente, Nevada | 37.62 | -114.37 | 48 | Escalante Desert, Utah | 38.09 | -113.14 | 116 |
| Carson - Eagle Valley, Nevada | 39.16 | -119.77 | 49 | Eureka, Utah | 39.95 | -112.05 | 117 |
| Carson Sink, Nevada | 39.67 | -118.67 | 50 | Fifth Water, Utah | 40.10 | -111.31 | 118 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Colado, Nevada | 40.24 | -118.43 | 51 | Hill Air Force Base, Utah | 41.08 | -111.96 | 119 |
| Coyote Springs, Nevada | 37.83 | -114.97 | 52 | Little Drum - Keg Mountains, Utah | 39.48 | -113.13 | 120 |
| Deeth, Nevada | 41.23 | -115.27 | 53 | Little Mountain, Utah | 41.59 | -112.25 | 121 |
| Desert Peak-Brady Hot Springs, Nevada | 39.78 | -119.00 | 54 | Midway, Utah | 40.53 | -111.47 | 122 |
| Dixie Valley, Nevada | 39.86 | -118.01 | 55 | Monroe-Red Hill, Utah | 38.63 | -112.11 | 123 |
| Excelsior, Nevada | 38.33 | -118.59 | 56 | Newcastle, Utah | 37.66 | -113.57 | 124 |
| Fallon NAS - Carson Lake, Nevada | 39.41 | -118.62 | 57 | Roosevelt Hot Springs, Utah | 38.51 | -112.84 | 125 |
| Fish Lake -Alum - Emigrant, Nevada | 37.86 | -118.08 | 58 | Spor Mountain, Utah | 39.72 | -113.22 | 126 |
| Fly Ranch, Hualapai Flat, Gerlach, NV | 40.83 | -119.33 | 59 | St. George Basin, Utah | 37.05 | -113.53 | 127 |
| Hawthorne, Nevada | 38.54 | -118.66 | 60 | Twin Peaks, Utah | 38.74 | -112.75 | 128 |
| Humboldt House - Rye Patch, Nevada | 40.55 | -118.25 | 61 | | | | |
| Jersey Valley, Nevada | 40.20 | -117.48 | 62 | Baker Mountain, Washington | 48.76 | -121.81 | 129 |
| Kyle Hot Springs - Granite Mountain, NV | 40.36 | -117.90 | 63 | Ohanapecosh, Washington | 46.66 | -121.51 | 130 |
| Leach Hot Springs-Grass Valley, NV | 40.55 | -117.61 | 64 | | | | |
| MacFarland Hot Springs, Nevada | 40.01 | -118.77 | 65 | Cody, Wyoming | 44.50 | -109.00 | 131 |
| McCoy, Nevada | 39.85 | -117.53 | 66 | Laramie, Hanna & Shirley Basins, WY | 42.40 | -106.45 | 132 |
| Moana -Steamboat Springs, Nevada | 39.39 | -119.76 | 67 | Yellowstone National Park, Wyoming | 44.46 | -110.44 | 133 |

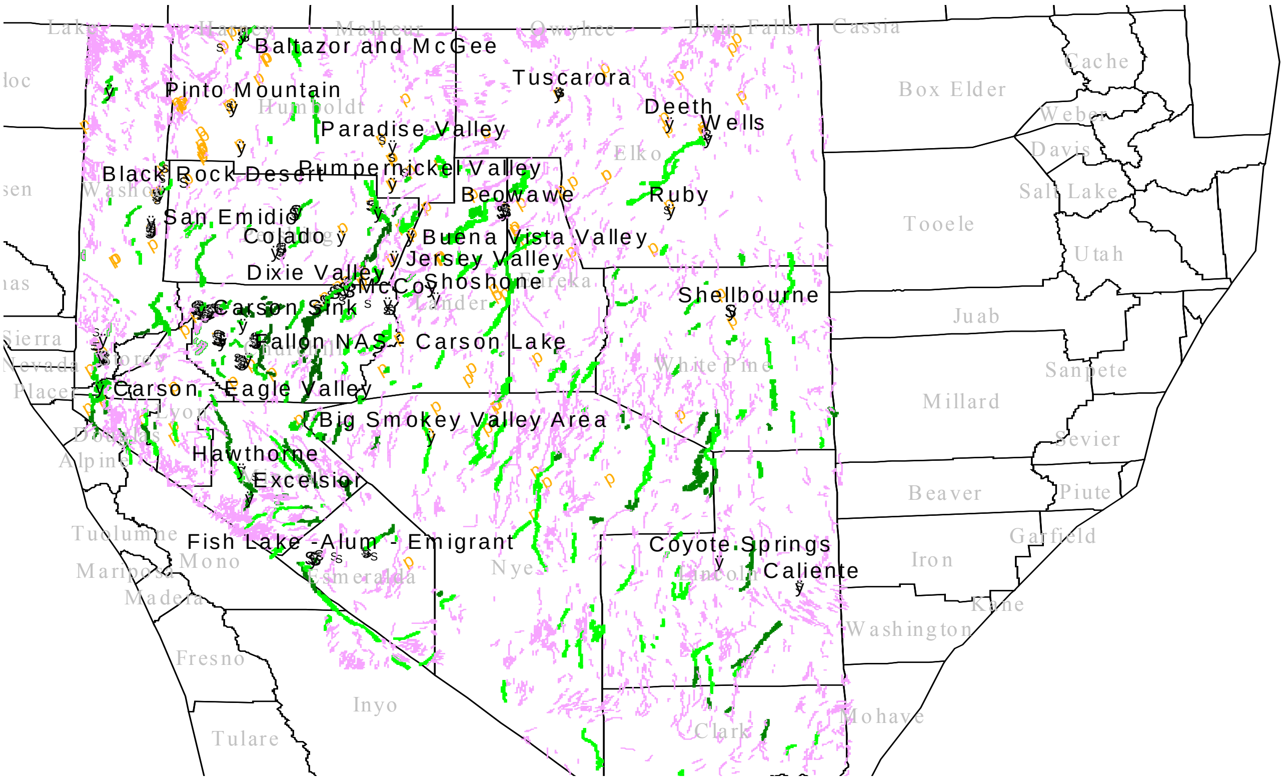


**Figure 2.** The faults are shown as lines of varying thickness and color. The lighter (pink) the line the younger the fault, starting with Historic and the darkest (green) lines represent Late Pleistocene faults. The circles represent gradients with the hottest ones are largest. Geothermal springs are represented by a dot with a tail (golden color).

# DEVELOPMENT AND APPLICATION OF 3-D SEISMIC IMAGING METHODS FOR GEOTHERMAL ENVIRONMENTS

M. Feighner, E.L. Majer, R. Gritto, and T.M. Daley
Lawrence Berkeley National Laboratory

## KEY WORDS

Seismic imaging, 3-D reflection imaging, geophysics

## PROJECT BACKGROUND AND STATUS

As part of DOE's program in geothermal research, Lawrence Berkeley National Laboratory (LBNL) has been cooperating with The Industrial Corporation (TIC) and Transpacific Geothermal Inc. (TGI) to evaluate and apply modern state-of-the-art seismic imaging methods for geothermal reservoir definition.

The overall objective of the work was to determine if modern off-the-shelf techniques in three-dimensional surface seismic profiling could be successfully applied in geothermal environments. If not, could they be modified to derive useful information on reservoir structure. Past efforts using 2-D seismic reflection have proved marginally successful in some cases but due to extreme heterogeneity in many geothermal areas 2-D seismic has not been cost effective.

The region chosen to test these techniques was the Rye Patch field in Northern Nevada. Initial geothermal exploration efforts in the area in the late 1980s and early 1990s resulted in one successful well (44-28); the other wells were either too cold or had not enough fluid flow. In 1997 TGI proposed a 3-D seismic survey to determine the geologic structure on the (hypothesized) fault-controlled reservoir. This would possibly be the first application of the 3-D seismic method to a geothermal field and therefore of interest to the entire geothermal community.

Although the 3-D seismic method has proven an integral part of modern oil and gas exploration efforts, the heterogeneous and hydrothermally altered nature of geothermal reservoirs makes all seismic imaging more difficult. It was not known how well the methods routinely used in the petroleum industry could be transferred to the geothermal environment.

Before conducting a full-scale 3-D survey, however, DOE contracted LBNL to investigate the reflectivity of the target zone in order to assess the viability of reflection seismic imaging in the Rye Patch area. Therefore in December 1997, LBNL obtained a vertical seismic profile (VSP) in well 46-28 (see Figure 1) to determine the seismic reflectivity in the area and to obtain velocity information for the design and processing of the proposed 3-D seismic survey (Feighner et al., 1998). Because the results of the VSP indicated apparent reflections, TGI proceeded with the collection of 3.0 square miles of 3-D surface seismic data over the Rye Patch reservoir in July of 1998. In FY-1999 the effort focused on processing and interpreting the 3-D seismic data as well as transferring the results to the industry for application.

## RESEARCH RESULTS

The 3-D surface seismic survey was conducted to provide as much resolution (50 foot-bin sizes) in order to explore in as much detail as possible the structure of the Rye Patch geothermal reservoir. It was assumed that relatively small elements (i.e., fractures, faults) are important features controlling the productivity of the reservoir.

The receiver group interval was 100 feet and the receiver line spacing was 800 feet. The source interval was 100 feet, while the source line spacing was 400 feet. The sources were comprised of four vibrator trucks arranged in a box array. A variety of array tests and noise tests were performed before the survey was conducted to optimize the acquisition parameters. The seismic processing involved, among other steps, the picking of over 700,000 of the possible 1 million traces to determine first arrival travel time, normal move out correction, 3-D stack, deconvolution, time migration, and depth conversion.

The seismic processing included field statics to smooth sudden changes in elevation, followed by a bandpass filter and automatic gain control. Stacking velocities were picked for several horizons. After normal move-out correction and 3-D stack, a coherency filter was applied to the stacked data to enhanced the strength of the weak reflectors. This was followed by a time migration using smoothed stacking velocities that were shifted to the final datum of 4735 feet above sea level. The time data was finally converted to depth using 103 % of the VSP velocities. These VSP velocities provided a match between the top of the clastic unit (the feature identified in the VSP data to be a good reflector) on the VSP and the center of the wavelet on the reflection data.

Using the VSP velocities to convert from time to depth was appropriate at the well; however, the velocities certainly change with distance away from the well. Therefore, the calculated depths away from the well are only approximate and the uncertainty could easily approach several hundreds of feet. The only other alternative would have been to use a percentage of the stacking velocities. However, the stacking velocities would have been unreliable for depth conversion and we believe the resulting errors in depth would have been much greater than using the extrapolated VSP velocities. Additional VSP wells would have been useful in adding control to the depth conversion process and we would recommend this for future 3-D seismic surveys in geothermal areas

***Travel Time Tomography***

From the beginning of the project it was believed that 3-D heterogeneity in the near surface and the subsurface due to tectonic activity and hydrothermal alteration would combine to reduce the effectiveness of standard 3-D seismic processing. The goal to understand the near-surface heterogeneity led us to attempt tomographic analysis using first arrival times. These times represent a 3-D experiment independent of the Common Midpoint (CMP) reflection processing, one which probes the shallow region of the reservoir. Before analysis could begin the first arrival travel time data set had to be constructed. Since standard industry automatic time picking algorithms could not be applied, it was decided to hand-pick the first arrivals in the seismic data.

The original idea of a 3-D data volume of estimated P-wave velocities throughout the survey area had to be abandoned because of the nature of the survey geometry and the data acquisition process. While all 12 receiver lines had 87 or more receivers in the north-south direction, there were only 12 receiver lines in the east-west direction. This geometry prevents any reasonable resolution of inversion estimates in the E-W direction. Furthermore, only the four nearest receiver lines in the immediate vicinity of the source locations recorded these shots. Therefore, only the lines in the N-S direction were processed, and 2-D ray tracing and travel time inversions were performed along these lines.

An initial velocity model which resembled the estimated velocity profile of the VSP survey was created. The 2-D ray-tracing algorithm is based on the shooting method, while the inversion uses a back projection algorithm. Although inversions were done for all 12 receiver lines, reliable results were only obtained for few of them. Clear first-arrival energy for intermediate distances was missing in the data of most lines. This lack of first-arrival time picks results in poor ray coverage at intermediate depth. Since the ray coverage was always poor for depths below 1500 ft, the missing time picks limited reliable velocity estimates to the upper 500 feet.

## DISCUSSION AND CONCLUSIONS

The 3-D seismic reflection data provided interpretable results for a depth range below 500 ft, whereas the tomographic travel time inversion produced reliable results down to 500 ft only. The first notable result of the 3-D seismic processing is that neither refraction nor reflection static corrections helped to increase the data quality. The refraction static processing was unsuccessful because near-offset first-break arrivals were weak and could not be determined for most shots locations. On the other hand, the target horizon for reflection statics (the clastic unit at depth) revealed incoherent reflections throughout the receivers lines, likely caused by faulting throughout the reservoir area. However, estimating correct surface statics could improve the Common Depth Point (CPD) image.

The depth mapping of the time migrated data was based on velocity values equal to 103 % of the VSP velocities. This approach lined up the reflection of the clastic unit in the VSP and reflection data at depth. However, these velocities are only valid in the vicinity of the VSP well, and have to be extrapolated at greater distance from it. We still feel that this method is more exact than using stacking velocities, which are questionable due to the lack of horizontal continuity of the reflectors at depth. An interpreted section of the 3-D results is shown in Figure 2.

The travel time tomography results indicate a possible graben structure along crossline 93, bound by two faults to the South and North. This interpretation is partially supported by the reflection seismic results, which indicate the presence of the southern fault of the hypothetic graben structure. The lack of first-arrival energy from the far offset shots in the shadow of the graben structure supports the tomography results as the graben faults may inhibit the waves on their propagation across this feature.

## FUTURE WORK

This initial attempt at using 3-D seismic techniques in geothermal environments is very encouraging, especially considering the geologic characteristics of the Rye Patch area and the fact that rather standard industry practices were used. Future work will concentrate on using less standard but still commonly available techniques for complex media. Current technology and research in the oil-and-gas sector aimed at naturally fractured rock could possibly provide a large base to work upon for geothermal environments. It is clear that the highest resolution methods will be required for successful geothermal application, thus implying coupling with borehole methods such as VSP, crosswell and single well.

## INDUSTRY & TECHNOLOGY

The project has been a joint effort with The Industrial Corporation and Trans-Pacific Geothermal Inc. The results are currently being used for locating a new well in the Rye Patch geothermal field.

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## CONTACTS

Marshall Reed
Office of Geothermal and Wind Technologies, EE-12
U.S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076 e-mail: marshall.reed@hq.doe.gov
Fax: (202) 586-8185

Ernie L. Majer Phone: (510) 486-6709 e-mail: elmajer@lbl.gov
Roland Gritto Phone: (510) 486-7118 e-mail: rgritto@lbl.gov
Thomas M. Daley Phone: (510) 486-7316 e-mail: tmdaley@lbl.gov
Earth Sciences Division Bldg. 90-1116
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Fax: (510) 486-5686

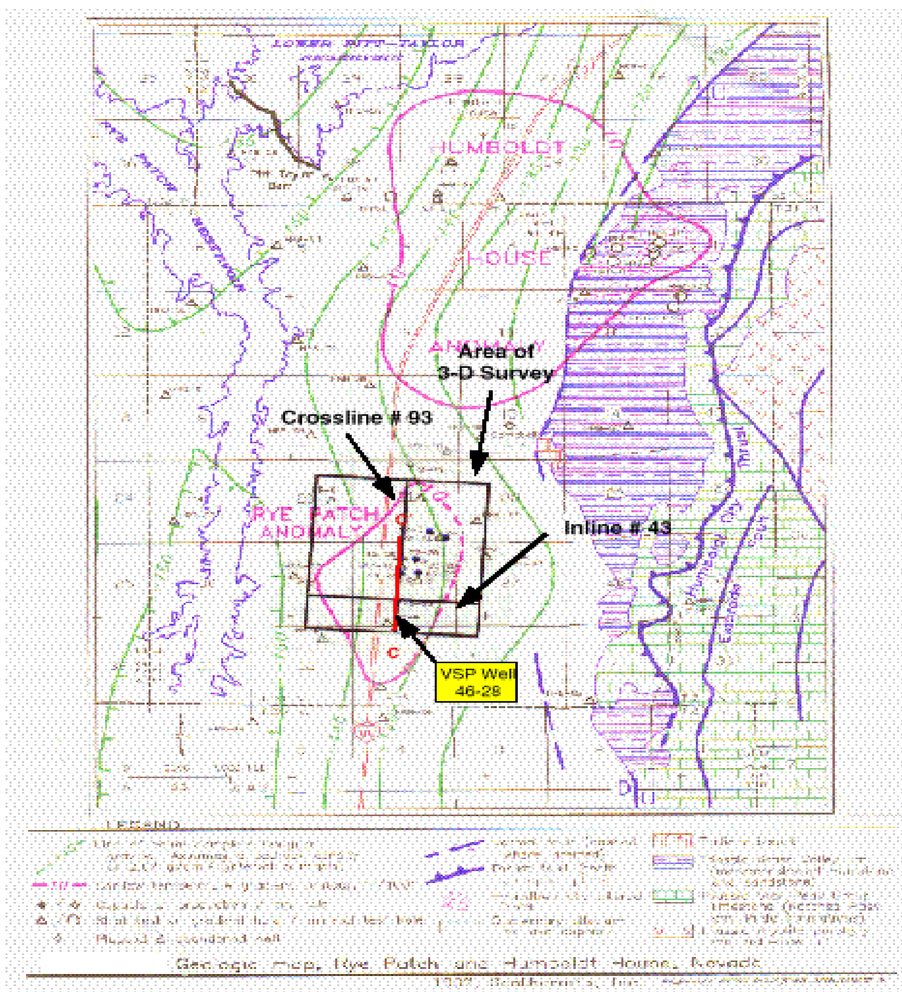


**Figure 1.** Location of the Rye Patch geothermal field with the area of the 3-D survey indicated by the black square. The VSP well 46-28 is located within the Rye Patch anomaly.

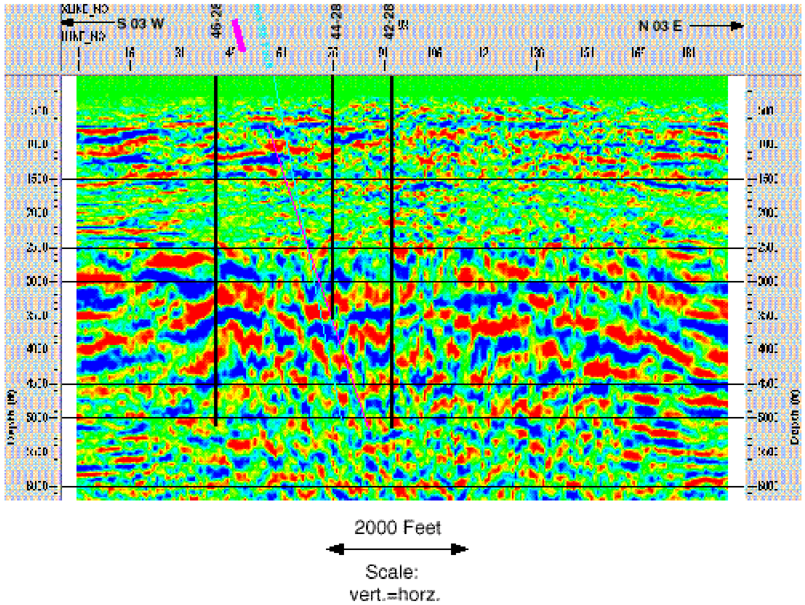


**Figure 2.** Interpreted North-South section (C-C' in Figure 1) across the Rye Patch field. In general, the clastic unit has poor reflectivity in the area of interest around the production well. The unit is more coherent to the South and appeared to terminate just North of VSP Well 46-28. This discontinuity is generally very distinct on many north-south crosslines and could be the location of a reservoir fault. This fault has been interpreted from the seismic data (GeothermEx, 1997 SE Fault) in conjunction with a second interpretation (SE Fault, after Teplow, 1999). The figure shows a final migrated depth section (crossline 93). The boreholes and the fault interpretations are superimposed for reference purposes.

# GEOTHERMAL CHEMISTRY, EXPLORATION and RESERVOIR PROCESSES

Fraser Goff
Los Alamos National Laboratory

Cathy J. Janik
U.S. Geological Survey

## KEY WORDS

Fluid geochemistry, water composition, gas composition, isotope composition, Dixie Valley geothermal system, The Geysers-Clear Lake geothermal region, reservoir models, scaling, recharge, $CO_2$ flux.

## PROJECT BACKGROUND AND STATUS

The current project, which has been ongoing since FY91, provides expertise on geothermal exploration and reservoir processes and provides chemical analyses, bulk gas analyses, and selected isotope analyses for several interagency, DOE geothermal efforts. During FY99, we worked on projects in Dixie Valley (NV), Steamboat Springs (NV), The Geysers-Clear Lake region (CA), the Cheyenne River Sioux Reservation (SD), and Awibengkok (Indonesia), and provided analyses for private contractors concerned with geothermal resource assessment in the international arena. In FY99, the total number of chemical and isotopic analyses obtained by our laboratories exceeded 450. We collaborated with Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, Earth and Geosciences Institute, Oxbow Power Services, Inc., Calpine Geothermal Corp., Caithness Power, Inc., the US Environmental Protection Agency, NRECA, Geothermal Management Company, and the US Bureau of Indian Affairs.

FY99 highlights included continuation of a series of investigations at Dixie Valley to: 1) evaluate fluid origins and rates of recharge to the geothermal system; 2) determine origin, dimension, and growth-rate of a new fumarolic area north of the power plant (the “dead zone”); and 3) monitor temporal geochemical changes in production fluids. Within The Geysers-Clear Lake region, we 1) continued our investigation of increased fumarolic activity in thermal manifestations at Anderson Springs; 2) continued our gas flux and mercury transport studies at Sulphur Bank Mine; and 3) produced reports on gas compositions from The Geysers geothermal field. At the request of the US BIA, we performed a one-time assessment of low-temperature resource potential at the Cheyenne River Sioux Reservation. We contributed to a study of hydrothermal breccias at Awibengkok geothermal system, Indonesia. We organized an upcoming special issue of Chemical Geology on $CO_2$ flux in geothermal and volcanic environments. We published our results in several venues and contributed an invited chapter on “Geothermal Systems” for the reference book Encyclopedia of Volcanoes.

## PROJECT OBJECTIVES

This project produces and uses geochemical data to infer the structure of geothermal reservoirs, estimate subsurface temperatures, and identify processes that cause temporal changes in fluid compositions. Our primary objectives are to: 1) provide comprehensive major/trace element analyses, bulk gas analyses, and isotope analyses of fluids, dissolved constituents, and minerals on samples collected for geothermal projects sponsored by the U.S. Department of Energy; 2) provide geothermal/geochemical exploration, modeling, and monitoring expertise for the above projects as required.

***Technical Objectives***

- Complete study of regional recharge to the Dixie Valley geothermal system.

We have systematically collected samples of streams, cold and thermal springs, domestic wells, irrigation wells, and exploration wells in Dixie Valley, adjacent valleys, and surrounding mountains during two fiscal years to determine sources and ages of reservoir fluids. We have completed the following analyses on three suites of samples from about 50 sites around the region: bulk chemistry, water isotopes, some tritium, $^{18}O$ of dissolved $SO_4$, $^{13}C$ of dissolved inorganic carbon (DIC), $^{14}C$ DIC, $^{36}Cl$, $Sr^{87/86}$, and U-Th disequilibrium. Our contributions to this research were presented at the 1999 GRC annual meeting which won a Best Paper Award (Nimz et al., 1999).

- Complete study of $CO_2$ flux and temperature distribution in the Dixie Valley "dead zone."

In-situ measurements of soil $CO_2$ have greatly progressed since the invention of portable devices that report real-time concentrations and fluxes of this important diagnostic gas. At Dixie Valley, a new zone of fumarolic activity and plant kill formed in 1996, between the Stillwater Fault and the northern section of the geothermal field. In FY98 we began monitoring temperature, $CO_2$ concentrations and flux in this zone to determine its dimension, growth-rate and seasonal variation (Bergfeld et al., 1998; Bergfeld et al., in prep.). Discussions with other scientists and technical experts were initiated on the problem of $CO_2$ flux measurements in geothermal and volcanic environments. We organized a Special Session at the December 1998 Fall Meeting of AGU (FY99) to bring together national and international scientists to explore this issue. From this we organized a special volume of the journal Chemical Geology to publish research results on this topic.

- Complete study of temporal variations in production-fluid chemistry, Dixie Valley.

The Dixie Valley geothermal field has been operational since 1988. Injection of spent brine began shortly after production commenced and has been continuing to present. Over the lifetime of the field, the production-fluid composition has significantly increased in chloride and heavy water isotopes and decreased in noncondensible gas concentrations, indicating co-production of injectate. Returning injectate will eventually cool the reservoir. It is therefore necessary to quantify the volume of injectate co-produced with the indigenous reservoir fluid and the rate at which this volume increases in order to predict the likelihood or onset of cooling. Fluid chemistry is more sensitive than temperature to the emergence of injectate in production fluids. In FY98 and FY99 fluids were collected from production and injection wells to perform comprehensive chemical and isotopic analyses. Data obtained were compared with data provided by Oxbow on samples collected from 1986 (pre-production) through 1996 in order to evaluate the present reservoir conditions. We contributed to a report on quantification of injection returns (Kennedy et al., 1999).

- Continue our investigations of rapid physical changes at the Anderson Hot Springs area, Southeast Geysers.

Rapid temperature increases in existing springs, formation of new fumaroles, tree kill areas, and changes in gas flux and composition document possible links between surface geothermal features and the subjacent vapor-dominated geothermal reservoir. Some members of the village of Anderson Springs have raised questions concerning environmental impacts (Goff and Janik, 1999; Janik et al., 1999).

- Continue our investigations of gas and mercury flux from the Sulphur Bank Mine geothermal system.

Sulphur Bank Mine contains a subjacent geothermal reservoir (215°C) that has not been commercialized for several reasons. Historically, SBM has been the 6th largest mercury mine in the US. It is located on the shore of Clear Lake, the largest fresh-water lake wholly contained within California. SBM became a Superfund Site in the early 1990s. The US EPA wants our research on gas and Hg flux at SBM to continue so that they can formulate an appropriate environmental model and remediation plan for the site.

- Publish data reports on the chemistry and isotopic composition of gases from The Geysers steam wells (Lowenstern et al., 1999a; 1999b).

- Provide a one-time geothermal assessment of the Cheyenne River Sioux Reservation (SD).

The reservation contains several deep geothermal aquifers that have been tapped by water and oil wells. Because the local economy is depressed, the US BIA requested that we provide an evaluation of the geothermal potential. We published a report on geothermal potential in the reservation, which won a Best Paper Award at the 1999 annual GRC meeting (Bergfeld et al., 1999).

- Contribute to a report on hydrothermal breccias in the Awibengkok geothermal system, Indonesia (Hulen et al., 1999).

- Provide high-quality analyses and data interpretations for DOE-sponsored geothermal projects on sites of interest in Bolivia, Peru, Argentina, and the Caribbean.

- Publish chapter on Geothermal Systems for Encyclopedia of Volcanoes (Goff and Janik, 2000). Publish other results as listed.

- Supervise the Ph.D. project of D. Bergfeld (University of New Mexico).

Ms. Bergfeld has now completed a paper on $CO_2$ systematics in The Geysers-Clear Lake region and is writing papers on $CO_2$ flux at Dixie Valley and Sulphur Bank Mine to complete her dissertation requirements (Bergfeld et al., in press; in prep.).

***Expected Outcomes***

- Perform chemical and isotopic analyses for DOE-sponsored projects. The analyses are necessary to understand fundamental reservoir parameters and processes.

- Contribute to international geothermal exploration that may identify energy sources for under-developed countries in need of electricity.

- Research the effects of natural geothermal processes and manmade geothermal developments on ecosystems and drinking water.

- Complete the special volume of Chemical Geology on $CO_2$ flux measurements in geothermal and volcanic environments (primary editor: D. Bergfeld).

- Publish data reports and journal manuscripts accessible to the geothermal community.

## APPROACH

General Statement: We explore for new geothermal systems and obtain basic knowledge of existing systems using geochemical methods. We collect and analyze fluids and minerals to characterize regional and reservoir fluid properties, define boundary conditions such as reservoir age and fluid sources, and determine if newly explored sites justify exploration drilling. In developed fields, we determine processes related to fluid extraction and injection, model scaling/corrosion potential, evaluate parameters that affect reservoir productivity and lifetime, and provide geochemical insights to help manage resources and improve reservoir performance (energy output). Our work provides the US geothermal community with data and interpretations that aid in making development and environmental policy decisions, increasing domestic profits and improving the competitive edge abroad.

Dixie Valley Investigations: We are completing three geochemical investigations at Dixie Valley: 1) monitor changes in chemical and isotopic compositions of production fluids to identify reservoir processes; 2) determine reservoir fluid origins, age, and rate of recharge; and 3) determine dimensions, growth-rate, and source of a zone of plant kill and fumarolic activity north of the power plant. Two sampling trips were conducted in FY99.

> **Note:** We are working cooperatively with Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, and Energy Geosciences Institute on the Dixie Valley projects. We do not expect problems now that ownership of the field has been transferred from Oxbow Power Services, Inc., to Caithness Power, Inc.

$CO_2$ flux measurements: This new domain of research uses portable instruments to obtain real-time data on $CO_2$ concentration and flux. We have conducted studies at The Geysers-Clear Lake area (Bergfeld et al., in press) and are completing an investigation at Dixie Valley (Bergfeld et al., 1998; in prep.) to determine the practicalities and potential of these methods for geothermal exploration and monitoring. A special volume of Chemical Geology (to be published in late FY2000) will be devoted to this research topic.

The Geysers-Clear Lake region: In late FY99, we received inquiries about possible changes in thermal manifestations around Anderson Springs, located near the Southeast Geysers geothermal field. We conducted a literature search and reviewed our own data files, which revealed that the temperature of Anderson Spring ranged from 42 to 63°C between 1889 and 1992, but measured about 77°C in 1995. When we returned in September 1998 to investigate the area, we measured boiling temperatures (about 99°C) and identified a new fumarole area, and collected samples for chemical and isotopic analysis. We initiated dialogue with local residents and contacted Calpine Corporation for further information to determine the cause and significance of these observations. As of late 1999, the fumarole area had slightly expanded and had apparently killed nearby trees (Goff and Janik, 1999; Janik et al., 1999).

We also have been continuing our $CO_2$ and Hg flux research at the Sulphur Bank Mine Superfund Site in conjunction with the US EPA. We conducted one sampling trip in FY99. They need a geothermal model to appropriately remediate this Superfund Site.

## RESEARCH RESULTS

Dixie Valley Recharge: Chemical and isotopic analyses of Dixie Valley regional waters indicate several distinct groups ranging in recharge age from Pleistocene (<20 ka) to recent (<50a). Valley groundwater is older than water from perennial springs and artesian wells in adjacent ranges, with Clan Alpine range (east) much younger (<50a) than Stillwater range (west; most >1000a). Geothermal reservoir fluids (~12 to 14 ka) are derived from water similar in composition to non-thermal groundwater observed today in valley artesian wells (also ~14 ka). Geothermal fluid interaction with Jurassic mafic rocks (Humboldt Lopolith) appears to be common, and significant reaction with Cretaceous granodiorite may also occur. Despite widespread occurrence of Paleozoic carbonate rocks, large-scale chemical interaction appears minor. Age differences between the ranges, more extensive interaction with deep-seated waters in the west, and distribution of springs and artesian wells suggest the existence of a regional upward hydrologic gradient with an axis in proximity to the Stillwater Range (Nimz et al., 1999).

Dixie Valley "Dead Zone:" A map of the $CO_2$ flux across the newly formed area of plant kill and hot ground in the NW part of the Dixie Valley geothermal system was constructed to monitor potential growth of a fumarole field. Flux measurements were recorded using a LiCor infrared analyzer. Sample locations were restricted to areas within and near the dead zone. The data delineate two areas of high $CO_2$ flux in different topographic settings. Older fumaroles along the Stillwater Range front produce large volumes of $CO_2$ at temperatures near boiling. High $CO_2$ flux values were also recorded at sites along a series of recently formed ground fractures at the base of the dead zone. The two areas are connected by a zone of partial plant kill, moderate $CO_2$ flux, and elevated temperatures on an alluvial fan. Results from this study indicate a close association between the range front-fumaroles and the dead-zone fractures (Bergfeld et al., 1998; in prep.).

Dixie Valley Reservoir Variations: Chemical, stable isotope, and noble gas data can be used to quantitatively assess the recycling of injectate fluids. In the Sec. 7 area there is an apparent continuous recycling of injectate, increasing at 5 to 7 % per year. Currently, the Sec. 7 wells produce fluid that is between 60 and 100% recycled injectate, which when combined with the total volume of fluid injected provides an estimate of the circulating fracture volume (~0.12 $km^3$). In the Sec. 33 area, chloride concentrations increased over the first four years of production suggesting that as much as 60% of the produced fluid was recycled injectate. Since then chloride has steadily decreased, such that currently only 37% of the production fluid can be recycled injectate (Kennedy et al., 1999).

The Geysers-Clear Lake region:

We published our preliminary observations and data concerning physical and chemical changes at Anderson Springs (Goff and Janik, 1999; Janik et al., 1999).

We contributed to publication of a database on gas geochemistry at The Geysers steam field (Lowenstern et al., 1999a; 1999b).

Three Geothermics manuscripts summarizing carbon isotope systematics, thermal modeling, and K-Ar dating of illites in the region are in press (Bergfeld et al., 2000; Stimac et al., 2000; and WoldeGabriel et al., 2000).

Cheyenne Sioux Indian Reservation:

A report on low-temperature geothermal potential of the reservation was published (Bergfeld et al., 1999).

Awibengkok, Indonesia:

A paper on hydrothermal breccias in the Awibenkok geothermal system was published (Hulen et al., 1999).

Book Chapter, Geothermal Systems:

An invited review was published in the Encyclopedia of Volcanoes (Goff and Janik, 2000).

## FUTURE PLANS

In FY2000 we will complete our various collaborative investigations of the Dixie Valley geothermal system, as described above. The results will be used to: 1) complete models of scaling processes and to offer solutions for preventing scaling and corrosion, 2) determine indigenous reservoir-fluid origins and age, and 3) evaluate the effects of injection and production (joint studies, LANL - USGS - LLL- LBL - EGI - Oxbow Power Services, Inc.). Data will be made available to collaborators; results and interpretations will be presented at appropriate scientific meetings and published in suitable journals.

In FY2000 we will: 1) continue our investigations on environmental impacts of two geothermal systems in The Geysers-Clear Lake region; 2) analyze geothermal fluid samples from other DOE-sponsored geothermal sites, as required; 3) publish a special volume on $CO_2$ flux in volcanic and geothermal environments in Chemical Geology, and 4) complete a journal article summarizing geochemistry of magmatic, metamorphic, and connate fluids in The Geysers-Clear Lake region.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER (1997 to present)

| Organization | Type and Extent of Interest |
|---|---|
| Caithness Power, Inc. | Modeling/tracer studies, Steamboat Springs |
| Calpine Corporation | The Geysers-Clear Lake studies |
| Geothermal Management Co. | Analyses for Caribbean and Latin America |
| NRECA | Analyses for Latin America |
| Oxbow Power Services, Inc. | Active participation in Dixie Valley studies |
| SB Geo, Inc. | Modeling/tracer studies, Steamboat Springs |
| Southwest Tech. Devel. Inst. | Analyses for Fort Bliss geothermal project |
| Union Geothermal Co. | Permission to use data/cores |
| Bureau of Indian Affairs | Cheyenne Sioux Indian Reservation |
| Environmental Protection Agency | Geochemistry of Sulphur Bank Mine |

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## CONTACTS

Dr. Marshall Reed
Geothermal Division, EE-122
US Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Tel: (202) 586-8076
Fax: (202) 586-8185
e-mail: marshall.reed@ee.doe.gov

Fraser Goff
EES-1, MS D462
Los Alamos National Laboratory
Los Alamos, NM 87545
Tel: (505) 667-8060
Fax: (505) 665-3285
e-mail: fraser@lanl.gov

Cathy J. Janik
US Geological Survey, MS 910
345 Middlefield Rd.
Menlo Park, CA 94025
Tel: (650) 329-5213
Fax: (650) 329-5203
e-mail: cjanik@usgs.gov

# ISOTOPE GEOCHEMISTRY IN GEOTHERMAL RESEARCH

B. Mack Kennedy
Lawrence Berkeley National Laboratory

Donald J. DePaolo
Department of Geology and Geophysics
University of California, Berkeley

Alfred H. Truesdell
Consultant

## KEY WORDS

Magmatic, acid, and re-injected fluids; noble gases; isotopes; heat; Dixie Valley; Imperial Valley; Tongonan, Mahanagdong and Mt. Apo, Philippines; Tibet; The Geysers.

## PROJECT BACKGROUND AND STATUS

*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.

*Acid Fluids:* An important factor in reservoir management and development is the origin, evolution, and distribution of corrosive acid fluids in geothermal systems. Fluids encountered in Philippine geothermal fields have a wide range of chemical compositions, some if which are highly acid. 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. Because 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), the origin and location of acid reservoir fluids is of international economic interest. 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 Philippine and U.S. governments to understand and anticipate the occurrence of these fluids. This joint research project and continuing cooperation by the research team will contribute to these objectives.

*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 $^{4}He$ 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.

*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.

## PROJECT OBJECTIVES

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.

### *Technical Objectives*

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

- *Acid Fluids:* Develop a better understanding of the origin and fate of acid fluids.

- *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.

- *Flow in Fractured Reservoirs:* Expand models describing the flow and fate of phase partitioning tracers in fractured reservoirs.

### *Expected Outcomes*

- *Natural Injectate Tracers:* Provide reliable and sensitive quantitative assessments of (1) the volume of co-produced injectate and (2) the rate re-injected fluids are replacing an original reservoir fluid. The ultimate goal is predicting when and where thermal breakthrough will occur.

- *Acid Fluids:* Develop a better understanding of the origin and fate of acid reservoir fluids common to most Philippine geothermal fields.

- *Helium and Heat:* Identify the relative proportions of heat in geothermal systems derived from crustal and magmatic sources. Identify heat sources in moderate to high temperature geothermal systems that are not closely associated with recent volcanism. Develop heat and helium coherence as a potential exploration tool. Use the coherence of heat and helium to further our understanding of heat and volatile extraction from cooling magmas.

- *Flow in Fractured Reservoirs:* Exploit 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.

## APPROACH

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.

## RESEARCH RESULTS

*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 (e.g. Benoit, 1992). 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, and (4) an estimate of the reservoir volume (Kennedy et al., 1999).

*Acid Fluids:* The goal of this part of the project is to develop a better understanding of the origin and fate of acid fluids common to most Philippine geothermal fields associated with recent andesitic volcanoes. As part of our initial survey of Philippine geothermal systems, we have found an interesting correlation between helium isotopic compositions, helium enrichment factors, and well locations. In collaboration with scientists from the PNOC, we have been evaluating a potential 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 are pursuing this co-variation and its significance.

*Helium and Heat:* Because ~75% of the Earth's heat budget and all of the $^4$He is produced from natural U and Th radioactivity, theoretically there should be a well-defined $^4$He to heat production ratio ($^4$He/Q) of ~$3.7 \times 10^{-8}$ cm$^3$STP/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 $^3$He/$^4$He 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 ~$0.5 \times 10^{-12}$ $cm^3$STP/Joule. It has been demonstrated by others that the $^3He/Q$ ratios in fluids circulating through mid-ocean ridge spreading centers vary from ~$0.1\text{-}1 \times 10^{-12}$ $cm^3$STP/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 ~$1 \times 10^{-15}$ $cm^3$ STP/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).

*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 $25^{th}$ Stanford Workshop on Geothermal Reservoir Engineering (Pruess et al., 2000).

## FUTURE PLANS

*Natural Injectate Tracers:* Recently we collected another field wide suite of samples from Dixie Valley production wells and injection lines. Analyses of these samples will provide our first time series look at the proportion of co-produced injectate as determined from noble gas abundances. We will also explore the source of excess helium in the Dixie Valley production fluids. Presently, the production fluids are ~75% injectate. The measured injection fluids do not contain any significant helium excess relative to the other noble gases. However, excess helium persists in the production fluid. Two possible sources include (1) continued flow of helium-enriched deep thermal fluids into the production reservoir or (2) helium is added to the injected brine trough water-rock interaction while flowing from the injection point to the reservoir. In the first case, helium excesses can be used to estimate the flux of indigenous fluid into the reservoir. In the second case, helium excesses may be used to constrain the surface area of water-rock interaction along the flow path of the re-injected brine.

*Acid Fluids:* This project, as applied to the Philippine geothermal systems, is still in the early interpretive stage. We will continue to evaluate potential correlations between noble gases, solute chemistry, and fluid acidity. We are also working on quantifying the proportion of injectate that is currently being co-produced and mapping the injectate distribution relative to the known zones of high acidity. Observed co-variation between helium isotopic composition and heat/helium ratios suggests a relationship between neutralization and/or distribution of acid fluids and the relative proportion of co-produced injectate.

*Helium and Heat:* We plan to continue developing our understanding of the inherent coherence between helium isotopic composition and the source of heat in geothermal systems and those processes responsible for the fractionation of heat from helium and other volatile species ($CO_2$, $H_2S$, etc.). One goal is to identify the relative proportions of heat in geothermal systems derived from crustal and magmatic sources. This is of particular interest in moderate to high temperature geothermal systems that are not closely associated with recent volcanism, such as encountered in the Basin and Range in the U.S. and along the Tibetan Suture Zone (e.g. the Yangbajing Field, Tibet). A second goal is to develop heat-helium coherence into a new geothermal exploration tool.

*Flow in Fractured Reservoirs:* Continue development of models describing the flow and fate of phase partitioning tracers in fractured reservoirs. This project is in the early stages and needs further work and refinement. One future objective is to add new tracers to the code that are selected specifically to optimize different transport efficiencies resulting from solubility differences. The divergence of tracer behavior can be expected to provide sensitivity to the transport models.

*New Project:* We will conduct a field wide study of noble gas, Sr, C, H, and O isotope compositions in the CalEnergy Salton Sea, California geothermal. This project will be carried out under the coordination of Will Osborne of CalEnergy.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| CalEnergy Corporation | Origin and distribution of fluid types in Salton Sea geothermal systems. |
| Unocal | Sources and potential for production of chemically hostile fluids in geothermal systems closely associated with active volcanoes. |
| Oxbow Energy Co. | Origin of heat, size of resource, and injectate return. |
| Philippine National Oil Co. (PNOC) | Origin, distribution, and fate of acidic reservoir fluids. |

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## CONTACTS

Marshall Reed
Office of Geothermal and Wind Technologies
U.S. Department of Energy, EE-12
Washington, DC 20585
Phone (202) 586-8076
Fax (202) 586-8185
e-mail: marshall.reed@hq.doe.gov

B. Mack Kennedy
Lawrence Berkeley National Laboratory
Earth Sciences Division, MS 70A-3363
Berkeley, CA 94720
Phone: (510) 486-6451
Fax: (510) 486-5496
E-mail: bmkennedy@lbl.gov

Donald J. DePaolo
Department of Geology and Geophysics
University of California
Berkeley, CA 94720
Phone: (510) 643-5063
Fax: (510) 486-5496
E-mail: djdepaolo@lbl.gov

Alfred H. Truesdell
700 Hermosa Way
Menlo Park, CA 94025
Phone: (650) 322-6135
Fax: (650) 324-4009
E-mail: ahtruesdell@lbl.gov

# BEHAVIOR OF RARE EARTH ELEMENTS IN GEOTHERMAL SYSTEMS: A NEW EXPLORATION/EXPLOITATION TOOL?

William Shannon
Scott A. Wood
Department of Geology and Geological Engineering
Box 443022
University of Idaho, Moscow, ID 83844-3022

Kevin Brown
Geothermal Institute
University of Auckland
Private Bag 92109
Auckland, NZ

Greg Arehart
Department of Geological Sciences
University of Nevada, Reno
Reno, NV 89557-0138

## KEY WORDS

Rare earth elements, geochemistry, geothermal systems, New Zealand, California, Nevada, Oregon, exploration, water-rock interaction

## PROJECT BACKGROUND AND STATUS

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 this 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.

Until recently, relatively few studies had been conducted on the behavior of the REE in geothermal fluids. The REE concentrations in these fluids are comparatively low, and techniques for their analytical determination were either unavailable, or prohibitively expensive and difficult to carry out. However, with continued improvements in analytical techniques, the number of studies reporting REE concentrations in both continental and seafloor geothermal fluids has increased slowly but steadily. Data on the REE in continental geothermal fluids from the Salton Sea geothermal system, California (Michard, 1989), the Valles Caldera, New Mexico (Michard, 1989), Yellowstone National Park (Lewis et al., 1994), Larderello, Italy (Michard, 1989), Japan (Honda et al., 1989a,b; Oi et al., 1990), France (Michard et al., 1987; Sanjuan et al., 1988), Bulgaria (Michard & Albarède, 1986), Tibet (Michard & Albarède, 1986), Dominica (Michard, 1989) and Idaho (van Middlesworth and Wood, 1997) have been published. However, the number of studies of REE contents in geothermal fluids remains too small to fully assess the potential of using REE contents in geothermal fluids as a potential exploration tool. Moreover, up until the study reported here, data on REE in geothermal fluids from important geothermal areas in New Zealand, the Philippines, Indonesia and the U.S. were unavailable. Finally, the controls on REE concentrations in geothermal fluids are poorly understood, and their utility to the geothermal industry has not yet been demonstrated.

This project was designed to expand the database on REE concentrations in fluids in continental geothermal systems, establish the controls on these REE concentrations, and explore their potential as a tool for the geothermal industry. The project commenced on January 1, 1998 and will terminate on September 30, 2001. We are just about at the midway point of the project as of December 1999.

## PROJECT OBJECTIVES

### *Technical Objectives*

1) Establish baseline information on REE contents in geothermal fluids from around the world.

2) Determine whether there are any distinctions in REE contents of fluids from producing or potentially producing geothermal fields on the one hand, and geothermal fields which are not economically viable on the other.

3) Establish relationships between REE contents and fluid chemistry and temperature.

4) Establish relationships between REE contents and host (aquifer) rocks.

5) Determine whether there are seasonal changes in REE geochemistry of geothermal fluids.

6) Ascertain whether REE geochemistry changes systematically over the production history of a producing geothermal field.

7) Assess the potential of aqueous REE geochemistry as an exploration tool.

### *Expected Outcomes*

1) Use of REE by the U.S. geothermal industry as an aid in exploration for new, and reservoir management of existing, economically exploitable geothermal systems.

2) An improved understanding of water-rock interactions governing liquid-dominated geothermal systems.

## APPROACH

In order to meet the above goals, we have taken samples from hot springs and geothermal wells from the following areas thus far: 1) the Taupo Volcanic Zone (TVZ), New Zealand (Wairakei, Broadlands, Rotokawa, Tauhara, Orakei Korako, Waiotapu, Waimangu, Te Kopia, Waikite and Mount Ruapehu); 2) four thermal areas outside the TVZ (Miranda, Te Aroha, Te Puia and Morere); 3) the eastern Cascades, Oregon (Bagby, Breitenbush, Bigelow, Belknap, Terwilliger, Wall Creek, McCredie, and Umpqua); 4) the Alvord Desert, Harney Basin and Owyhee Canyon areas, Southwestern Oregon (Crane, Mickey, Alvord, North and Middle Borax Lakes, White Horse Ranch, and Snively); 5) Nevada (Dixie Valley, Beowawe); 6) Salton Sea and Heber, California; and 7) Dieng, Central Java, Indonesia. We have also obtained downhole samples of geothermal fluids from the Palinpiñon geothermal field in the Philippines.

At each site, we typically measure temperature, pH, and conductivity in the field. Two one-liter samples, one filtered through a 0.45-μm membrane and the other unfiltered, are taken and preserved with 2% high-purity nitric acid for REE analysis. Two 250-mL filtered samples are also taken, one preserved with 1% trace metal grade nitric acid for boron and alkali, alkaline earth and transition metal analysis, and the other untreated for anion and alkalinity determinations. Back in the laboratory, alkalinity is determined via Gran titration, alkali, alkaline earth and transition metals, silica and boron are determined using ICP-AES, and anions ($Cl^-$, $F^-$, $Br^-$, $SO_4^{2-}$, and $PO_4^{3-}$ are determined using ion chromatography. The REE are determined by ICP-MS after separation and pre-concentration by co-precipitation with ferric hydroxide.

The analytical data for silica and the alkali and alkaline earth metals are used to obtain estimates of the temperature of last equilibration of the fluids with their aquifer rocks using chemical geothermometry. The pH, anion and alkalinity determinations are used to classify each water sampled as to type, e.g., acid-sulfate-type or neutral chloride-bicarbonate-type. Chondrite-normalized plots of the REE contents are prepared for each group of fluids. More detailed descriptions of the procedures we employ and the results obtained to date are given in Shannon and Wood (1999) and Shannon et al. (1999).

## RESEARCH RESULTS

We have obtained REE concentrations for all fluids sampled to date, except for those from Indonesia and California. Some representative data are shown in chondrite-normalized form in Figure 1. Our results indicate the following: 1) REE contents in geothermal fluids can range over at least four orders of magnitude, from below detection up to $10^{-1}$ times chondrite (e.g., Mt. Ruapehu); 2) As previously noted in the literature, pH appears to exert a dominant, first-order control on REE contents, with low-pH, acid-sulfate waters having the highest measured REE concentrations and near-neutral to alkaline chloride-bicarbonate waters having lower REE. However, within the latter category, the pH dependence is not clear, and other factors in addition to pH play important roles in determining REE content; 3) In general, the near-neutral to alkaline chloride-bicarbonate waters investigated here yield lower total REE contents than those previously reported for similar thermal waters from the vicinity of the Idaho Batholith (van Middlesworth and Wood, 1998). Potential reservoir rocks in the latter area are enriched considerably in REE, Th and U relative to average crustal rocks, and the higher REE content in the Idaho fluids may indicate a control of the nature of the reservoir rock on the REE contents of the fluids; 4) In acidic thermal waters, the concentrations of REE in filtered and unfiltered samples are approximately equal, suggesting that most of the REE are present in solution as dissolved species; 5) In many near-neutral to alkaline thermal waters, the REE contents in the unfiltered samples can be considerably higher than those in the filtered solution, suggesting that the bulk of the REE are present in particulate form. Whether the particulate fraction of the REE are present sorbed onto pre-existing particles or as precipitated REE minerals is yet to be determined; 6) There are a number of reasons to suspect that liquid-vapor phase separation (or boiling) may cause the loss of REE from solution, and this may also explain the very low REE contents measured in some thermal fluids; 7) Our data provide some support for the hypothesis that thermal fluids from producing fields with high flow rates may have lower total REE contents than thermal fluids from areas of low flow rate; 8) Neutral-chloride-type fluids have chondrite-normalized REE patterns that vary from negative to positive slopes; and 9) Neutral-bicarbonate-type fluids have chondrite-normalized REE patterns that vary from negative to relatively flat slopes.

## FUTURE PLANS

Our plans for the second half of this project include the following: 1) Resampling a number of previously sampled areas to determine whether temporal variations exist in these systems; 2) Analyzing historic samples from the Wairakei geothermal field; 3) Sampling and analyzing fluids from additional areas not covered in the first half of the project, i.e., additional areas in Washington, Oregon, Idaho, Montana, Nevada and the Philippines; 4) testing the hypothesis that the REE are lost on phase separation (by taking more downhole samples, analyzing samples of scale from geothermal wells for their REE content, and carrying out reaction-path modeling to simulate phase separation using geochemical codes such as Chiller, Reed, 1982); 5) analyzing drill core from selected geothermal fields for their REE content for comparison with the geothermal fluids; 6) conducting experimental simulations of water-rock interaction designed to elucidate the behavior of the REE during such processes; and 7) using statistical and geochemical modeling methods to firmly establish the major controls on REE concentrations in geothermal fluids.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The following companies have assisted in obtaining samples and have expressed interest in the results of this study:

1) Ogden Geothermal Operations, Inc.
2) Oxbow Power
3) CalEnergy Operations, Inc.

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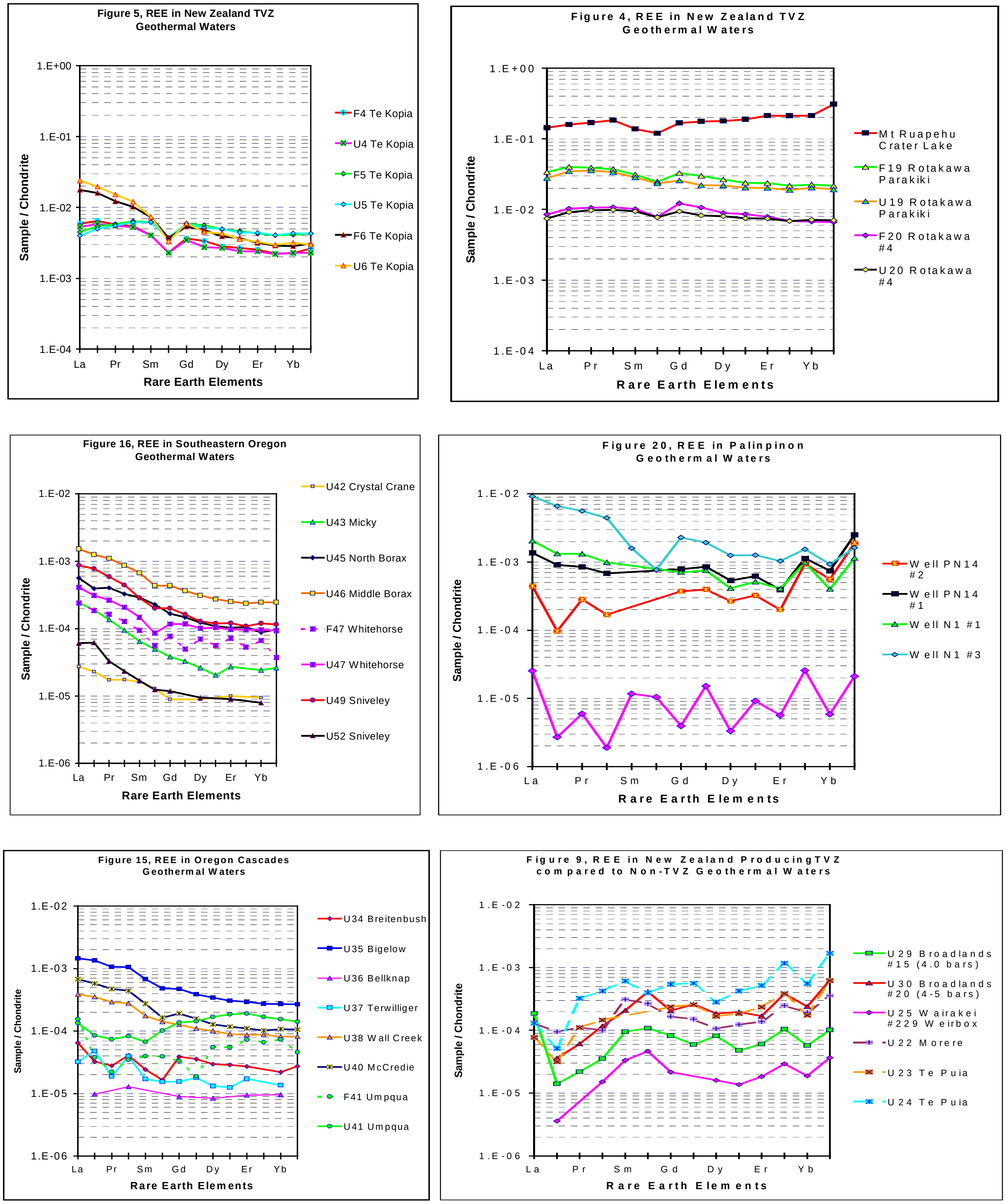


**Figure 1.** Representative Data Shown in Chondrite Normalized Form

## CONTACTS

William Shannon
Department of Geology and Geological Engineering
University of Idaho
Moscow, ID 83444-3022
Billshan@uidaho.edu

Joel L. Renner, INEEL
PO Box 1625
Idaho Falls, ID 83415-3830
tel: 208-526-9824
fax: 208-526-0969
e-mail: jrenner@inel.gov

Marshall Reed, EE-12
5H-065/FORS
DOE-HQ
1000 Independence Ave, S.W.
Washington, D.C. 20585
tel: 202-586-8076
fax: 202-586-8185
e-mail: marshall.reed@hq.doe.gov

Willettia D. Amos
U.S. Department of Energy
Idaho Operations Office
850 Energy Drive
MS-1225
Idaho Falls, ID 83401-1563

# THERMODYNAMICS AND PHASE RELATIONS OF AQUEOUS GEOTHERMAL FLUIDS AND HIGH-TEMPERATURE GRANITE MELTS

J. G. Blencoe, L. M. Anovitz, D. R. Cole, J. Horita, Donald A. Palmer, and J. M. Simonson
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory

## KEY WORDS

acid-chloride steam, volatility, corrosion, silicate melts, geothermal fluids, fluid-rock interactions, thermodynamics, phase equilibria, modeling, granite

## PROJECT BACKGROUND AND STATUS

Geothermal resources are genetically linked to silicic magmatism in numerous localities worldwide. Two important manifestations of this link are heat transfer from the magmas to superjacent geothermal systems, and mixing of magmatic fluids with meteoric waters. In mixed-fluid systems the initial chemical compositions of magmatic fluids are strongly influenced by the bulk composition and thermodynamic mixing properties of the magma, incompatible melt components are preferentially partitioned into the aqueous fluids that separate from silicic magmas, and geochemical reactions can potentially produce significant changes in the compositions of magmatic fluids prior to or during mixing with meteoric waters. New thermodynamic and kinetic models are needed to characterize accurately the magma-hydrothermal processes in these systems.

A comprehensive thermodynamic model for granitic magmas would facilitate quantitative geochemical investigations of granite-hosted, magma-hydrothermal systems. With such a model, crystallization paths for the melts could be calculated. These paths correlate with release of latent heat, which is an important factor in the overall heat budget of the system. They also define both the P-T-X conditions at which an aqueous fluid begins separating from the magma, and the composition of that fluid. The "haplogranite" system, $NaAlSi_3O_8$ (albite) - $KAlSi_3O_8$ (sanidine) - $Si_4O_8$ (quartz) - $H_2O$ (water), is widely regarded as an excellent analog for granites and granitic pegmatites. Thus, we are conducting systematic investigations of the thermodynamics and phase relations of haplogranitic melts. Currently, our attention is focused on measuring the equilibrium Na/K exchange between crystalline feldspars and melt, and the mutual solubility of haplogranite melt and water. We are also developing fundamental equations of state for binary haplogranite melts that can be extended for reliable representation of the thermodynamics and phase relations of ternary and quaternary haplogranite melts.

A further question of phase equilibria arises once geothermal fluids are in place in the reservoir and steam is produced, either directly in vapor-dominated reservoirs or as a result of rapid production or steam flashing in liquid-dominated systems. Solutes which are not volatile at low temperatures (e.g., strong acids and salts) distribute from brines to steam at high temperatures. Relatively low concentrations of solutes in steam may result in very high concentrations in liquids formed on partial condensation of the steam due to the strong temperature dependence of the phase equilibrium. The total amounts of solutes in steam will depend on brine temperature, concentration, and pH. Reliable determination of the sources of corrosive (acid-chloride) steam and the development of economical mitigation methods are dependent on an understanding of brine chemistry and liquid-vapor phase behavior over wide ranges of temperature, pressure, and brine composition, including the effects on solution pH on interactions between reservoir rocks and geothermal brines. Having determined the volatilities of a number of pure and mixed electrolyte solutions (brines) appropriate for understanding liquid-vapor phase behavior, we are currently focusing on the effects of equilibration of brines and steam with reservoir rocks on the pH of reservoir brines and the corresponding volatility of acid chlorides.

## PROJECT OBJECTIVES

The immediate goal of the research is to perform laboratory experiments that elucidate the phase relations and thermodynamic mixing properties of haplogranitic melts and associated aqueous fluids, and the chemical thermodynamics and solute speciation governing the partitioning of corrosive solutes between geothermal brines and steam. The resulting fundamental thermochemical data can be applied in quantitative modeling of heat and fluid flow in geothermal systems associated with silicic magmas, and in determining appropriate mitigation methods for the protection of system components against corrosion by acid-chloride steam. The ultimate aim of the work is to develop comprehensive thermodynamic models for high-temperature geothermal fluids, including information on sources of water, noncondensible gases, and solutes from silicate melts.

### *Technical Objectives*

- Measure the partitioning of Na and K between crystalline alkali feldspar(s) and haplogranitic melt as a function of the silica and water contents of the melt, and acquire new and more accurate data on the boundaries of melt-crystal phase fields.
- Determine the alkali aluminosilicate composition of aqueous fluid in equilibrium with haplogranitic melt, and the solubility of water in haplogranitic melts, at 250 MPa, 950°C.
- Develop a comprehensive thermodynamic model for the haplogranite system at crustal pressures and temperatures.
- Complete measurements of the volatility of chlorides over NaCl(aq) brines in contact with rock samples from The Geysers at temperatures to 350°C.
- Complete development of thermodynamic models for chloride volatility from mixed electrolyte brines to provide an accurate prediction of the concentrations of chloride and counterions in steam over geothermal brines as a function of temperature, brine composition, and pH.

### *Expected Outcomes*

- The new experimental data on haplogranitic melt systems will be used to develop thermodynamic equations of state for calculating crystal–melt phase relations and water solubilities in silicic melts, and for predicting the solubility of granitic components in high-temperature geothermal fluids.
- Primary products of research on the volatility of potentially corrosive acid chlorides in geothermal brines will include thermodynamic data and quantitative models for predicting solute volatility under reservoir conditions, and suggested methods for mitigating corrosion problems caused by the transport of acid chlorides during production.

## APPROACH

The integral thermodynamic mixing properties of hydrous haplogranitic melts can be determined if sufficient, accurate experimental data are obtained on: (1) the hypersolidus phase relations of haplogranitic systems, and (2) the free energies of fusion of stoichiometric silicate components. To obtain these data, experiments are being performed in an internally-heated pressure vessel. This equipment is part of the unique assemblage of laboratory devices at ORNL for studies of chemical equilibria, thermodynamics of brine systems, liquid-vapor molecular and isotopic partitioning, and other phase behavior. In addition, literature data are being evaluated to constrain the melting thermodynamics of the albite-water system.

The problem of predicting the transport of acid chloride solutes in geothermal steam is addressed through laboratory measurements of liquid-vapor partitioning equilibria coupled with the development and application of quantitative thermodynamic models to represent and interpret the experimental results. The partitioning of chlorides to the vapor phase has been measured at temperatures to 350°C over pure HCl(aq), from aqueous mixed brines at concentrations ranging to salt saturation, and from brines in contact with rock samples from The Geysers. Thermodynamic models have been developed to represent accurately the distribution of chlorides between phases over the mixed brines characteristic of geothermal reservoir fluids.

## RESEARCH RESULTS AND VARIANCES

### *Haplogranite Melt–Feldspar Exchange Equilibria*

This year we continued our research to elucidate the equilibrium partitioning of Na and K between haplogranite melt and alkali feldspar, and the solubility of water in feldspar-rich haplogranitic melts. At a fixed pressure, temperature and mole fraction $Si_4O_8$ , a bulk composition is chosen for which the tie-line is to be determined. Two melt compositions and two feldspar compositions are then synthesized which, when mixed in the proper proportions, lie along tie lines which cross at the bulk composition of interest, and bracket the expected equilibrium feldspar and melt Na/K ratios. During an experiment the Na/K ratios of both the feldspars and melts will migrate towards, and ideally reach, their equilibrium values. This constrains the equilibrium Na/K compositions of the feldspar and the melt.

Pseudo-gels were synthesized from nitrate solutions and finely ground high-purity silica glass, for use in preparing nine anhydrous glass and four feldspar compositions. These were sealed in evacuated Pt tubes with appropriate amounts of water, prior to reaction at elevated pressures and temperatures. Glass compositions were reacted at >300 MPa, 950°C, and feldspar compositions at 50 MPa, 900°C, each for one week. These materials are currently being characterized, and additional glasses synthesized, for the anticipated Na/K exchange experiments.

### *Fluid-Composition Experiments*

A number of factors have limited the ability of previous researchers to determine the composition of aqueous fluid coexisting with haplogranitic melt. The most serious is that the high P-T composition of the fluid is not retained on quenching. When experimental samples are brought to ambient P-T conditions at the conclusion of an experiment, silicate materials precipitate as films and "quench roe" (amorphous silica-rich spheres). This prevents direct analysis of the high P-T fluid. The tendency of the silicate to precipitate on the glass further complicates the analysis. We have developed a triple Pt-capsule method that overcomes many of these difficulties, and are currently determining the compositions of aqueous fluids equilibrated with haplogranitic melts. These experiments establish the Na, K, Si, and Al composition, as well as δD and $\delta^{18}O$, of an aqueous fluid coexisting with haplogranitic melt.

Hydrous haplogranitic glasses of known chemical and isotopic composition were synthesized as starting materials for the experiments. Nine compositions were prepared, five haplogranites, three on the bounding binaries (250 MPa minimum melt compositions), and albite. In each, water-oversaturated and undersaturated glasses were prepared to allow reversal of the equilibrium water content of the melt. Experiments were performed on four of these compositions at 250 MPa, 950°C, for periods ranging from 1 to 35 days. To date, time-dependent data have been obtained from samples reacted in two sets of experiments using two different waters. The aim was to determine the solubility of a Si-poor and a eutectic haplogranite reacted at 950°C, 250 MPa for 1, 2, 4, 8, 11 and 35 days. In addition, two other compositions – a K-poor haplogranite, and a composition on the quartz-orthoclase binary minimum – were reacted at the same P-T conditions for 35 days. This work has been reported at two annual meetings of the Geological Society of America, and was very well received (Anovitz and Blencoe, 1997b, 1999b). The resulting data suggest that: the total solubility of these compositions in water range from 1.8 to 3.0 wt. percent; dissolution is incongruent, with a significant increase in Si in the fluid over that in the melt; Al is mobile in aqueous fluids, even in the absence of complexing anions; and significant Na/K partitioning occurs between the water and melt. Preparation of a manuscript describing these results is in progress.

Measurements of the compositions of coexisting brine and steam at high temperatures during this period focused on determination of the total chloride concentration, and the identification and quantitative analysis of counterions (e.g., $H^+$, $Na^+$) in steam equilibrated with NaCl(aq) in contact with rock samples from The Geysers. Extensive modifications were made to our static volatility apparatus in an effort to achieve improved reproducibility of sampling. In the new configuration the high-pressure vessel containing the chemically inert (platinum-alloy) liner and sampling tubes has been inverted, and all samples (liquid and steam condensate) are withdrawn from sampling valves located below the liner. This change helps to insure that all steam condensate forming in the vapor-phase sample line is removed from the system for analysis, preventing the possible reflux of steam condensate which may have increased the sampling uncertainty in our previous results. We have also focused on a more positive identification of counterions for chloride in the steam condensate samples. Earlier results for equilibrations including Geysers rock samples indicated relatively high (but not quantified) concentrations of ammonium or other counterions, in addition to hydrogen ion and the expected low levels of $Na^+$ from partitioning of NaCl.

***Evaluation of Phase Equilibria and Thermodynamic Modeling***

Any model of the thermodynamic properties of haplogranite melts needs to take into account the existing experimental database describing phase equilibria for haplogranites. To provide a basis for the expansion of the preliminary thermodynamic model developed by Blencoe et al. (1994), we are reanalyzing data for albite-water melts, which have been extensively investigated. Our paper on the dry melting of albite (Anovitz and Blencoe, 1999a) has just been published, and currently we are completing work on a paper that evaluates phase equilibrium and density data for the hydrous part of the system. Despite the copious amount of work performed, the system is, in fact, very poorly known. In the dry system neither the reversed experimental data, nor the thermodynamic data, strongly constrain the melting of albite as a function of pressure and temperature. Therefore, we have derived new thermodynamic quantities for this reaction, including realistic uncertainties for each parameter (Anovitz and Blencoe, 1999a). Our examination of the hydrous phase relations in the albite-water system has demonstrated the need for reversed experiments. Many of the apparent inconsistencies amongst various experimental data sets disappear when only carefully reversed data are considered. Our work on the hydrous part of this system was presented at the 1997 spring meeting of the American Geophysical Union (Anovitz and Blencoe, 1997a).

The ultimate goal of this effort is development of a thermodynamic model for the entire (four component) haplogranite system. Work to date suggests that the commonly held belief that excess molar volume is independent of water content and independent of anhydrous melt composition cannot be correct. The model currently being developed will be extended to a generalized form to account for the effects of anhydrous composition as well as water content.

Values of the equilibrium constant for the partitioning of a particular species between geothermal brines and steam at high temperatures form the thermodynamic basis for calculating the concentrations of solutes in coexisting phases over the wide ranges of temperature, salinity, and pH which may be encountered in the production of geothermal fluids. However, quantitative modeling of phase equilibria in complex, multicomponent brines requires additional consideration of the effects of activity coefficients of various species in the liquid phase on the extent of partitioning of that species to the vapor. A new model has been developed for activity coefficients of solutes in the prototype system of acid-chloride geothermal brines [i.e., {NaCl + HCl}(aq)] which enables accurate calculation of the chloride concentration in steam over wide ranges of brine salinity and pH. The model is currently being expanded to account for the effects of other ionic and neutral species in brines on the total chloride partitioning to steam.

## FUTURE PLANS

The immediate future goals of our research on (haplogranite melts + water) are to complete a manuscript describing our new experimental results on the mutual solubility of haplogranite melt and water at 250 MPa, 950°C; continue experiments on the partitioning of Na and K between coexisting haplogranite melt and feldspar; and complete our evaluations of phase equilibrium data for haplogranitic melts within the constraints of available data. We expect to conclude studies of the partitioning of chlorides to steam from NaCl(aq) brines in contact with Geysers rocks, and to continue to extend the thermodynamic model for solute volatility to include additional solutes present in geothermal brines.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Laboratory techniques developed for acquiring highly precise and accurate data on the volatile contents and bulk chemical compositions of very small masses of aluminosilicate material have numerous potential practical applications in geothermal R&D. We have reported preliminary results of our work at technical meetings (e.g. Anovitz et al., 1995; Anovitz and Blencoe, 1997b, 1999b). Researchers and technologists interested in the progress of our research are encouraged to contact us for further information. Volatility results have been communicated frequently to the geothermal community through focused update meetings and our participation in geothermal conferences of broader scope. In addition, direct contact and consultation on the application of these results to field problems arising from solute volatility are expected to continue.

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## CONTACTS

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D. C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O. Box 2008, Bldg. 4500S, MS 6110
Oak Ridge, TN 37831-6110
FAX: (865) 574-4961

James G. Blencoe Phone: (865) 574-7041
Lawrence M. Anovitz Phone: (865) 574-5034
David R. Cole Phone: (865) 574-5473
Juske Horita Phone: (865) 576-2750
Donald A. Palmer Phone: (865) 576-5109
J. M. Simonson Phone: (865) 574-4962

# ACTIVE FAULTING AND STRESS REDISTRIBUTIONS IN THE DIXIE VALLEY, BEOWAWE, AND BRADYS GEOTHERMAL FIELDS: IMPLICATIONS FOR GEOTHERMAL EXPLORATION IN THE BASIN AND RANGE

S. John Caskey
Department of Geosciences
San Francisco State University

Steven G. Wesnousky
Center for Neotectonic Studies
University of Nevada, Reno

## KEY WORDS

neotectonics, active faulting, static stress, geothermal, fracture permeability, fault mechanics, Dixie Valley, Beowawe, Bradys

## PROJECT BACKGROUND AND STATUS

It is widely accepted that geothermal activity is largely associated with areas of active faulting, and, it is commonly accepted that faults play a role in this association by sometimes forming conduits for upward movement of ground water. Similarly, in geothermal reservoirs, it is thought that it is necessary to have recent fault movements in order to maintain open fractures and permeability. However, the question of how the mechanics of the faulting process may play a causative role in the factors that influence geothermal production remains poorly understood. A better understanding of the faulting processes that create and maintain reservoir permeability can potentially reduce geothermal exploration costs if it can be used to more accurately target successful wells.

With this objective in mind, during the Spring, Summer and Fall, 1999, we conducted aerial photo reconnaissance and detailed field studies of active faults in the Dixie Valley (Oxbow Geothermal Corp.), Beowawe (Oxbow Power of Beowawe), and Bradys (Florida Power and Light) geothermal production fields to characterize the distribution and recency of fault movements. To evaluate how the mechanics of the faulting process may influence the geothermal environment, we have constructed models showing the redistribution of stresses associated with the most recent identifiable fault ruptures in the vicinity of the Dixie Valley and Beowawe geothermal fields.

The Dixie Valley portion of the project is near completion, however, we intend on conducting exploratory trench studies at key locations along the Dixie Valley fault during the Summer 2000, in order to better constrain the timing of the most recent faulting events. The status of the Beowawe study is preliminary, however we feel that our efforts thus far have resulted in a first order assessment of the distribution and the relative ages of surface faulting events. Continued field studies during the Summer 2000 may refine our neotectonic assessment and hence our evaluation of stress redistributions. We anticipate that the next phase of this study will also involve exploratory trench investigations. The Bradys portion of the project is in an initial phase, but we intend on conducting detailed field studies and stress analysis for this area during the Summer 2000. We expect to complete these studies, as well as to conduct reconnaissance investigations at other geothermal fields in the Basin and Range in order to test the hypotheses generated from the initial studies at the Dixie Valley, Beowawe, and Bradys geothermal fields. We expect that our project will be completed during the Fall 2000.

## PROJECT OBJECTIVES

The fundamental objective of our study is to gain an understanding of the spatial association of geothermal reservoirs to active faults, and how the mechanics of the faulting process may influence factors related to the state of stress and fracture permeability in geothermal reservoirs.

### *Technical objectives*

- A better understanding of the faulting processes that create and maintain reservoir permeability can potentially reduce geothermal exploration costs if it can be used to more accurately target successful wells. With this goal in mind, the technical objectives of this study are to; 1) characterize the distribution and recency of surface fault ruptures in the vicinity of selected geothermal fields in the Basin and Range, 2) use the distribution of recent fault ruptures to model the resultant redistribution of stress changes, and 3) analyze these stress changes with respect to their possible influences in the respective geothermal environments.

### *Expected Outcomes*

- We expect that our investigation will result in an unprecedented assessment of the spatial affinities between the locations of productive geothermal fields and active fault ruptures.

- Models of stress redistributions and their possible influences on fracture permeability will potentially shed new light on how fault rupture mechanics can work to localize favorable conditions for geothermal production.

- We envision that our results may be used to modify existing conceptual models of the processes which work toward fracture permeability in geothermal reservoirs, and that an improved understanding of these processes will ultimately result in more efficient exploration practices by helping to more accurately target reservoir prospects.

## APPROACH

We use the approach of Reasenberg and Simpson (1992) and Stein *et al.* (1992), based on the methodology of Okada (1992), to calculate the static stress changes resulting from displacements on individual fault segments (i.e. dislocations) embedded in an elastic half space. This simple approach has been used by countless researchers (e.g. refer to Harris, 1998), and has been successful in explaining diverse aspects of earthquake interactions such as triggered earthquake sequences (e.g. Caskey and Wesnousky, 1997) and aftershock clusters following large earthquake ruptures. For our models, individual fault ruptures are identified from aerial photos and field verification. Average displacements on faults are based on profiles and field measurements of vertical offsets across fault scarps. The values of static stress changes are then used to calculate the Coulomb Failure Function (CFF) (failure stress changes) on the faults associated with the geothermal fields, where CFF is defined as

$$CFF = \Delta\tau_S + \mu(\Delta\sigma_n),$$

where $\Delta\tau_S$ is the static shear stress change (positive in the direction of fault slip), $\Delta\sigma_n$ is the normal stress change (positive for tensile stress changes), and $\mu$ is the coefficient of static friction. Possible changes in pore fluid pressure are not considered in the stress calculations. Stress changes moving a fault closer to failure are reflected by positive values of CFF. CFF values are calculated for an assumed dip slip sense of shear (i.e. rake = -90˚). In order to evaluate the relative contributions of shear and normal stress changes to CFF values, we determined CFF for $\mu$ = 0.0 (where only $\Delta\tau_S$ affects CFF) and $\mu$ = 0.40-0.75

(consistent with laboratory rock mechanics experiments (Byerlee, 1978)). For Dixie Valley calculations, normal stress contributions were determined by subtracting the shear stress changes from the total CFF values.

## RESEARCH RESULTS

### *Dixie Valley Geothermal Field*

"The Dixie Valley Geothermal Field (DVGF) is, in many respects, the classic Basin and Range geothermal reservoir developed along an active major range-front fault" (Benoit, 1995). It is located along the southeast-dipping Dixie Valley fault and within the Stillwater Seismic Gap (Wallace and Whitney, 1984); a 45 km-long section of the fault between the 1915 (M7.7) Pleasant Valley and 1954 (M6.8) Dixie Valley earthquake rupture zones to the north and south, respectively. Within the Stillwater Gap, Wallace and Whitney (1984) recognized discontinuous Holocene fault scarps along the Stillwater range front, and they interpreted this to mean that the gap has experienced at least one large Holocene earthquake. Our field studies of these surface ruptures indicate that ruptures to the north and south of the DVGF are likely of different ages and that the geothermal field lies within a ~10 km gap with respect to these Holocene earthquake ruptures. For example, profiles of fault scarps north of the DVGF are generally more degraded with shallower scarp slope angles compared with those to the south, indicating an older age of formation. Fault scarps to the south, with few exceptions, exhibit steep scarp slope angles, essentially at angle of repose (~30˚) for unconsolidated alluvial fan gravel deposits. Our interpretation of different ages for these scarps is in agreement with previous, more detailed scarp profile analyses of Pearthree (1990) for the Dixie Valley region. There is no evidence for Holocene fault ruptures along the 10 km portion of the range front in the vicinity of the DVGF. It is possible that the lack of scarps in the DVGF is a result of non-preservation due to erosion and/or burial of scarps. However, several landslides and fan surfaces along the range front interpreted to be pre-Holocene in age are apparently not faulted, indicating that this portion of the range front has not ruptured at the surface in the Holocene.

Holocene fault ruptures south of the DVGF overlap with the 1954 Dixie Valley rupture zone by 22 km and can be traced northward for a distance of 45 km, to ~5 km south of the DVGF. The interpreted older Holocene scarps can be traced from ~4 km north of the DVGF to the Sou Hills. The age of fault ruptures south of the DVGF is constrained from field relations. Faulted alluvial fan deposits in the Stillwater Gap area contain or overly Mazama tephra (~7 ka) at two locations (Caskey et. al, 1996; work in preparation). Unfaulted fan deposits along the southern portion of the rupture zone contain Turupah Flat tephra (1.5 ka) (Bell and Katzer, 1990). Hence, the absolute age of faulting is bracketed as 7 ka-1.5 ka. Similarly, Pearthree's (1990) analyses of scarp profiles suggest that these scarps may be as young as 2 ka. Presently, we have no absolute age control on Holocene scarps north of the DVGF. However, Pearthree's (1990) profile analyses indicate that these fault ruptures may be several thousand years older than those south of the DVGF. The observations indicating that scarps north and south of DVGF appear to represent different aged events gives us confidence that the ~10 km gap we observe between Holocene ruptures may be real rather than a consequence of non-preservation.

The possibility that the DVGF lies between the endpoints of recent earthquake ruptures has important implications for the redistribution of stresses and their influence on geothermal activity in the DVGF. Our model of stress changes associated with Holocene fault ruptures in the Stillwater Gap suggests that the Dixie Valley fault and parallel fractures in the vicinity of the DVGF have experienced large positive stress changes (>10 bars). These large stress changes in the DVGF are due to its proximity to the endpoints of Holocene fault ruptures to the north and south. Stress changes resolved on the Dixie Valley fault plane as well as proximal, fault-parallel fractures largely result from a decrease in normal stresses (i.e. increase in tensile stresses), although a significant increase in shear stress is also evident.

An examination of CFF values in the Stillwater Gap associated with slip on historic ruptures along the west-dipping 1915 (M7.7) Pleasant Valley and the east-dipping 1954 (M6.8) Dixie Valley rupture zones yields similar results for the DVGF, although the stress change values from historic slip are considerably lower in the geothermal field. This is due to the greater distance of the geothermal field from the endpoints of the historic fault ruptures. Mapping along piedmont fault scarps at the north end of Dixie Valley, just south of the Sou Hills, revealed a small, localized 0.10-0.15 m-high scarp in recent alluvial deposits. The well-preserved nature of such a subtle feature indicates that the scarp is probably historic, and therefore, likely formed during the nearby 1915 earthquake. The likelihood that the scarp represents a previously unrecognized 1915 rupture appears to demonstrate that stress changes associated with the 1915 earthquake were large enough to trigger fault slip in northern Dixie Valley.

***Beowawe Geothermal Field***

The Beowawe Geothermal Field (BGF) lies in a more complex structural setting than the DVGF and, at present, has not been field investigated with respect to fault activity to the extent of the Stillwater Gap. However, aerial photo analysis and field reconnaissance mapping during Summer 1999 have resulted in a first order assessment of the distribution and relative ages of the most recently active faults in the vicinity of the BGF.

The Beowawe facility is located within Whirlwind Valley, a small reentrant valley that sits within the Shoshone Range. The west flanks of the Shoshone Range, Dry Hills, and the Cortez Range are each bounded by active faults. The east boundary of Whirlwind Valley is marked by a sharp escarpment which is clearly produced and controlled by the Malpais fault zone. However, it is only along the northern portion of the escarpment that we have observed fault scarps in Quaternary alluvium. These appear to be late Pleistocene to early Holocene-aged scarps based on the estimated age of the youngest alluvial fan deposits offset along the fault. The southernmost limit of observed alluvial scarps along the Malpais fault is approximately 3 km northeast of the town of Beowawe, where we measured vertical offsets of 0.7 m across the scarp. Curiously, the apparent southern limit of surface faulting corresponds to the location of local hot springs along the fault.

Structural relations along the southern portions of the Malpais fault in the BGF were most recently investigated by Benoit (1995), who similarly reported an absence of recent scarps. The age of surface faulting along the southern section of the fault appears to predate Quaternary landslide deposits and adjacent bedrock slump blocks approximately 5 km west of the geysers. These landslide deposits are apparently not faulted; an observation supported by mapping in the area by Smith et al. (1979). Future efforts will focus on placing firmer constraints on the ages of the oldest, unfaulted Quaternary deposits along the southern portion of the Malpais fault, and the age of surface faulting along the northern portion of the fault.

Structural and stratigraphic relations along the west flank of the Shoshone Range indicate multiple Quaternary faulting events. We interpret the most recent event as being early to mid-Holocene in age based on the estimated age of the youngest, faulted alluvial fan deposits at the mouth of Mt. Lewis Canyon. In this area, older fan deposits exhibit progressively greater vertical offset, which attests to repeated Quaternary fault movements. In the same fashion, the Dry Hills fault exhibits multiple Quaternary displacements, the youngest of which clearly shows Holocene surface expression.

In summary, aerial photo analysis and preliminary field studies show that fault ruptures have been most recent along the Shoshone, Dry Hills, and northern section of the Malpais fault, with no evidence for late Quaternary fault movements in the BGF and elsewhere along the southern Malpais fault. Our model of stress changes associated with these most recent fault ruptures suggests that the Malpais fault in the vicinity of the BGF has experienced a significant increase in failure stress on the order of 1-2 bars at 3 km depth. The positive CFF values result from slip on both the Shoshone fault and the northern section of the Malpais fault. Slip on the Dry Hills fault results in negative CFF values along the southern Malpais fault. CFF values calculated for depths of 6 km yield similar results, although these calculations are not included herein.

CFF calculations in the BGF for a friction value of zero are less than those for a value of friction of 0.4. This indicates that the positive CFF values are a result of both increases in shear stress and decreases in normal stress. The sense of stress changes is similar to the changes in the DVGF. However, the stress changes in the BGF are considerably smaller owing to the greater distance between the geothermal field and the most recent fault ruptures.

***Bradys Geothermal Field***

Mapping by Bell (1984) indicates that the Bradys Geothermal field lies at the endpoint of Holocene fault ruptures. These ruptures lie within the pluvial Lake Lahontan basin, and are therefore required to be younger than the most recent latest Pleistocene occupation of the lake. We are currently conducting detailed field studies to more completely assess the distribution and age of surface faulting, and have yet to analyze stress changes associated with the fault ruptures. Our preliminary studies indicate that the southern extent of ruptures is accurately portrayed by Bell (1984), but that the fault ruptures may extend farther to the north. These relations would indicate that the Bradys area lies in an area of pronounced stress change owing to its close proximity to a recent fault rupture endpoint. From our previous models of the DVGF we anticipate that these stress changes would result from both increases in shear stress and decreases in normal stress resolved parallel to normal slip on the fault.

## DISCUSSION

Our models for the Dixie Valley geothermal field indicate that induced stress changes near the endpoints of recent fault ruptures appear to promote favorable conditions for geothermal production. The stress changes result in an increase in failure stress on unruptured, along-strike portions of the fault. But perhaps more importantly, these stress changes are characterized by significant decreases in fault-normal stress that are particularly enhanced in the upper few kilometers of the crust. Intuitively, this sense of stress change would influence the flow dynamics of geothermal fluids along the fault and fault-parallel fractures. Our models of Holocene stress changes in Dixie Valley, suggest the area between the northern- and southernmost geothermal production wells coincides with the portion of the fault most strongly affected by tensile stress changes. Stress changes in the geothermal field induced by the 1915 and 1954 earthquakes are in the same sense as in the Holocene stress model. However, these changes are smaller because of the greater distance between the geothermal field and the historic rupture endpoints. Both the Holocene and historic stress changes we calculate are consistent with results from recent investigations of in-situ stress and fracture permeability in the Dixie Valley geothermal field (e.g. Barton et. al, 1996; Hickman et al., 1997). These studies show fractures parallel to the fault zone are both critically stressed for failure and hydraulically conductive.

Our preliminary assessment of the neotectonic framework of the Bradys geothermal field indicates that this production area lies at the endpoint of a Holocene earthquake rupture, a setting that is analogous to the Dixie Valley geothermal field. We anticipate that stress models for the Bradys area will yield similar results as for the Dixie Valley geothermal field. The Beowawe geothermal field lies in a more complex structural setting. However, our model for late Pleistocene-Holocene stress changes along the southern Malpais fault shows both increases in shear stress and decreases in normal stress in the Beowawe geothermal field.

In summary, we find that the Basin and Range geothermal production fields we have investigated do not appear to lie along the most recently active portions of faults. Our studies show that induced stress concentrations at the endpoints of fault ruptures promote conditions for fracture permeability and geothermal production. The observations would suggest that in regions of high heat flow, areas along normal faults which act as persistent rupture segment boundaries may also be areas of enhanced hydrothermal activity. Studies of normal fault segmentation show that fault trace salients (i.e. convex fault strike changes such as at the Dixie Valley geothermal field) and fault trace steps appear to act as the most persistent fault rupture boundaries (Crone and Haller, 1991; Machette et al., 1991).

## FUTURE PLANS

Our future efforts will focus on constraining better the absolute ages and distribution of fault ruptures in the Dixie Valley, Beowawe, and Bradys areas and on investigating the recent fault history and stress changes for geothermal production fields elsewhere in the Basin and Range province.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and extent of interest |
|---|---|
| Oxbow Geothermal Corp. | general |
| Oxbow Power of Beowawe | general |
| Florida Power and Light | general |

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## CONTACTS

John Caskey
Department of Geoscience
San Francisco State University
1600 Holloway Ave.
San Francisco, CA 94132
(415) 405-0353 (phone)
(415) 338-7705 (fax)
caskey@sfsu.edu

Steven G. Wesnousky
Center for Neotectonic Studies
MS 169
University of Nevada
Reno, NV 89557
(775) 784-6067 (phone)
(775) 784-1382 (fax)
stevew@seismo.unr.edu

John W. Bell
Nevada Bureau of Mines and Geology
Mackay School of Mines and Geology
University of Nevada
Reno, NV 89557
(775) 784-1939 (phone)
jbell@unr.edu

# RESERVOIR TECHNOLOGY

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

G. N. Boitnott
New England Research, Inc.

## KEY WORDS

Awibengkok, AWI 1-2 corehole, Core measurements, Seismic properties, Electrical properties, Shear modulus, Shear weakening, Mineralogy

## PROJECT BACKGROUND AND STATUS

The Awi 1-2 corehole produced over one kilometer of continuous core from the Awibengkok Geothermal Field in Indonesia. The core is now the focus of a DOE funded interdisciplinary study to better understand fundamental reservoir properties of complex andesitic systems. This work involves of multi-year study of the Awi 1-2 core, to be followed by similar studies of other fields selected by the DOE Geothermal Program. The study focuses on constraint and characterization of geophysical properties of the rock matrix, including seismic and electrical properties, to improve modeling and interpretation of reservoir properties.

## PROJECT OBJECTIVES

Through the use of laboratory measurements in conjunction with model development, this work is aimed at developing physically based models of key geophysical properties with the goal of improving reservoir characterization and monitoring.

***Technical Objectives***

- Systematic study of the shear weakening phenomena (rock water interaction)
- Quantifying core scale heterogeneity.
- Field Scaling of seismic, electrical, and flow properties.

***Expected Outcomes***

- Improved methods of well-log analysis.
- Assessment of the feasibility of seismic detection of steam caps in andesitic systems
- Development of methods to constrain fracture system characteristics from geophysical observations.

## APPROACH

Laboratory measurements of ultrasonic velocities, complex electrical impedance, permeability, and other core scale physical properties are being made on a representative suite of samples from the AWI 1-2 corehole in order to develop a dataset from which to build physical models of geophysical properties. The data is being analyzed in conjunction with petrographic and mineralogic analyses performed in collaboration with Dr. J. Hulen at EGI. Laboratory measurements are also being coordinated with others working on related issues, such as J. Roberts and B. Bonner at LLNL who are working or electrical properties during boiling in similar cores. With the core measurements as a foundation, specialized experiments aimed at characterization of core scale heterogeneity and the physical properties of joints and fractures will be performed to constrain model development. The physical models developed from the results of these experiments will then be used as inputs to field scaling models in order to address log and field scale issues.

## RESEARCH RESULTS

### *Seismic Properties*

Laboratory studies of ultrasonic velocities of cores from The Geysers and Awibengkok have lead to the discovery that the presence of water causes a significant reduction in the dynamic shear modulus of the rock matrix. This shear weakening is large enough in many rocks to counteract traditionally accepted poroelastic mechanisms, changing standard interpretations of field seismic anomalies [Boitnott and Kirkpatrick, 1997].

Originally observed on core from The Geysers, the phenomena has since been observed in the Awibengkok cores as well [Boitnott and Johnson, 1999]. Recent mineralogic data provided by J. Hulen at EGI has confirmed a correlation between the amount of shear weakening and the weight percent illite contained in the samples (see Figure 1). Previous data from The Geysers had exhibited a strong correlation between weight percent illite and the percent reduction in shear modulus upon saturation. The data from Awibengkok cores follows a similar, but less well defined trend. Including both the Awibengkok and The Geysers data, the correlation appears strongest between weight percent illite and the magnitude of the shear modulus reduction (rather than the fractional change). While these details are still poorly understood, the differences may reflect the dramatically different porosities and textures found at Awibengkok. Still unresolved is the importance of interlayer smectite in the illite and the extent to which chlorite can contribute to shear weakening. Also under investigation is the effect of changing temperature, brine salinity and partial saturation.

Combined with future experiments on the seismic properties of rock joints and fractures, these results will form the basis for an assessment of steam cap visibility through seismic monitoring as well as improve interpretation of seismic logs.

### *Electrical Properties*

One characteristic of the Awibengkok cores is a weak correlation between porosity and core scale physical properties. This is observed both for velocities and for resistivity. A summary plot of measured formation factors (sample resistivity divided by pore fluid resistivity) versus porosity is shown in Figure 2. Note that among the higher porosity samples, as much as a factor of three variation in resistivity is observed for a given porosity.

Electrical impedance is being measured as a function of pressure, temperature, and brine chemistry in an attempt to better understand the conduction mechanisms operating in these rocks. Some representative results are shown in Figure 3. In many of the cores, the frequency dependence exhibits a broad band dispersion, with a gradually decreasing real part and a relatively constant imaginary part. This is typical of clay rich rocks, being indicative of electrochemical phenomena occurring at the surfaces of clay grains and electrical conduction across pore/clay boundaries. A number of samples exhibit a stronger dispersion, commonly concentrated at frequencies between 10 Hz and 10000 Hz. The dispersion in the real part of the impedance is accompanied by a prominent bump in the complex impedance. This behavior appears to correlate with the volume fraction of opaque minerals, and is consistent with the effects of induced polarization from oxidation reduction reactions occurring at the electrically conductive grains. The data for samples containing conductive minerals is being modeled using the electrochemical model of Wong [1979], which predicts that the frequency band of the dispersion is controlled by geometrical aspects of the conductive grains and the magnitude is controlled by volume fraction. By combining this model with models for the primary surface and ionic conduction mechanisms, we hope to build a predictive understanding of the effects of temperature and partial saturation on the electrical properties of the matrix.

***Mapping electrical properties***

In an attempt to better understand the factors controlling electrical properties of these samples, methods are being developed to map the spatial distribution of electrical impedance. As a starting point, a probe has been developed to allow the measurement of frequency dependent electrical properties as a function of position on a slabbed surface of core.

The Awibengkok cores are rich with heterogeneity at the core scale (mm to meters). In particular, the lahars and tuffs, being comprised of fragments of various rock types and textures, display strong visual heterogeneity. Little is known as to whether this visible heterogeneity corresponds to electrical and mechanical heterogeneity, and how that might influence larger scale electrical and seismic properties.

Preliminary results from the resistivity mapping on a tuff sample is shown in Figure 4. 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 variabilities on the order of a factor of three or more at length scales near 1 cm. This indicates 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 are thought to reflect regions dominated by ionic conduction though pores, while regions of high phase shift are associated with concentration of electrically conductive minerals such as pyrite and hematite. A better understanding of the electrical heterogeneity should lead to improved interpretations of FMI and induction logs.

## FUTURE PLANS

Future work will concentrate on extending the laboratory measurements to include elevated temperature, partial saturation, and variations in pore fluid chemistry. Work will also continue on mapping electrical and mechanical heterogeneity in selected cores. New initiatives will include experiments to study properties of rock joints and fractures and to develop physical scaling laws to address field scale issues.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| UNOCAL<br>Calpine Corp. | Improved reservoir characterization and modeling |
| LLNL<br>LBL<br>LANL | Support for geophysical R&D |

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## CONTACTS

Marshall Reed
Geothermal Division, EE-122
U.S. Dept. of Energy
Washington, DC
20585
Tel: 202-586-8076
MARSHALL.REED@ee.doe.gov

Joel Renner
INEL
PO Box 1625
Idaho Falls, ID
83404-3830
Tel: 208-526-9825
rennerjl@inel.gov

Greg Boitnott
New England Research Inc.
331 Olcott Drive, Ste L1
White River Junc. VT
05001-9263
Tel: 802-296-2401
boitnott@ner.com

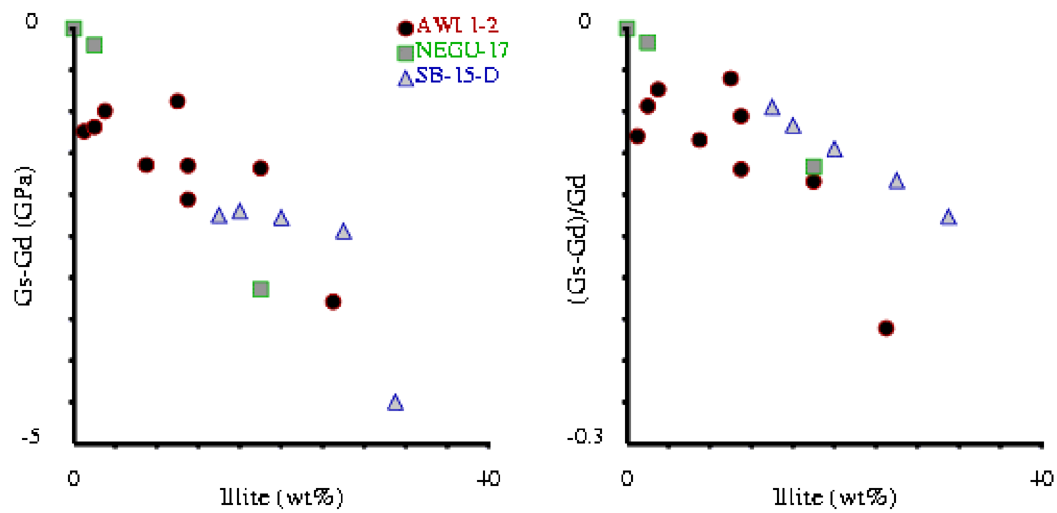


**Figure 1.** Shear modulus reduction (left) and relative shear modulus reduction (right) from laboratory tests on samples from Awibengkok (AWI 1-2) and The Geysers (NEGU-17 and SB-15-D) versus weight percent illite in the samples. Gs and Gd are the saturated and dry shear moduli, respectively.

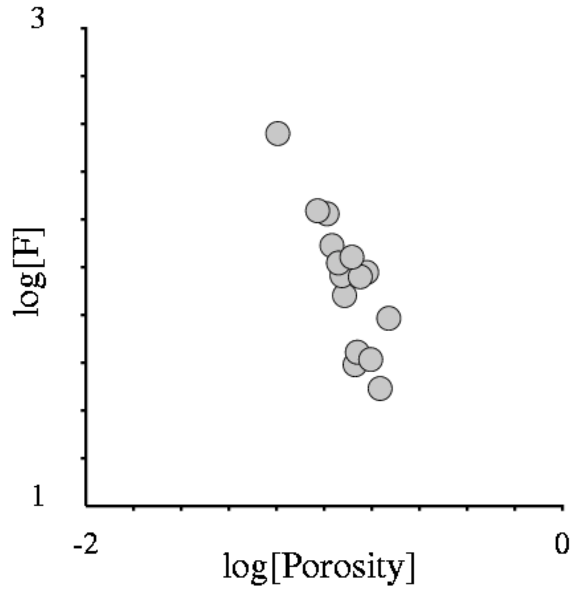


**Figure 2.** Logarithm of the formation factor versus logarithm of porosity for selected samples from AWI 1-2. Samples were saturated with a 12000 ppm NaCl brine and measurements were made at 5 MPa effective pressure. Note the large scatter at higher porosities.

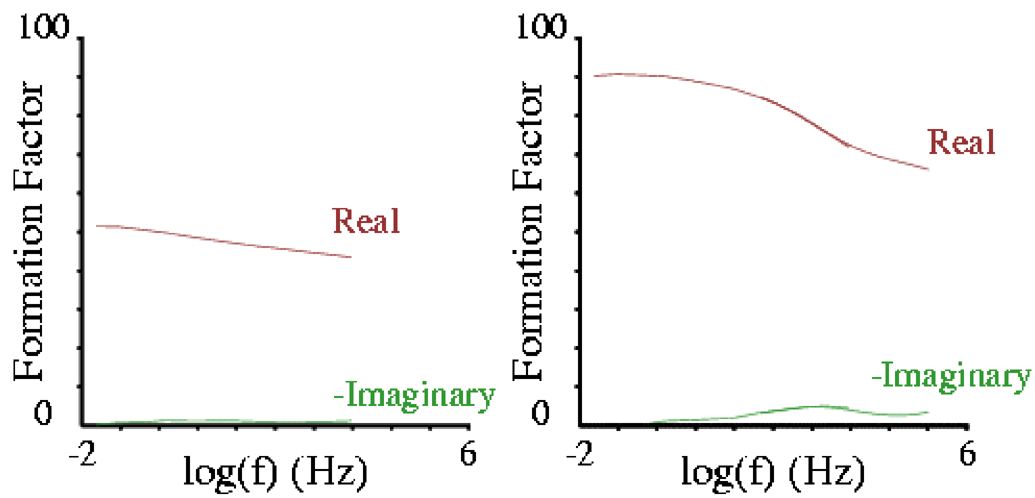


**Figure 3.** Impedance spectra for two representative samples from AWI 1-2. On the left is the complex Formation Factor for a dacite autobreccia from 3100 ft. On the right is the spectrum for a lahar from 4072 ft. Note the prominent bump in the imaginary impedance and the strong dispersion in the real impedance for the lahar sample. This is thought to reflect the presence of disseminated sulfides throughout the sample.

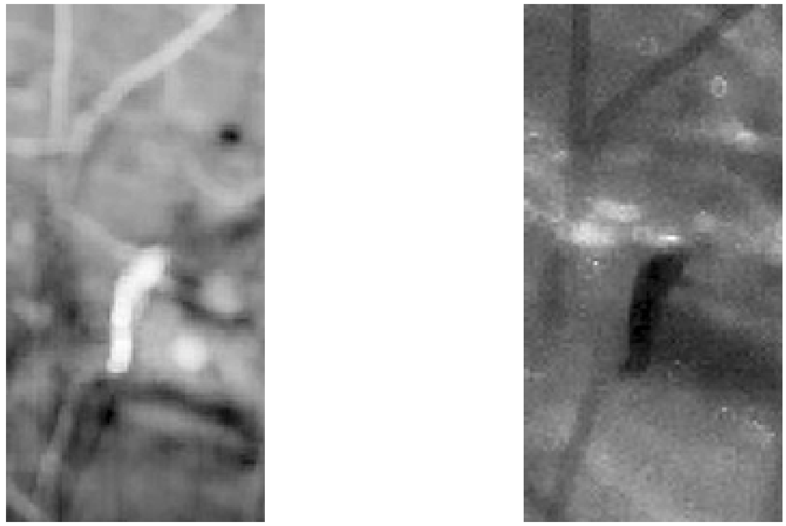

**Figure 4.** Example of an electrical impedance map of a tuff sample from 4990 ft in AWI 1-2. Image dimensions are 6 cm by 12 cm. On the left is the real part of the impedance, with light indicating conductive (white=1900 ohms) and dark being resistive (black=9000 ohms). On the right is the phase shift with dark indicating little phase shift (black=-3.6 mrad) and light indicating high phase shift (white=-39.0 mrad). Note the wide variety of features present in the resistance map. The regions of high phase shift are thought to reflect high concentrations of conductive minerals such as pyrite and hematite.

# THE THERMAL AND CHEMICAL EVOLUTION OF THE HYDROTHERMAL MINERALS IN AWIBENGKOK 1-2, AWIBENGKOK GEOTHERMAL FIELD, INDONESIA

Joseph Moore
Energy & Geoscience Institute

David I. Norman
New Mexico Institute of Technology

## KEY WORDS

Awibengkok, fluid inclusions, gaseous species, hydrothermal alteration

## PROJECT BACKGROUND AND STATUS

Awibengkok is the largest producing geothermal field in Indonesia, with an installed capacity of 330 Mwe. Through an agreement with Unocal Geothermal Indonesia (UGI), the DOE obtained 1.1 km of continuous core from Awibengkok 1-2, a well drilled on the eastern side of the field in the shallowest portion of the reservoir (Hulen and Anderson, 1998). The material is significant because extensively cored reservoir sections of andesite-hosted systems are only available to DOE researchers from three fields, Tiwi in the Philippines, Karaha-Telaga Bodas in Indonesia, and Awibengkok. This project described here is part of a broader DOE-UGI research program focussed on Awibengkok 1-2. Other studies will be directed toward evaluation of porosity and permeability within the core hole, rock and secondary mineral distributions, and the assessment of present-day pressure-temperature relationships in the reservoir. Preliminary results on studies of Awibengkok 1-2 were presented in a series of papers at the 1999 Annual meeting of the Geothermal Resources Council.

Awibengkok 1-2 was cored from depths of 762 to 1830 m. The rocks encountered in the well consist mainly of altered andesite and dacite flows and lahars, although a thin microdiorite sill was penetrated at a depth of about 1700 m (Hulen and Anderson, 1998; Hulen and Lutz, 1999). Above 1175 m, the rocks are argillically altered. At greater depths, the rocks display propylitic alteration.

## PROJECT OBJECTIVES

### *Technical Objectives*

- Document paragenetic relationships among the mineral assemblages in the cored portion of Awibengkok 1-2.
- Determine the origins of the geothermal fluids and the conditions of hydrothermal alteration through measurement of fluid-inclusion homogenization temperatures, salinities, and gas contents.
- Integrate the mineralogic and fluid-inclusion data with the results of studies on Awibengkok 1-2 conducted by other researchers.
- Develop an evolutionary model of the mineralization in Awibengkok 1-2 that can be incorporated into a time-temperature-composition history when $^{40}Ar/^{39}Ar$ spectrum dating become available.

***Expected Outcomes***

- Development of an improved conceptual model of the Awibengkok geothermal field that will aid in future development of the system.
- Formulation of better exploration models of andesite-hosted geothermal systems that can be applied to the evaluation of new geothermal fields.
- An improved understanding of the water-rock interactions in geothermal systems.

## APPROACH

Fluid inclusions trapped in hydrothermal minerals contain snapshots of the conditions that existed in the geothermal system at different times in its history. By combining the temperatures, salinities, and gas compositions of the inclusion fluids, information on reservoir processes (e.g., boiling, heating, cooling) and the origin of the fluids (e.g., meteoric, crustal, or magmatic) can be obtained (see e Norman et al., 1996; Moore et al., 1997; Norman and Moore; 1999).

A time-temperature-composition history of the geothermal system can be developed when the relative or absolute age of the mineral host is known. Relative ages can be determined through crosscutting vein relationships and infilling sequences within the veins. $^{40}Ar/^{39}Ar$ spectrum dating can be used to determine the absolute ages of the minerals and the ages of thermal perturbations they have experienced. Recent investigations of the Tiwi, Philippines geothermal field (Moore et al., 1997) have demonstrated the value of integrating detailed paragenetic and fluid-inclusion data in developing detailed thermal histories of geothermal systems.

## RESEARCH RESULTS

Veins from depths between 893.3 and 1803.5 m were studied. Two episodes of vein mineralization were recognized. Calcite was deposited by saline fluids during the earliest event. These fluids had salinities up to 18.1 weight percent NaCl equivalent and temperatures close to 270$^{o}$C. The high salinities suggest that the fluids were magmatic in origin and were related to the microdiorite intrusion encountered in the well. Subsequent vein mineralization appears to be related to the modern geothermal system. Veins deposited by the geothermal fluids are characterized by successive fillings of quartz + epidote + sulfides, wairakite, and calcite, although multiple cycles of mineralization are found in some samples (Fig. 1). Mineral textures and assemblages indicate that boiling occurred intermittently during the deposition of these minerals. The maximum temperatures recorded by the fluid inclusions are near 320$^{o}$C and are consistent with the presence of trace amounts of actinolite (Fig. 2). However, most of the mineralization appears to have occurred at temperatures of less than about 275$^{o}$C.

The geothermal fluids had salinities up to 3.5 weight percent NaCl equivalent and low noncondensable gas contents. Ratios of $CO_2/CH_4$ vs. $N_2/Ar$ indicate that the gases trapped in the inclusion fluids were derived mainly from crustal sources (Fig. 3). The trapping of $CH_4$-rich fluids suggests that the mineralization occurred early in the history of the system, before significant degassing had occurred. Temperature-salinity relationships among the inclusion fluids indicate that the early fluids were progressively diluted by steam-heated meteoric water with a temperature between about 200$^{o}$ and 225$^{o}$C (refer to Fig. 2). The thermal and chemical evolution of the rocks in Awibengkok 1-2 may be typical of the marginal parts of andesite-hosted geothermal systems, where there is little input of magmatic fluids and the effects of fluid mixing, rather than boiling are dominant.

## FUTURE PLANS

UGI has provided samples from other Awibengkok wells to the Energy & Geoscience Institute for study. We will work closely with J. Hulen on petrographic, fluid inclusion, and dating investigations of this material.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The development of conceptual models of volcanic-hosted geothermal systems is of significant interest to U.S. geothermal companies that are actively involved in exploration and development of overseas resources. Two geothermal companies have demonstrated an interest in expanding our investigations of these systems. Union Geothermal Indonesia has provided samples of other wells for expansion of studies at Awibengkok. The Karaha-Bodas Company, LLC has provided, at no charge to DOE, more than 4 km of core and all supporting geologic, geochemical, geophysical, and reservoir engineering data on the Karaha-Telaga Bodas geothermal system in Indonesia. The staff of Caithness Energy has been involved in this project and we will be working with them on the study.

The initial results of work on Awibengkok 1-2 were presented at the 1999 annual GRC meeting (Moore and Norman, 1999).

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## CONTACTS

DOE Program Manager:
Marshall Reed
U. S. Department of Energy
Geothermal Division, EE-122
1000 Independence Ave., SW
Washington, D. C. 20585
Tel: (202) 586-8076
Fax: (202) 586-8185

Principal Investigator:
Joseph N. Moore
Energy & Geoscience Institute
423 Wakara Way
Salt Lake City, UT 84108
Tel: (801) 585-6931
Fax: (801) 585-3540

DOE Idaho Operations Office Program Manager:
Peggy Brookshier
U. S. Department of Energy
Idaho Operations Office
795 DOE Place, MS 1220
Idaho Falls, ID 83401-1563
Tel: (208) 526-1403
Fax: (208) 526-5964

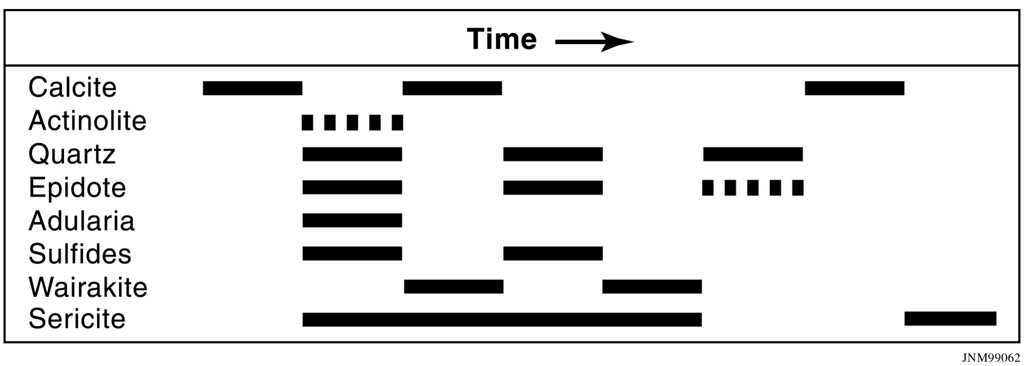


**Figure 1.** Generalized paragenesis of veins studied in Awibengkok 1-2. Dashed lines indicate that the mineral is present in trace amounts.

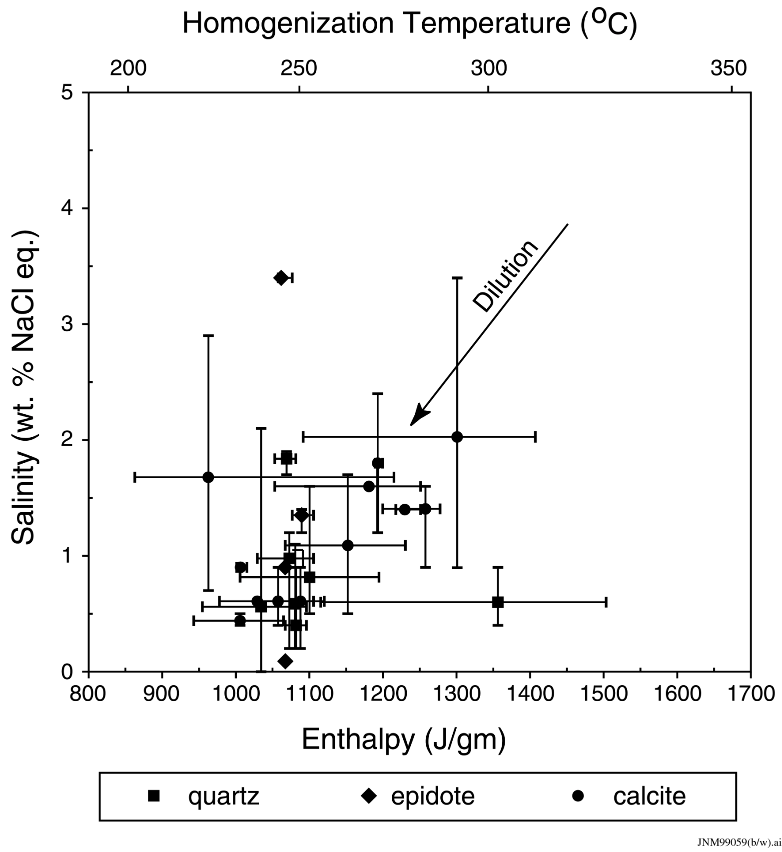


**Figure 2.** Ranges of homogenization temperatures and salinities (in weight percent NaCl equivalent) of fluid inclusions. Data on high-salinity fluid inclusions trapped in calcite from 1533.9 m was excluded. The heavy arrow shows a possible dilution trend.

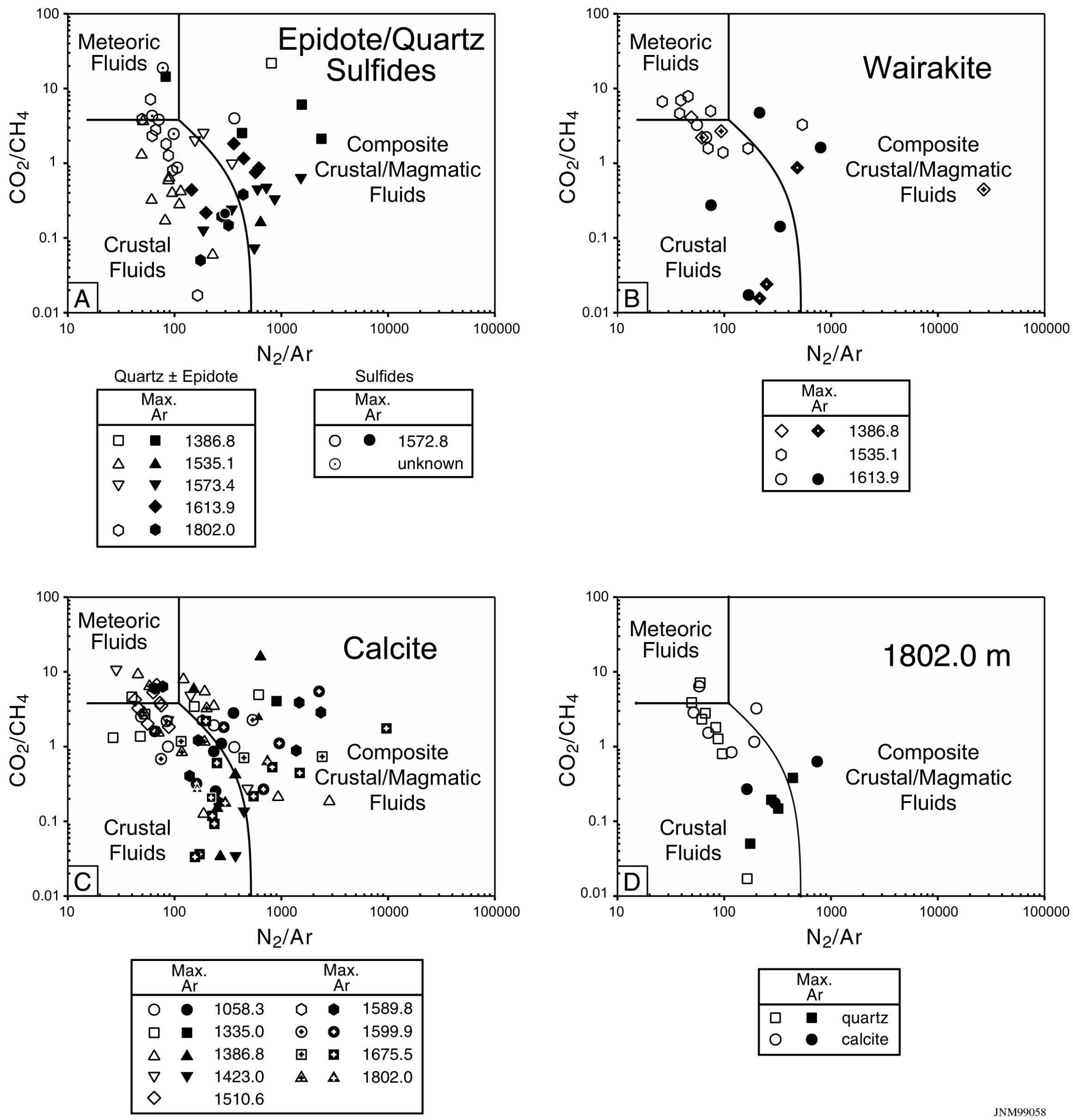


**Figure 3.** Plots of $CO_2/CH_4$ vs. $N_2/Ar$ of inclusion fluids. Sample depths are shown in meters. Max. Ar = calculated maximum argon content. (from Norman and Moore, 1999).

# LABORATORY INVESTIGATION OF FRACTURE CLOSURE UNDER HYDROTHERMAL CONDITIONS

Peter Persoff
Earth Sciences Division
Lawrence Berkeley National Laboratory

## KEY WORDS

pressure solution, creep, fracture closure, mineral precipitation

## PROJECT BACKGROUND AND STATUS

Laboratory measurement of rock properties and processes provides a basis for modeling and management of geothermal reservoirs. Previously we have measured permeability and other rock properties on fractures from Dixie Valley, Nevada and core plugs from The Geysers, California fields.

In our studies of The Geysers cores, we found more mineral-filled, impermeable veins than permeable veins. The prevalence of sealed veins (formerly permeable fractures) in recovered core indicates that natural fractures have a finite productive life. The lifetime of fractures is especially important in evaluating the economic potential of reservoir stimulation by hydro-fracking, or fracking with sand propping.

Fractures in the subsurface are held open by asperities, points of rock-to-rock contact. This is true for both a small fracture (millimeter scale), consisting of the open space between two imperfectly matched rough surfaces with isolated asperities, and for a large fracture or fracture zone (meter scale) that is filled with rubble. In general, the lithostatic stress on the rock is greater than the pore pressure, and this unbalanced force provides one of the driving forces for fracture closure.

Several mechanisms can potentially cause fractures to close, and one of the goals of this project is to identify which ones are important in geothermal reservoirs from the fluid production point of view. Within the rock itself, the rock may break or creep to close the fracture. In addition to these, it is paradoxical that both dissolution and precipitation can also close the fracture. Precipitated mineral phases can fill and close the pore space. But dissolution can also close the fracture, if the asperities themselves are dissolved away.

Pressure solution appears to be an important cause of fracture closure. Generally pore water is at lower pressure than the solid phase (hydrostatic vs. lithostatic pressure). But depending upon mineral surface charge density, a film of water up to 100 angstroms thick can be held between asperities, where the water pressure equals the solid phase pressure. Because of this elevated pressure, minerals are more soluble in this water film than in the bulk water.

Most previous studies of pressure solution phenomena have been done with pure compounds and simple geometries. This will be the first experiment to investigate these phenomena in a natural fracture under field conditions of temperature, pressure, and mineral heterogeneity.

Because the pressure solution mechanism only acts in water films held between asperities, dissolution only occurs at the asperities. As a result, dissolution of a minute amount of material decreases the average fracture aperture over a relatively large area. The resulting decrease in permeability is much greater than could be caused by an equivalent amount of mineral precipitation.

A specially-designed pressure vessel, capable of 23,000 psi at 800 °C has been fabricated for this project. The pressure vessel will be heated externally by a tube furnace which can reach 1200 °C. We will use a core-test system of computer-controlled pumps and pressure transducers for permeability measurements. In our experiments, 1-inch x 2-inch cylindrical samples will be fitted with endcaps, encased in a gold membrane, and subjected to 400°C and confining pressure of 20,250 psi. Water will be pumped through the sample at a lower pressure of about 10,000 psi, simulating hydrostatic pressure.

Preliminary calculations have been done to check that, for water at this temperature and pressure, and for fractures of aperture 0.1 to 100 µm, both the flow rate and pressure drop will be within easily measured ranges. Although we are simulating a geological process in the laboratory, experiments reported in the literature indicate that under these conditions measurable or even dramatic permeability decrease should be observable within a one month period.

Mineral samples will be examined by X-ray diffraction, scanning electron microscopy and electron microprobe analysis to identify the phases dissolved and precipitated. Water samples will be analyzed for appropriate constituents to measure dissolution rates. The data will be analyzed to calculate kinetic constants for mineral dissolution and precipitation.

## PROJECT OBJECTIVES

The objective of the project is to understand mechanisms that contribute to fracture closure in geothermal reservoirs.

### *Technical Objectives*

- Determine the processes involved in fracture closure under carefully controlled laboratory conditions.
- Construct a “map” of temperature-pressure space for a few important minerals (e.g. quartz) delineating the areas in which various mechanisms for fracture closure dominate
- Construct a similar map for natural fractures in the core tested in the laboratory (from well Awibengkok 1-2) and explain discrepancies from the pure-mineral map, if any.

### *Expected Outcomes*

- Kinetic data to predict rates of pressure solution of important minerals under geothermal reservoir conditions.
- Ability to predict approximately the expected decrease in permeability of a typical or specific fracture during exploitation of a geothermal reservoir.
- Improved confidence in reservoir management plans, including operations that could reduce or avoid closure of fractures in production and injection wells.

## APPROACH

The technical will consist of controlled laboratory experiments using both ideal and natural fractures. Ideal fractures are machined from pure mineral with smooth parallel walls and uniform aperture, propped open at a few points. In natural fractures, the roughness of the fracture walls, the local and average aperture, and the mineralogy are “as received” from the field. Experiments will be done at reservoir-relevant conditions of temperature, pore pressure, and confining pressure. Essentially, each experiment consists of flowing water through the fracture at a constant rate and observing changes on pressure drop. In an ideal fracture, decrease in permeability can be precisely related to dissolution of the asperities, from which dissolution kinetics can be calculated. Experiments with natural fractures will test how far the theory can be applied to conditions encountered in geothermal reservoirs.

## RESEARCH RESULTS

Aperture profile, volume, and permeability are related indicators of fracture closure. In this project, we measure all three properties of fractures samples. First, these properties are measured with flowing gas through the sample at room temperatures, Then permeasbility changes will be monitored by flowing liquid under reservoir conditions, and finally, all three properties re-measured using gas flow.

FY2000 is the second year of this planned three-year project. During the first year, the apparatus described earlier, including computer-controlled core test system , pressure vessel, and data acquisition system was assembled. A sample containing a natural fracture from the Awibengkok field was obtained and machined to size. The initial characterization of the sample has been completed. A “before” aperture profile was produced by photographic and image-digitizing techniques; a partial profile is shown in the accompanying digitized photograph (Figure 1). “Before” aperture volume and permeability have been measured by gas-pressure-pulse-decay (GPPD). Mathematical techniques have been derived for data analysis, some of which are presented in the references given below.

## FUTURE PLANS

During FY02000-2001 several series of experiments on both ideal and natural systems will be performed. The laboratory data and their interpretation will be communicated to the industry and feedback will be sought to guide selection of conditions for further experiments.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Fracture closure is an undesired phenomena in geothermal reservoirs because fracture apertures control the amount of fluids allowed to flow through the reservoir and from (or into) wells. The development of deep geothermal reservoirs will depend on the presence of open fractures with enough permeability to sustain commercial-scale fluid flow indefinitely, or at least for the design life of production or injection wells intersecting the fractures.

All companies interested in developing geothermal resources located at depths more than 2-3 km, at temperatures and pressures higher than in reservoirs presently in commercial operation, need to know how fractures behave under those harsher conditions.

This project will improve understanding of fracture behavior in geothermal reservoirs and provide input to Unocal’s operations at Awibengkok, Indonesia. Knowing the expected life of fractures would help to evaluate the decision of hydrofracturing of a given reservoir from an economical point of view.

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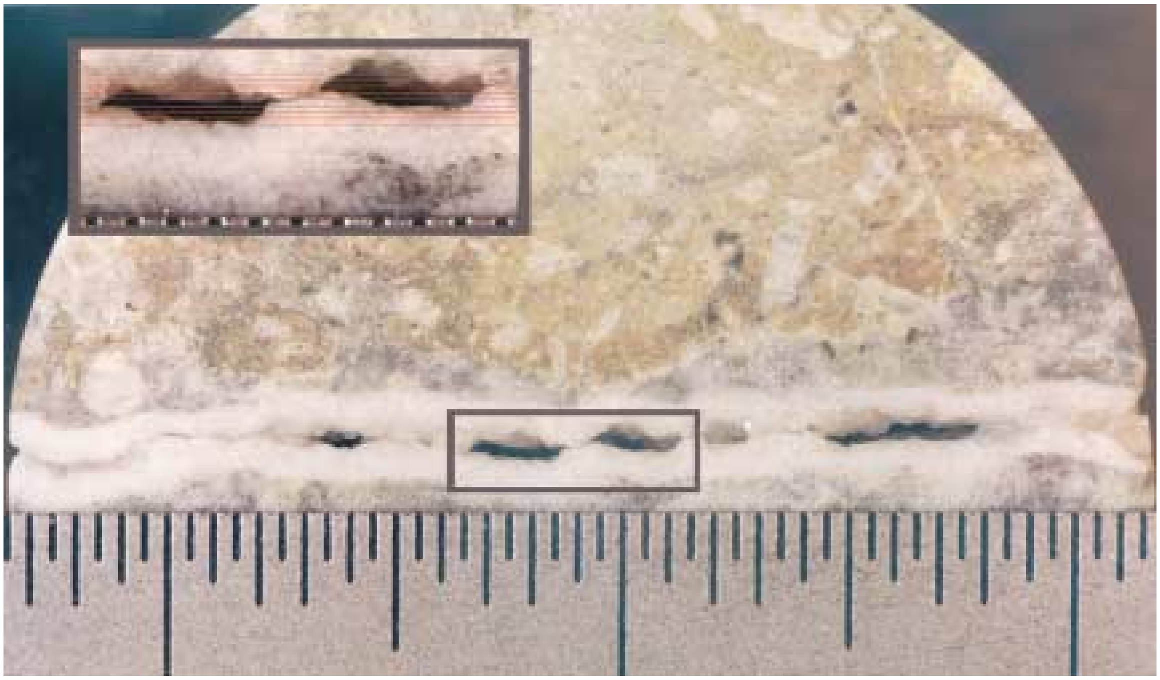

**Figure 1.** Natural Fracture in a 1-inch Core Plug from Awibengkok 1-2 Well, 4502 ft. Parallel lines in the inset are 127 micrometers apart

## CONTACTS

Marshall Reed
Office of Geothermal Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-8076
Fax: (202) 586-8185

Peter Persoff
Lawrence Berkeley National Laboratory
Earth Sciences Division
One Cyclotron Road, Mail Stop 90-1116
Berkeley, CA 94720
Phone: (510) 486-5931
Fax: (510) 486-7079
Ppersoff@lbl.gov

# GEOCHEMISTRY OF ALUMINUM IN HIGH TEMPERATURE BRINES

P. Bénézeth, D. A. Palmer, D. J. Wesolowski
Chemical and Analytical Sciences Division, Oak Ridge National Laboratory

## KEY WORDS

aluminum, solubility, kinetics, potentiometry, permeability, alteration, aluminosilicates, modeling

## PROJECT OBJECTIVES

The objective of this research is to provide quantitative data on the equilibrium and dynamic properties of aluminum minerals required to model changes in permeability and brine chemistry associated with fluid/rock interactions in the recharge, reservoir, and discharge zones of active geothermal systems. The empirical and semi-empirical treatments of the solubility/hydrolysis experimental results on single aluminum mineral phases form the basis for the ultimate investigation of the behavior of complex aluminosilicate minerals. These treatments will also be incorporated into existing codes used by the geothermal industry to predict the chemistry of the reservoirs and will be tested for reliability against our laboratory results and field observations.

### *Technical Objectives*

- Complete analysis of all thermodynamic data pertaining to the solubility of gibbsite and boehmite garnered in this program with appropriate, verified data taken from the literature. This treatment will provide a unified set of equilibrium constants and associated thermodynamic parameters from ambient conditions to 300°C and ionic strengths of up to five molal.

- Kinetic studies of the dissolution/precipitation of gibbsite and boehmite will continue in the existing hydrogen-electrode concentration cells to gain unique rate data on these processes, instigated by small and large isothermal perturbations in pH from the equilibrium state. These investigations will then extend to more complex aluminosilicate minerals using this method and perhaps conventional flow-through reactors equipped with down-stream pH monitoring.

- The solubility quotients for gibbsite and boehmite obtained in this program will be substituted into the codes commonly used in the geothermal industry. In particular, the Pitzer ion-interaction model will be used to treat the solubility/hydrolysis quotients, $Q_{S0}$ and $Q_{S4}$, as well as isopiestic data on the Na-$Al(OH)_4$-Cl system gathered earlier in this program. Note that the current limit of the EQ3-6 code for this system is 100°C.

- Solubility measurements will also be carried out on aluminum-rich scales obtained from active geothermal fields.

### *Expected Outcomes*

- A consistent set of thermodynamic parameters will be generated, which will define the prevalent aqueous aluminum species, as well as the chemical composition of solutions in equilibrium with rock-forming minerals, at geothermal reservoir conditions.

- The results will be treated to allow them to be readily incorporated into chemical reaction and transport computer codes in common use by the geothermal industry.

- The dissolution/precipitation kinetics and solubilities of aluminosilicates will be studied with the intent of addressing problems associated with brine reinjection, scaling, and corrosion in down-hole and in-plant systems.

- Solubility results on actual scales should provide information on expected incongruent reactions that release constituents to the aqueous medium. Quantitative knowledge of these nonequilibrium reactions will provide a guide for scale removal and mitigation procedures used in the industry.

## PROJECT BACKGROUND AND STATUS

Accurate models for the thermodynamics and kinetics of processes at mineral-aqueous interfaces are essential to the prediction of corrosion and scale formation in geothermal systems. The effects of other activities, such as fluid extraction and spent fluid reinjection on reservoir porosity and permeability, can also benefit from model calculations based on sound fundamental data obtained in the laboratory.

The solubility of gibbsite in NaCl solutions to 5 molal over a wide range of pH to 80°C was investigated in the initial phases of this program. These studies were performed using a batch technique, which involved either calculations of pH from the stoichiometric concentrations of initial acid or base and the measured concentration of aluminum in solution with a known speciation, or the use of pH buffering agents. The solubility studies (Wesolowski, 1992; Palmer and Wesolowski, 1992; Wesolowski and Palmer, 1994) were complemented by a potentiometric determination of the first hydrolysis quotient for $Al^{3+}$, which was carried out to 5 molal ionic strength (NaCl) and 125°C (Palmer and Wesolowski, 1993). Combination of these results yielded solubility quotients for gibbsite to form $Al^{3+}$, $Al(OH)^{2+}$, $Al(OH)_2^+$, and $Al(OH)_4^-$. Additional solubility experiments in non-complexing sodium triflate solutions established that no detectable ion pairing occurred, at least at 50°C, between $Al^{3+}$ and $Cl^-$, which was the dominant anion in the supporting electrolyte used throughout this entire investigation. Moreover, other experiments in sodium nitrate media with gibbsite that had never been exposed to chloride ion, established that chloride had no specific effect on this solid phase that could be detected as anomalous solubility.

The second stage of this research program involved a thorough study of the thermodynamics of aqueous aluminum at temperatures above 100°C, which required a different approach, in that use of pH buffers is impractical due mainly to their limited thermal stabilities and to the likelihood that their interactions with dissolved aluminum species would become even stronger with increasing temperature. Furthermore, the batch method was considered too time-consuming to investigate not only the temperature dependencies of the solubility equilibria, but also the influence of salinity on speciation, which is substantial and most directly relevant to geothermal environments. Note that the effect of salinity has not been addressed in any of the previous high temperature studies. The current program focuses on the solubility of boehmite in the 100-290°C range at ionic strengths of 0.03 to 5 molal (27.5 wt %) using the hydrogen-electrode concentration cell, which allows continuous pH monitoring in conjunction with periodic sampling and analysis of aluminum in the aqueous phase, and the kinetics of gibbsite and boehmite dissolution/precipitation reactions using the pH-perturbation method.

This research program benefits substantially from three projects funded by the DOE Office of Basic Energy Sciences, namely two from the Geoscience Research Program entitled "Fundamental Geochemistry of Geothermal Systems", and "Experimental Studies of Hydrothermal Processes Employing *In Situ* pH Measurements", as well as the project entitled "Basic Aqueous Chemistry to High Temperatures and Pressures", funded by the Chemical Sciences Division. These programs permit more detailed, fundamental studies of certain aspects of aluminum chemistry, such as complexation by organic and inorganic ligands occurring in natural and experimental solutions.

## APPROACH

Detailed laboratory-scale measurements of the solubility of gibbsite and boehmite have been made under controlled conditions of temperature and ionic strength. The technique of monitoring pH *in situ* during each solubility experiment was developed in this program and has proven invaluable at high temperatures by providing accurate, expedient and unique thermodynamic and kinetic results. This is particularly apparent at the solubility minimum for boehmite, which was found to be lower by almost a log unit at 300°C than previously acknowledged. Initial kinetic studies have been initiated on the dissolution/precipitation reactions of gibbsite and boehmite by monitoring the associated change in pH as a function of time. Modeling efforts were also initiated to establish the reliability of codes used by the geothermal community in regard to aluminum chemistry.

## RESEARCH RESULTS AND VARIANCES

Treatment of the recently acquired boehmite solubility data in NaCl solutions is complete and now a consistent set of thermodynamic quantities are available for the boehmite dissolution equilibria from 100 to 290_C, and from infinite dilution to five molal ionic strength. Moreover the hydrolysis quotients obtained at these conditions are fully consistent with those derived from gibbsite dissolution and already published from our earlier program. The effect of increasing ionic strength (from 0.03 to 5 molal) is to shift the solubility minimum to higher pH, increasing the stability of $Al^{3+}$ and minimizing the stability fields of the hydrolyzed species other than that of the aluminate anion (Bénézeth et al., 1997). Note that three manuscripts describing the thermodynamics of boehmite dissolution are currently in preparation (Palmer et al, 2000a,b; Bénézeth et al., 2000).

A logical extension of the solubility studies on boehmite in NaCl brines was to conduct a number of solubility studies in tetramethylammonium chloride (TMACl) solutions in basic solutions at 200°C (I = 0.1 molal). The $TMA^+$ cation is known to form very weak ion pairs with singly-charged aqueous anions. However, we were unable to detect any increase in solubility with increasing sodium concentration at constant ionic strength and pH, and can therefore only place a possible maximum value on an $Na^+$-$Al(OH)_4^-$ ion pair formation constant at this time.

As yet unpublished isopiestic data on sodium aluminate solutions from 100 to 169°C are available from measurements carried out in our laboratory for the geothermal program. Although solubility data exist in the literature for boehmite in relatively high caustic solutions, it was decided to conduct some batch experiments to verify the accuracy of these results and to provide the needed “high aluminate concentrations” that would contribute to the modeling effort. A series of experiments was conducted from 100 to 200°C in a Teflon-lined autoclave up to approximately four molal total NaOH with aluminate concentrations up to 1.9 molal. Beyond this concentration, precipitation of an aluminate phase occurred in the sampling lines indicating the upper concentration limit for these experiments.

We have now successfully completed the first stage of the modeling program based on the Pitzer ion interaction treatment for the Na-$Al(OH)_4$ –OH system. The modeling effort incorporates the osmotic coefficient data (110-169°C) from Howard Holmes (retired, ORNL) and equilibrium solubility quotients for the reaction:

$$AlOOH + OH^- + H_2O \; Al(OH)_4^-$$

These quotients were either obtained in the current geothermal program last year. The values of $\$^0$, $\$^1$, C for $NaAl(OH)_4$, and the mixing parameters $2_{OH.Al(OH)4}$ and $R_{Na,OH,Al(OH)4}$, were fixed at 25°C according to Wesolowski (1992), which were based on the equivalent gibbsite solubility data. The infinite dilution solubility constants were taken from our boehmite solubility data. It was found that only 3 temperature-dependent terms were needed to fit the entire boehmite solubility/osmotic coefficient data set. The temperature-dependent terms were in the parameters $\$^0$ and $\$^1$ for $NaAl(OH)_4$ and $_{Rna.OH.Al(OH)4}$. We have also adapted the commercial code EQ3/6 database formulated on the Pitzer model to include the parameters of Wesolowski (1992) for sodium aluminate and NaOH from Simonson, Mesmer and Rogers (1989). This modification allows the code to run to 300°C for the $Na\text{-}Al(OH)_4\text{-}OH$ system. These parameters will next be replaced by the parameters derived from the present work. The current predictions of the modified EQ3/6 program to 300°C also confirm that only small modifications are needed (i.e., as indicated by the need for only three temperature-dependent adjustable variables), in order to fit the high temperature solubility data. This supports the overall conclusion that we now have a unified model for aqueous aluminum from ambient to high temperature, and from infinite dilution to solutions with ionic strengths on the order of 20 molal.

During this period, the boehmite and gibbsite dissolution/precipitation rates have been investigated in basic media. The aqueous speciation is less complicated compared to acid/neutral systems in that, over a wide pH, temperature and salinity range relevant to various geothermal and industrial systems conditions, the aluminate, $Al(OH)_4^-$, is the dominant species. The boehmite kinetic experiment was initiated at 100°C and 0.1 molal NaCl ionic strength, whereby boehmite was suspended in dilute NaOH in ca. 0.1 molal NaCl. Cell potential, temperature and pressure were recorded as a function of time and a sample withdrawn after 24 hours for analysis of aluminum by spectrophotometry. The pH was then perturbed by addition of an acidic titrant to create a solution supersaturated with respect to boehmite, thereby allowing us to follow the kinetics of the precipitation reaction. Several precipitation steps were performed in this way, with sampling of the solution before the following titrant addition. As the near-neutral pH region was approached, several additions of a basic titrant were then performed to follow the kinetics of the dissolution reaction. After completion of the precipitation/dissolution cycles at 100°C, the temperature was raised to 150°C to begin new sets of precipitation/dissolution cycles, at 50°C intervals up to 290°C.

The rates of both boehmite dissolution ($k_{diss}$) and precipitation ($k_{prec}$) are relatively fast at high temperature, so that only the dissolution runs performed at 100°C have been analyzed in detail. However, the equilibrium solubilities obtained after each addition of acid or base are in excellent agreement with our previous solubility measurements performed at the same conditions (from 100 to 290°C, 0.1 NaCl). The results of the boehmite dissolution experiment were first converted from $pH_m$ to total aluminum molality $[Al(OH)_4^-]$ versus time. The principle of detailed balancing was applied and hence:

$$d[Al(OH)_4^-]/dt = k_{diss}C - k_{prec}\,Cm_{H+}m_{Al(OH)4-} = 0$$

where C stands for the ratio of total surface area of boehmite to the mass of solution. Thus, a plot of rate, $d[Al(OH)_4^-]/dt$, versus $m_{H+}\cdot m_{Al(OH)4-}$ is linear with an intercept and slope proportional to the respective rate constants. The ratio of the forward and reverse rate constants should be equal to the overall equilibrium solubility quotient $Q_{s4}$. For the two dissolution cases investigated, the values of $\log(k_{diss}/k_{prec})$ are in excellent agreement, within 0.1 log units, with the corresponding equilibrium constants obtained from the fit of the boehmite solubility at the same conditions (100°C, 0.1 molal NaCl, $\log Q_{s4}$,=-12.74). Boehmite proved to be an ideal phase for study, in that its dissolution/precipitation kinetics permitted demonstration of reversible equilibrium solubilities at all temperatures studied and no other phases formed as a result of incongruent dissolution or precipitation from a supersaturated state. Similar experiments were recently initiated with gibbsite at 50°C and 0.1 molal NaCl ionic strength, whereby gibbsite was suspended in dilute NaOH in 0.1 molal NaCl. Again, equilibrium solubilities ($Q_{s4}$) obtained proved to be in excellent agreement with the previous batch gibbsite solubility results (Wesolowski, 1992, and Wesolowski and Palmer, 1994) for the entire pH range investigated (from 10.3 to 8.4). Using the same principle as applied to the boehmite reaction, the values of $\log(k_{diss}/k_{prec})$ are also in excellent agreement with our previous solubility data of Wesolowski and Palmer (1994) ($\log Q_{s4}$,=-13.86) within 0.1 log units. As the principle of detailed balancing works for both boehmite and gibbsite, we anticipate that their dissolution and precipitation rates can be obtained without the need of measuring both of them. Nevertheless, this hypothesis is currently being checked experimentally. In addition of the accurate measurement of pH, temperature and pressure, as well as surface characterization, several experimental variables are also being currently checked, such as stirring rate, solid/solution ratio, salinity, pH and temperature, to gauge their effect on the kinetics.

Also, during this period, siliceous scales deposited at the Salak geothermal field (Indonesia) were sent to us by D. Gallup (Unocal, Ca). This scale is a natural precipitate from injection brine at ~177°C and seems to consist of aluminum-rich amorphous silica. A portion of the composite was ground and sieved again to retain the fraction between 40 and 100 µm. Detailed characterization was performed on the powder and the corresponding composites by SEM and XRD. The SEM images of the dark composite showed colloidal agglomerated particles, probably corresponding to amorphous silica as the qualitative chemical analyses (EDS), performed at various locations on the selected sample, revealed silicon and oxygen as the predominant elements. Aluminum is also present in most of the particles with traces of S, Fe and Mg. Some needle-like crystals were also found and consist of $SiO_2$ associated with magnesium and sodium. The presence of iron is clearly associated with sulfur as shown by chemical analyses during the SEM imaging, and was confirmed by XRD, which revealed very well crystalized pyrite. As discussed below, we are now initiating dissolution/precipitation studies with this material.

## FUTURE ACCOMPLISHMENTS

The hydrogen-electrode concentration cell approach is entirely amenable to studies of the rates and equilibrium constants of mineral transformation reactions, such as the hydrolysis of feldspars via reactions like the alteration of potassium feldspar to muscovite and quartz:

$$3KAlSi_3O_8 + 2H^+ \; KAl_3Si_3O_{10}(OH)_2 + 2K^+ + 6SiO_2$$

If these phases react sufficiently rapidly to achieve equilibrium in a few weeks at temperatures of 200-300$^oC$ in our cells, which are magnetically stirred with high efficiency promoting rapid attainment of solid/liquid equilibrium, the kinetics of this reaction will be investigated in detail. This knowledge will aid in predicting, pH, steam corrosivity and scale formation in geothermal systems. Furthermore, by first establishing an equilibrium $K^+/H^+$ ratio, then quickly changing this ratio by titration of acid, base, or potassium into a solution in equilibrium with the mineral assemblage, and monitoring the rate of change of pH to a new equilibrium value, we can obtain the rates of reaction, both at near- and far-from-equilibrium conditions, as a function of temperature, pH, salinity, and mineral grain size.

Future studies will involve equilibrium solubility and dissolution/precipitation rate determinations of a number of aluminosilicate phases prevalent in geothermal reservoirs at higher temperatures, including the amorphous silica/alumina scale described above from the Indonesian geothermal system, using the hydrogen-electrode concentration cell. The only limiting factor in the use of these cells will be the formation of additional phases during the course of the experiments. Therefore, we have initiated studies of gibbsite, for which equilibrium data are available from earlier work in this program and we know that at least in the dissolution reaction, no other phases are formed. We will then undertake to investigate aluminosilicate solubility equilibria and kinetics by first determining the dissolution and precipitation kinetics of increasingly complex aluminosilicates, including kaolinite and dickite.

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## CONTACTS

Marshall Reed
Geothermal Division, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone (202)586-8076
Fax (202) 586-5124

Pascale Bénézeth Phone: (865)574-4960
Donald A. Palmer Phone: (865)576-1509
David J. Wesolowski Phone: (865)574-6903
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O. Box 2008, Bldg. 4500S, MS-6110
Oak Ridge, TN 37831-6110
FAX: (865)574-4961

# STEAM-WATER CAPILLARY PRESSURE IN GEOTHERMAL ROCKS

Roland N. Horne
Stanford University

## KEY WORDS

capillary pressure, performance forecasting

## PROJECT BACKGROUND AND STATUS

Steam-water capillary pressure has a significant effect on water injection into and production from geothermal reservoirs. The mass transfer between steam and water phases makes it very difficult to measure steam-water capillary pressure using routine methods such as the semipermeable porous plate method and centrifuge method. Due to the difficulties in measuring steam-water capillary pressure, very few steam-water capillary pressure data are available. We used a steady-state flow method to measure steam-water capillary pressures using an X-ray CT technique to monitor and measure the saturation and distribution of water in the core sample. The drainage steam-water capillary pressure was calculated using a formula derived from the Kelvin equation after measuring the pressures and temperatures of the water phase.

## PROJECT OBJECTIVES

### *Technical Objectives*

- To measure steam-water capillary pressure in rocks.
- To develop a correlation to permit the estimation of steam-water capillary pressure in geothermal reservoir rocks under reservoir pressure and temperature.

### *Expected Outcomes*

- A procedure to determine capillary pressure in geothermal reservoirs, for use in estimating future production performance. Optimizing production strategy by properly simulating the steam-water flow behavior has the potential to improve overall reservoir productivity by 30-50%
- A set of measurements of steam-water capillary pressure to establish a set of reasonable values for this parameter for reservoir calculations.

## APPROACH

In this project, a method to calculate steam-water capillary pressure has been developed using the data from steady-state steam-water flow experiments by Mahiya (1999). An X-ray CT technique was used to monitor and measure the water saturation and its distribution in the core sample. The pressures and temperatures of water phase in a Berea sandstone sample were measured at different axial positions. Water saturation was varied by changing the flow rates of steam and water at the inlet of the core sample. Experiments were conducted under near-adiabatic conditions controlled automatically by a computer. Steam-water capillary pressures in the Berea sandstone sample can be calculated using a formula derived from the Kelvin equation together with the measured values of the pressure and temperature of the water phase. Following that, the steam-water capillary pressure of a rock sample from The Geysers field can be computed on the basis of the results from the Berea sandstone sample by a method developed during the project using the concept of a J-function. The values estimated by this approach were compared to the vapor-water capillary pressures measured by Persoff and Hulen (1996) using an adsorption method.

## RESEARCH RESULTS

The steam-water capillary pressures calculated using the procedure described by Li and Horne (2000) with the experimental results of steady-state flow of steam and water in a Berea sandstone sample are shown in Figure 1 which shows a drainage capillary pressure curve. The entry capillary pressure of steam is very small for this sandstone sample. The steam-water capillary pressure in the Berea sandstone sample at a water saturation of about 30% is around 0.07 Mpa (10.4 psi). The water saturation remaining in the core sample after the drainage by steam flooding is about 28 %.

We scaled the experimental values of steam-water capillary pressure from Persoff and Hulen (1996) to the temperature of 120ºC. The surface tension of steam/water at 120ºC is 54.96 dynes/cm. The comparison of the steam-water capillary pressure for a Geysers rock by the calibrated steady-state flow of this project and the adsorption methods of Persoff and Hulen (1996) is shown in Figure 2, based on the same temperature. The two sets of steam-water capillary pressure values are remarkably consistent after the calibration.

## FUTURE PLANS

The results of steam-water capillary pressure calculated by applying the Kelvin equation to the data from steady-state steam and water flow experiments are very preliminary, although Figure 2 shows remarkable consistency between the capillary pressure values obtained by steady-state flow and adsorption methods. The main uncertainties are the J-function and the contact angle in steam-water-Berea and steam-water-geothermal rock systems. If the difference of the J-function and the contact angle between the steam-water-Berea and steam-water-geothermal rock systems could be identified, then we could calculate the steam-water capillary pressure of geothermal rocks more accurately. It takes much less time and effort to measure the steam-water capillary pressure in highly permeable rocks than in low permeability rocks. Unfortunately, few data for the J-function and the contact angle in geothermal rocks are available. Hence, the application of the steam-water capillary pressure model to geothermal reservoir engineering will depend on further research on these parameters.

Another important question also remains: is there any difference between steam-water capillary pressure and air-water or nitrogen-water capillary pressure? If there is no difference, we could measure air-water capillary pressure as a substitute of the steam-water capillary pressure. The air-water measurements are very much easier to conduct. We have embarked on a project to measure the steam-water and air-water capillary pressures using the same rock sample.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Industrial developers of geothermal energy have take an interest in this project and the possibility of improving production forecasting.

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## CONTACTS

Roland N. Horne, Kewen Li, Dorie Lysaght
Stanford Geothermal Program
Dept. of Petroleum Engineering
Stanford University
Stanford, CA 94305-2220
(650)725-2723, fax:(650)725-2099
e-mail: horne@pangea.stanford.edu

Marshall Reed
US Department of Energy
Office of Geothermal Technologies, EE-12
1000 Independence Avenue, SW
Washington DC 20585
(202)586-8076, fax: (202)586-8185
e-mail: marshall.reed@hq.doe.gov

Joel Renner
Idaho National Engineering Lab
PO Box 1625-3830
Idaho Falls, ID 83404-3830
(208)526-9825, fax: (208)526-0969
e-mail: rennerjl@inel.gov

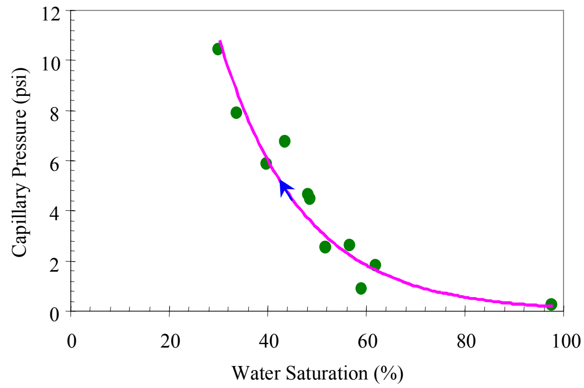


**Figure 1.** Steam-water capillary pressure curve calculated from the data of steady-state flow of steam and water in a Berea sandstone sample.

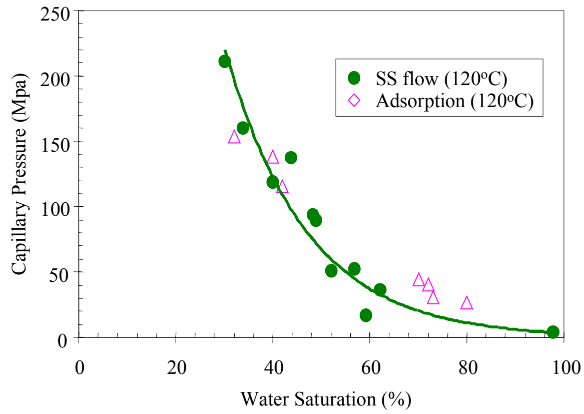


**Figure 2.** Comparison of steam-water capillary pressure curves by steady-state (SS) flow and adsorption methods for a rock from The Geysers field.

# STEAM-WATER RELATIVE PERMEABILITY IN GEOTHERMAL ROCKS

Roland N. Horne
Stanford University


## KEY WORDS

relative permeability, steam-water, phase change, X-ray CT scanner


## PROJECT BACKGROUND AND STATUS

The reliable measurement of relative permeability functions for steam-water flows in porous media is of great importance for reservoir simulation in order to forecast production performance of geothermal reservoirs. Despite their importance, these functions are poorly known due to the lack of understanding of steam-water flows, and to the difficulty of making measurements. Traditionally, these functions are taken directly from isothermal, immiscible gas-liquid displacement processes. However, the use of such functions is not appropriate because these processes do not involve the two important phenomena pertinent to steam-water flows: heat transfer and phase change. Therefore, the objective of this research project is to determine the appropriate relative permeability functions for steam-water flows in geothermal reservoirs, as well as to investigate their properties as a function of temperature and flow rate.

The Stanford Geothermal Program has used an X-ray CT (Computer Tomography) scanner to obtain accurate saturation profiles by direct measurement. During the earlier years of the project, we have carried out experiments with nitrogen-water flow and with steam-water flow, and examined the effects of heat transfer and phase change by comparing these sets of results. In porous rocks, it was found that the steam-water relative permeabilities follow Corey type relationships similar to those in nitrogen-water flow, but that the irreducible gas phase saturation is smaller for steam than for nitrogen. The irreducible saturations represent substantial fractions of the recoverable energy in place yet are hard to determine in the field. Understanding the typical magnitude of irreducible saturations will lead to a much clearer forecast of geothermal field performance. In fracture flow, indirect measurements suggested that the relative permeabilities follow a linear (or "X-curve") behavior -- but there is still considerable uncertainty in the knowledge of this behavior.

## PROJECT OBJECTIVES

### *Technical Objectives*

- To measure the steam-water relative permeabilities in rocks, in order to provide reasonable relationships for use in the simulation of actual reservoir performance.
- To determine the fundamental flow behavior of two-phase boiling flow in real rocks.

### *Expected Outcomes*

- A set of experimental relative permeability curves that can be used in reservoir simulation. Applying the correct behavior in simulation could make a difference in the calculated performance by as much as 50% of total production—hence the value in measuring relative permeability is a substantial increase in the certainty of prediction of reservoir performance.

- A set of relationships to determine the variation of relative permeability as a function of reservoir and flow conditions. Providing the correct relationships will improve the certainty of reservoir performance predictions.

## APPROACH

The physical parameters required to establish relative permeability curves are pressure, temperature, heat flux, flow rates and saturation. The experimental apparatus used during this project by Satik (1998) and Mahiya (1999) made use of a nonmetallic coreholder made of the material PEEK, with a series of pressure and temperature measurements made along the interior axis of the core. Steam and water were injected independently into two separate ports at the inlet end of the coreholder, each with their own positive-displacement pump. The water used for injection was deaerated by preboiling, and then reheated by immersion heaters that were constructed within the inlet endplate of the coreholder. This configuration reduced heat losses between the heater and the core entry that had been a concern to Sanchez and Schechter (1990). Heat losses from the core were cancelled out using thin-film guard heaters under automatic computer control.

## RESEARCH RESULTS

The results of the 1999 experiments are shown in Figure 1. The behavior of the relative permeability curves in these measurements is clearly of the Corey type, and shows little difference between drainage and imbibition processes. The relative permeability values are in close agreement with the values of both Satik (1998), for the same rock, and with the values of Sanchez and Schechter (1990), for an unconsolidated sand. Figure 2 shows the comparison in terms of $k_{rs}$ vs. $k_{rw}$, showing the agreement between these three measurements, and the substantial difference of the results of Ambusso et al. (1996). Also shown on Figure 2 are the relative permeability values for nitrogen and water (imbibition process), as measured in the same core and experimental apparatus used by Mahiya (1999)—although similar in shape, it is clear that the relative permeability to nitrogen is less than that to steam, mainly because the irreducible nitrogen saturation (about 0.3) is significantly greater than the irreducible steam saturation (about 0.2). The same data, plotted as a function of water saturation in Figure 3 shows that it is the gas relative permeability that differs most prominently between steam and nitrogen—the water relative permeabilities are almost the same.

## FUTURE PLANS

Although the experimental challenges involved in measuring steam-water relative permeability are daunting, the experience of the Stanford Geothermal Program and the facilities available to us provide expectation that the difficulties will be overcome. Unlike oil-water relative permeability, which is measured routinely in the oil business, steam-water flow is rendered much more complicated by the fact that the two flowing fluids, steam and water, can and do interchange freely by the processes of boiling and condensation. Measuring the in-place saturation using the X-ray CT scanner and using the pressure measurements over the section of the core that shows constant saturation obviates the phase interchange problem. Accurate measurement of the flowing saturation was a new challenge, since it required the estimation of the enthalpy. Although the determination of enthalpy was problematic, the use of thin-film guard heaters has alleviated this difficulty considerably since it has become possible to measure the enthalpy prior to injection into the core with the knowledge that the enthalpy will not change during transport.

The targets of the project will be two:

(a) The measurement of end-point saturation values in a low permeability geothermal rock sample. This experiment will take place over a longer period of time, and will be a static (or pseudostatic) rather than a flowing experiment. The low end-point values will be estimated by reducing the water saturation in the rock to its irreducible value, with a direct measurement of the saturation using the X-ray CT scanner. The high end-point values will then be estimated by resaturating the rock with water to find the saturation at which no more steam can be removed. Again, the saturation will be measured directly using the X-ray CT scanner.

(b) To determine the properties of the steam-water relative permeability in fractured rocks.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

In a recent DOE research strategy meeting, one industry participant made the observation that he had not until that time had any confidence in the values of relative permeability that had been used in the industry and therefore that he considered the Stanford results to be very welcome.

| Organization | Type and Extent of Interest |
|---|---|
| Maxwell Technologies | Proposed use of curves in reservoir simulations |

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## CONTACTS

Roland N. Horne, Kewen Li, Dorie Lysaght
Stanford Geothermal Program
Dept. of Petroleum Engineering
Stanford University
Stanford, CA 94305-2220
(650)725-2723, fax:(650)725-2099
e-mail: horne@pangea.stanford.edu

Marshall Reed
US Department of Energy
Office of Geothermal Technologies, EE-12
1000 Independence Avenue, SW
Washington DC 20585
(202)586-8076, fax: (202)586-8185
e-mail: marshall.reed@hq.doe.gov

Joel Renner
Idaho National Engineering Lab
PO Box 1625-3830
Idaho Falls, ID 83404-3830
(208)526-9825, fax: (208)526-0969
e-mail: rennerjl@inel.gov

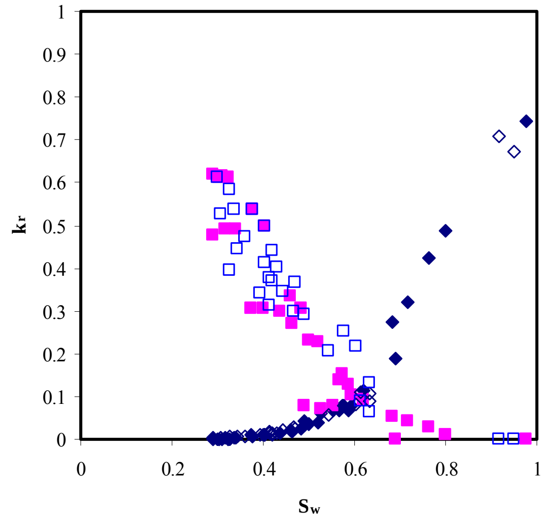


**Figure 1.** Experimental results from Mahiya (1999) adiabatic experiment. Closed symbols, drainage curves; open symbols, imbibition curves.

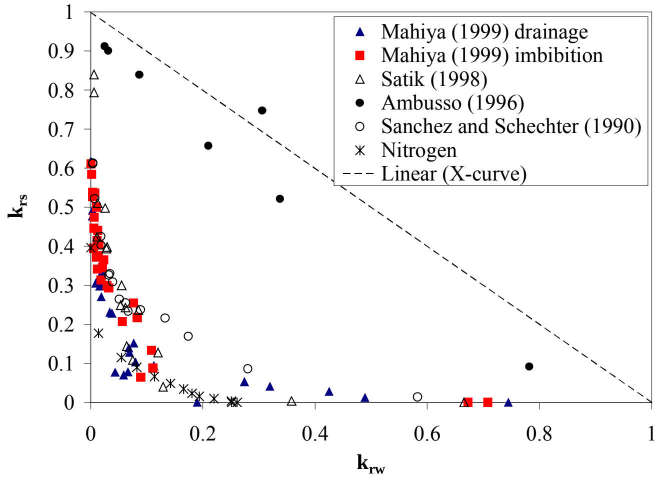


**Figure 2.** Comparison of results, $k_{rs}$ vs. $k_{rw}$.

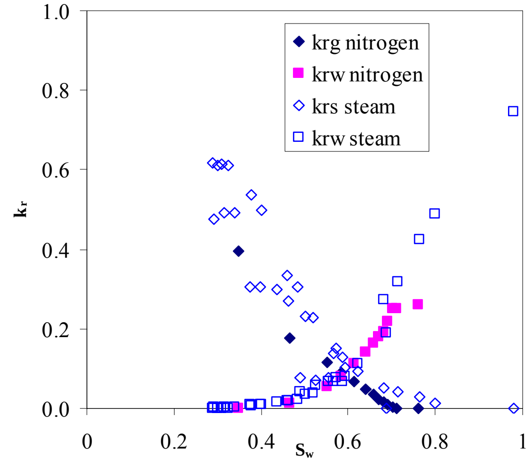


**Figure 3.** Comparison between steam-water (open symbols) and nitrogen-water imbibition (closed symbols) relative permeabilities on the same rock core.

# WATER ADSORPTION

Miroslaw S. Gruszkiewicz, Juske Horita, and J. Michael Simonson
Chemical and Analytical Sciences Division, Oak Ridge National Laboratory

## KEY WORDS

geothermal reservoir, adsorption, The Geysers, Awibengkok, rocks, porous materials

## PROJECT BACKGROUND AND STATUS

Any reliable model of the behavior of vapor-dominated geothermal reservoirs must include information about the amount of water retained on the surface of the rocks by adsorption and by capillary forces. All porous materials, including rocks, can retain water as multi-layer adsorbate on all of their internal surfaces, as pore-filling adsorbate in the micropores (widths up to about 20 A) and as multi-layer adsorbate and capillary condensate in the mesopores and macropores (widths up to about 1000 A). This retained water has a density close to the density of bulk liquid even if the temperature and pressure in the reservoir are in the superheated steam region. To estimate the size of the available resource and to predict pressure changes during operation it is important to know what fraction of the water is present in the reservoir as adsorbed layers and as capillary condensate with an equilibrium vapor pressure lower than that of bulk water. In liquid-dominated reservoirs, such as the Awibengkok geothermal field, West Java, Indonesia, vapor-dominated conditions may exist in native steam caps which expand during reservoir exploitation. Ideally, in such reservoirs, injection would be placed deep in the liquid zone, while the steam would be produced from the shallow steam and two-phase zones. Operating experience suggests that the water adsorbed in the pore system may act as either a source or a potential sink directly influencing the response to both production and reinjection. This response may be influenced by adsorption/desorption hysteresis. The same surface forces and pore system properties that cause vapor pressure lowering and water condensation on solid surfaces are also involved in the transport and separations of artificial tracers and natural components of geothermal fluids. Thus information obtained in studies of water adsorption can be useful in solving a wide range of issues where the solid-liquid interface plays an important role.

Since the physicochemical complexity of geothermal rocks makes it impossible to predict their water retention at different temperatures and pressures with any certainty, the most useful data are those obtained at temperatures near the actual reservoir temperatures. The temperature in most of The Geysers reservoir is approximately 240°C, and a higher temperature reservoir is found in the northwest area of the field. The temperatures measured in several Awibengkok wells range from 225ºC to 285ºC. The experimental data on water adsorption/desorption published in the literature have been limited to about 150°C, with most of the experiments conducted at 120°C or 130°C and below.

This project was undertaken in order to expand significantly our knowledge of the adsorption/desorption processes useful for operating geothermal reservoirs. The following work has been completed in this project:

- The Oak Ridge National Laboratory (ORNL) isopiestic apparatus was overhauled. Improvements were made to achieve the highest possible accuracy.

- The 150°C, 200°C and 250°C adsorption and desorption isotherms in the relative pressure range from vacuum to saturation were determined for 12 rock samples in three grain size fractions taken from three wells at the Geysers geothermal system, and for four pure mineral samples. Water adsorption/desorption isotherms at 150 and 200°C and adsorption isotherms at 250°C were measured on ten samples of AWI 1-2 core, two samples from The Geysers and two zeolite samples.

- The experimental data were reduced by fitting isotherms to empirical correlations of the amount of water retained as a function of relative pressure. Approximate pore size distributions were calculated from the water adsorption/desorption isotherms. A paper describing the results on The Geysers core samples was accepted for publication in *Geothermics*.

## PROJECT OBJECTIVES

### *Technical Objectives*

- Experimental determination of water retention capacities on geothermal rocks as a function of vapor pressure at temperatures from 150°C to 250°C when pressure is increasing (‘adsorption’ isotherms) and decreasing (‘desorption’ isotherms).

- Characterization of the rocks using high-temperature water adsorption results, mineralogical descriptions, and low temperature nitrogen adsorption data.

- Correlation of the water retention phenomena in the reservoirs with rock characteristics and T-p conditions.

### *Expected Outcomes*

- Obtain unique, reliable water retention data for representative core samples at the reservoir temperature. These data, including hysteresis behavior, will be available for use in reservoir models and in injection/production simulations.

- Resolve the issue of the temperature dependence of the amount of water retained.

- Determine the predominant water storage mechanism and the best way to model adsorption.

- Expand the available knowledge about the structure of the rocks and about rock-water interactions. Gain insights into both chemical and physical rock surface-water interactions that are present in geothermal reservoirs.

## APPROACH

The ORNL high-temperature isopiestic apparatus is a unique facility capable of precise and accurate measurements of the change of mass of a sample under high temperature-high pressure conditions. This capability makes it suitable for measurements of adsorption by materials characterized by small specific surface areas. The parameter measured is the mass of the solid as a function of vapor pressure. The sorptometers that have been used most often rely on measurements of vapor pressure in a chamber of known volume containing the sample. The total volume of the instrument is kept small to increase its sensitivity to relative pressure changes, but the small volume also makes the instrument more sensitive to leaks, temperature variation, and errors in calibration of the internal volumes. In the isopiestic apparatus the mass is measured directly *in situ* by comparison with a set of standard weights placed inside the pressure vessel together with the samples. The densities of the samples, which must be known in order to correct the results for the effect of buoyancy, are measured inside the isopiestic apparatus by weighing the samples in vacuum and then in the atmosphere of a compressed gas (e.g. Ar) of known density. The large volume of the isopiestic vessel (about 28 liters) makes the method relatively insensitive to leaks. These characteristics make it relatively easy to evaluate the time needed for reaching equilibrium, as the samples may be left under the same vapor pressure for many days and the change of mass with time can be monitored. The isopiestic apparatus is capable of, and has been previously used for, measurements to 250°C and 40 bar.

In conjunction with the high temperature water adsorption measurements, multipoint BET surface area analyses using nitrogen adsorption measurements at 77 K, and mercury porosimetry analyses were performed on the same rock samples by Micromeritics using state-of-the-art cryogenic sorptometers and high-pressure porosimeters in order to obtain information on specific surface area, total pore volume, and pore size distribution. With the pressure range from vacuum to 60,000 psia the mercury intrusion technique covers pores from 3 nm to over 100 μm, while low temperature adsorption is a well-developed standard method for determination of specific surfaces and provides the most accurate information about pores up to roughly 50 nm.

Scanning electron microscopy is also used to examine the structure of the samples and detect possible changes in the structure and the composition of the samples caused by exposure to steam at high temperature. Such changes are expected to be found, since both nitrogen adsorption and mercury porosimetry results indicated that the pore structure changed during water adsorption experiments.

## RESEARCH RESULTS AND VARIANCES

A series of water adsorption and desorption measurements on geothermal rock samples was carried out at 150, 200, and 250°C. This was the second experimental measurement of high-temperature water adsorption on geothermal solids using the ORNL isopiestic facility. The first run, including rock samples from three geothermal wells located at The Geysers reservoir, California, proved that the direct-weighing method is useful and accurate even for rocks with very small adsorption capacities. After several improvements of the apparatus were made, the overall uncertainty in the amount of water retained was reduced significantly. Some subtle features of water adsorption isotherms were found which could not be detected previously. The time needed for determining a complete isotherm (for 15 or 16 samples simultaneously) was also reduced, due to the increased overall reliability. The only problem remaining is the susceptibility of the electromagnetic balance suspension ribbons to rupture, usually at the highest temperature. One of the Elgiloy ribbons failed during the last run after the adsorption branch at 250 C was completed. The apparatus was shut down and the balance will have to be repaired before continuing the measurements.

Fragments of the continuous AWI 1-2 well core were obtained from the Energy and Geoscience Institute, Salt Lake City, Utah. Ten samples included in the current set were taken from nine depths between 871 m (2858 ft) and 1674 m (5492 ft). The samples were prepared in such a manner as to obtain representative aliquots for the core sections and to avoid segregation of the component minerals. The disk attrition mill, which was previously the source of contamination with steel powder, was not used. Each of the AWI 1-2 core fragments (7 to 10 cm in length) was cut in two parts along the length of the well. One part was crushed only to the extent necessary for it to pass entirely through a 4.75 mm standard sieve (No. 4), so that no large grain-size fraction was produced. A No. 35 standard sieve was then used to separate grains smaller than 0.5 mm. The amount of this fine fraction was relatively small, and its density was only slightly higher than that of the main fraction (e.g. 2.846 vs. 2.794 g/cm$^3$), indicating that the amount of very fine powder was small.

The experimental adsorption results could depend on sample grain size. Some of the possible effects of grain size reduction are:

- simple increase of the external surface area - most important in nonporous solids where all the available surface is external;
- exposing to the gas phase the surfaces and volumes of closed pores;
- exposing to the gas phase highly adsorptive minerals which might have been protected by a layer of less active solids;
- reduction of the time needed for the transport of water through open pores to all the internal surface of the solid.

Previous adsorption measurements on three grain size fractions have shown that there is no detectable effect of sample grain size as long as the grains are not very small (below 0.1 mm). The time needed to reach equilibrium did not depend on the grain size in the range investigated. The irreversible adsorption observed in the small grain size fractions was attributed entirely to the contamination of the samples with iron. In order to verify this conclusion, one of the small grain size fractions (AWI 1-2 11 sample from the depth of 1674 m) was included in the present run. The results supported the earlier conclusion. The shapes of the adsorption isotherms for the two grain size fractions of the sample AWI 1-2 11 (1674 m) were similar, with the specific surface area about 1.5 times greater for the fine fraction. No irreversible adsorption similar to that observed earlier was found.

Two samples from The Geysers, wells MLM-3 (1325 m) and CA1862-4 (1361 m) were also included in order to verify the results obtained by two laboratories using different methods. These samples were previously investigated by Satik *et al.* (Stanford University Geothermal Program) and the desorption branches were not in good agreement with our typical results. The present results are consistent with our earlier observations (Gruszkiewicz *et al.*, 1996). It seems that assuming a leak in the Stanford apparatus, either in the solenoid valves or the sample holder, can explain most of the observed differences. At low pressures the amount of water lost to the leak (and attributed erroneously to adsorption) was small, and the agreement with our results was good. However, obtaining a low vacuum necessary to completely degas the sample was not possible, and the sample was not completely dry at $p/p_0 = 0$. As a result the knee on the isotherms due to the completion of the monolayer was not visible. This caused the adsorption branch to shift down by 0.5 mg/g in the case of MLM-3 7BT. As the pressure increased to saturation, more water escaped the sample cell and was attributed to adsorption. For this reason the desorption branch was always high, and the hysteresis loops were not closed. It is not quite clear why the error was not evident on the adsorption branch and why the amounts adsorbed at the highest vapor pressure were lower. Since in the region close to saturation adsorption/desorption tends to be slow, the times allowed for equilibration could have been insufficient. The effect of incomplete equilibrium would counteract the effect of a leak on the adsorption branch and reinforce it on the desorption branch.

Two zeolite samples (potassium-exchanged clinoptilotite and mordenite) provided by Dr. R. Wilkin (Pennsylvania State University) were included in this measurement series. The purpose of this collaboration is to investigate the correlations between the interaction of these pure minerals with water and the structures of their various forms. Adsorption results on pure minerals are expected to help in analyzing the isotherms for geothermal rocks. Adsorption of water on silica gel, chlorite, magnetite, and anatase was investigated earlier. Zeolitic minerals (e.g., wairaikite) are present in the Awibengkok reservoir.

In order to obtain additional information about surface areas, volumes and structures of the pores, selected samples were investigated using nitrogen adsorption and mercury intrusion methods. These analyses were performed by Micromeritics (Norcross, Georgia). Samples of all the core fragments used in this work were sent back to Jeffrey Hulen (Energy and Geoscience Institute) who will provide their mineralogical and petrological descriptions.

Water adsorption capacity results for the AWI 1-2 samples show large differences between samples from the same well. Preliminary analysis shows a correlation of water adsorption with the lithology of the corehole. It appears that, as observed earlier, the proportion between the grain and matrix material is a good rough predictor of water adsorption capacity. The sample AWI 1-2 5 showed an extremely high water adsorption capacity (30 mg/g at $p/p_0 = 0.8$, more than any of the previously investigated geothermal rocks) while the next sample along the core (AWI 1-2 6) adsorbed ten times less water, close to the least adsorptive samples from The Geysers. Hydrothermal alteration mineralogy data compiled by Hulen show that sample 5 might contain less than 5 % plagioclase and over 50 % illite, while for the sample 6 these proportions could be reversed. Another interesting feature of sample 5 is a very wide low-pressure hysteresis loop persisting down to relative pressure at least as low as 0.02. The high-pressure hysteresis loop, due to capillary condensation, is narrower. This shape of the adsorption/desorption isotherm points to clay minerals interacting very strongly with water.

BET specific surface areas obtained from nitrogen adsorption are unusually high for several AWI 1-2 samples (up to 12.4 $m^2/g$). Although in general high BET specific surface areas contribute to high water adsorption capacity, nitrogen and water adsorption are not strictly correlated because of different chemical properties of the minerals. In many cases a larger specific surface area (as determined with nitrogen) corresponds to less water adsorption. Using water and nitrogen adsorption data for a large number of samples, it seems to be possible to classify geothermal rocks into four general types depending on the combination of their surface areas and average affinities of these surfaces to water. From the available data it appears that all four possible cases exist, but their occurrence in different reservoirs and wells requires further studies. The two mixed cases (high BET area associated with low affinity to water and vice versa) are more common than the extreme cases (high BET area associated with high affinity to water and vise versa). As a result, water adsorption capacities of various geothermal rocks vary less than would be expected from any single property of the solid. On a plot of BET specific surface area against the hydrophobic character of the surface, many hydrothermal rocks would be clustered along a line with a positive slope.

An interesting sudden decrease of adsorption was observed in several samples at 250°C. At $p/p_0 \approx 0.5$ four samples showed a decrease of the amount adsorbed with increasing vapor pressure. It is likely that an irreversible reduction of the available surface area occurred, caused by dissolution of a mineral or a structural change. All the samples showed some gradual, continuous decrease in the adsorption capacity with temperature. In some samples water or other adsorbent was apparently bonded to the surface very strongly, so that evacuation at next higher temperature was accompanied by a further mass loss and an apparent increase of the available specific surface area. For example, it appears that after prolonged evacuation of sample 9 at 150°C more than half of its surface was still covered with an adsorbent which was later removed at 250°C. As a result, the capacity for reversible adsorption tended to increase with increasing temperature at low vapor pressures and decrease with increasing temperature at high vapor pressures.

## FUTURE PLANS

The results of this work contain a wealth of information about the interaction of geothermal rocks with water. Adsorption isotherms for samples taken from a 800 m long section of well core show quite diverse behavior at both very low (surface or chemical properties) and very high pressures (pore structure). Pore area and volume distributions will be calculated from water adsorption results and compared with nitrogen adsorption data. The results will be checked for consistency with detailed mineralogical compositions. It is expected that general correlations of adsorption properties of geothermal reservoirs as a function of lithology, mineralogy, and hydrothermal alteration and reservoir physical properties will begin to emerge.

After examining the samples and comparing with photomicrographs taken earlier, the BET specific surface areas will be measured again. Taking into account the water adsorption results at 250°C described above, it would not be surprising to see a dramatic decrease in the BET specific surface area values after experiment for some samples. We will attempt to determine the reason for the irreversible changes at 250°C. If the changes are not visible in the low resolution images of the samples, scanning electron microscope will be used to examine and compare samples before and after experiment.

The lithology of the corehole AWI 1-2 and adsorption results indicate that very different rocks can often be found a small distance (several feet) apart. Therefore it may be important for a more accurate mapping of the adsorption properties of the reservoir to start another cycle of adsorption measurements with more samples. Some of the current samples will be included to see whether the changes described above were indeed irreversible and complete. Starting another experimental run with new samples and perhaps pure minerals would be more appropriate than obtaining the missing 250°C desorption isotherm for all the current samples.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Results of this study were presented at two Annual Stanford Geothermal Reservoir Engineering Workshops in Stanford, California (1996 and 1998) and were published in the Proceedings. They were also presented during two DOE Geothermal Program Reviews. The interest of the geothermal industry in continuing water adsorption studies was confirmed during the meeting of ORNL research staff with geothermal industry representatives in Santa Rosa, California in January 1998. The knowledge of the adsorption/desorption isotherms and of the hysteresis characteristics is considered to be essential in modeling the behavior of the reservoirs including the reservoir response to reinjection processes.

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## CONTACTS

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone (202) 586-8076
Fax (202) 586-5124

| | |
|---|---|
| Miroslaw S. Gruszkiewicz | Phone: (865) 574-4965 |
| J. Michael Simonson | Phone: (865) 574-4962 |
| Juske Horita | Phone: (865) 576-2750 |

Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P. O. Box 2008, Bldg. 4500S, MS-6110
Oak Ridge, TN 37831-6110
FAX: (423) 574-4961

# ELECTRICAL AND FLOW PROPERTIES OF GEOTHERMAL ROCKS

Jeff Roberts, Al Duba, Brian Bonner, and Paul Kasameyer
Lawrence Livermore National Laboratory

## KEY WORDS

core measurements, electrical properties of rocks, geothermal reservoir, electrical resistivity, steam cap detection, pore fluid composition

## PROJECT BACKGROUND AND STATUS

This project is an extension and generalization of The Geysers Scientific Corehole Project in which we used laboratory geophysical methods, such as x-ray-computed tomography and electrical properties, to characterize the transport and storage of geothermal fluids in core samples from The Geysers. The results of this study are of general interest because understanding the transport of geothermal fluids and the rock properties that control this transport process (porosity and permeability) are fundamental to the efficient use of any geothermal resource. Electrical measurements for graywacke from The Geysers show that boiling events can be detected through increases in resistivity. Under laboratory conditions of constant imposed pressure, our results show that changes in resistivity are not abrupt, as expected for the brine–steam transition in bulk media, but are spread over a range of temperatures. Boiling in fine pores is retarded when capillarity causes a decrease in vapor pressure, and only the fluid in the largest pores boils at the phase boundary determined for a bulk liquid (Roberts et al., 1997). These results have implications both for geophysical exploration and reservoir management during production.

The current phase of this project began in FY97 with design of the apparatus. In FY98, we constructed and tested the apparatus and collected our first data. During FY99, we have improved the apparatus but have emphased measuring the properties of a variety of porous rocks, aiming at generalizing our previous results and improving understanding of how resistivity changes are related to boiling.

## PROJECT OBJECTIVES

Conduct laboratory core studies at elevated temperatures and pressures to determine how geothermal fluids are stored, released, and transported at reservoir conditions and relate these characteristics to geophysical data collected in the field.

### *Technical Objectives*

- Design, fabricate, and test the first laboratory system capable of long-term measurements of resistivity under conditions appropriate for geothermal reservoirs
- Use this system to provide ground-truth geophysical data to interpret field resistivity measurements made by surface and borehole methods
- Use coordinated laboratory measurements, including resistivity, ultrasonic velocity, and permeability, to characterize the behavior of geothermal fluids at reservoir conditions

### *Expected Outcomes*

- Successful construction and operation of a high-temperature pressure apparatus capable of simulating reservoir conditions

- A data base of electrical properties needed to monitor and interpret processes (such as in situ boiling and the formation of a steam cap) in evolving liquid-dominated geothermal systems such as Awibengkok

## APPROACH

Our approach is to determine the resistivity of geothermal rock for simulated field conditions by using laboratory core studies (1) to calibrate electromagnetic surveys and resistivity logs, and (2) to observe and characterize processes that control resistivity anomalies observed in the field. Previous work (Llera et al., 1990; Roberts et al., 1997) demonstrated that the resistivity of geothermal rocks depends on the pressure, temperature, composition, and state of the pore fluid. In our work, we measured samples for which permeability and pore size distribution had been determined in earlier studies. These measurements served a dual purpose: (1) test and debug the apparatus using well-characterized samples that produce results that can be predicted within limits, and (2) take conclusions drawn from measurements for rocks from well characterized geothermal areas and apply them to other rock types and region.

## RESEARCH RESULTS

### *Apparatus Development*

The original laboratory apparatus, which was fabricated for resistivity measurements of rocks from The Geysers and is described by Roberts et al. (1997), was inadequate for quantitative long-term measurements continuing for several months. In particular, we needed to add (1) automatic and active control of confining and pore pressures, and (2) software to coordinate control, data acquisition, and plotting. Measurement hardware, procedures, and electrode geometry were not changed from The Geysers study, although the high-pressure electrical feedthroughs were improved for better long-term performance and for ease of maintenance.

To generate confining and pore pressures, we specified a new pumping system, which was custom built by a commercial supplier and then integrated with the existing pressure vessel. This system is capable 500-MPa confining pressure and separately controlled 50-MPa pore pressure. Differential pore-pressure control makes it possible to flow fluid through the sample when the permeability is adequate. Software written in National Instruments LabView provides control for the pressure system and coordinates data acquisition and storage. A schematic of the apparatus is shown as Figure 1.

### *Resistance Measurements*

Measurements were first performed for samples that were well characterized in previous studies. A tuff from Nevada and a ‘synthetic rock’ (fused-glass beads) were selected for testing. In both cases, permeability, electrical properties, and pore-size distribution had already been determined for less severe pressure and temperature conditions. Therefore, baseline data were available for comparisons during apparatus testing. The volcanic tuff has a porosity of ~11% and is a reasonable surrogate for rock from composite hosted geothermal areas.

Two boiling events for the Nevada tuff are presented in Figure 2. The data trace shows that, in the first event, sample resistance nearly doubled (from ~7000 to ~13,400 ohm) when pore pressure was reduced at one end of the sample after ~4645 minutes at a constant temperature of 146°C and at a confining pressure of 34 MPa (500 psi). This increase is not instantaneous, but occurs gradually as the fluid in smaller pores boils and as the two-phase fluid redistributes within the pore network. The sample’s resistance largely recovers when the pore pressure is returned to the starting value, quenching the vapor phase. The second boiling event was initiated by lowering pore pressure at the other end of the sample. The behavior is quite different than the first event, suggesting access to larger pores near that sample end. The decrease in resistance after approximately five minutes of boiling is not understood and is being investigated. The resistance change is approximately equal for each boiling event, suggesting that the boiling region, which is localized near the end of the sample in low-permeability samples, has similar gross properties and geometry.

We chose to investigate the fused-glass-bead sample because of its high permeability (about 1 darcy) and porosity (18%). High permeability ensured that pressure would be transmitted through the sample during tests, and that the entire sample would contain two-phase fluid during boiling events. A particularly interesting and unanticipated behavior of the resistance was observed during boiling events at an elevated pressure and 145°C. Time dependent fluctuations in the data appear to originate in the sample. These changes may to be caused by making and breaking electrical conduction paths as the two-phase fluid (consisting of conducting brine and insulating water vapor) moves and rearranges within the sample. It is well known that dripping liquids can be described by nonlinear dynamics, e.g., chaos. It appears that the time dependence of resistance observed during boiling in this high-permeability sample may be controlled by nonlinear dynamics of fluid movement. If confirmed in further experiments, this result may lead to a new geophysical diagnostic that is based on measuring ‘electrical noise’ for boiling in high-permeability areas of geothermal reservoirs.

Repeated boiling of the fused-glass-bead sample caused salt deposits to form as sodium chloride dissolved in the precipitated pore fluid. Our attempts to redissolve the precipitate were unsuccessful, and the experiment was terminated. Examination of the sample after the experiment showed that additional porosity was created by a process analogous to the salt shattering of rock observed in desert climates. This effect is under further investigation and may lead to a new method of permeability alteration that is based on controlled precipitation and dissolution of solids dissolved in geothermal brines.

Preliminary measurements for andesite from Awi 1-2 were also conducted. The observed behavior is similar to that for the tuff analog. All results are discussed in more detail in the GRC Proceedings (Roberts et al., 1999) as listed in the references.

## FUTURE PLANS

Our immediate goal is to conduct measurements for additional sub-core from Awibengkok (Awi 1-2) to determine resistivity at elevated temperatures and pressures for this sequence from an andesitic composite volcano. Measurements by Boitnott (1999) will be used to guide sample selection. Additional analysis and experiments will be conducted to determine (1) if nonlinear fluid dynamics control the fluctuations in resistance observed for high-permeability samples, and (2) if this result will scale to the field. The possibility of permeability alteration caused by salt shattering at reservoir conditions will be investigated further.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Calpine Corp. | Understanding and monitoring injection |
| EMI | Calibration of effects detected by long EM tool |

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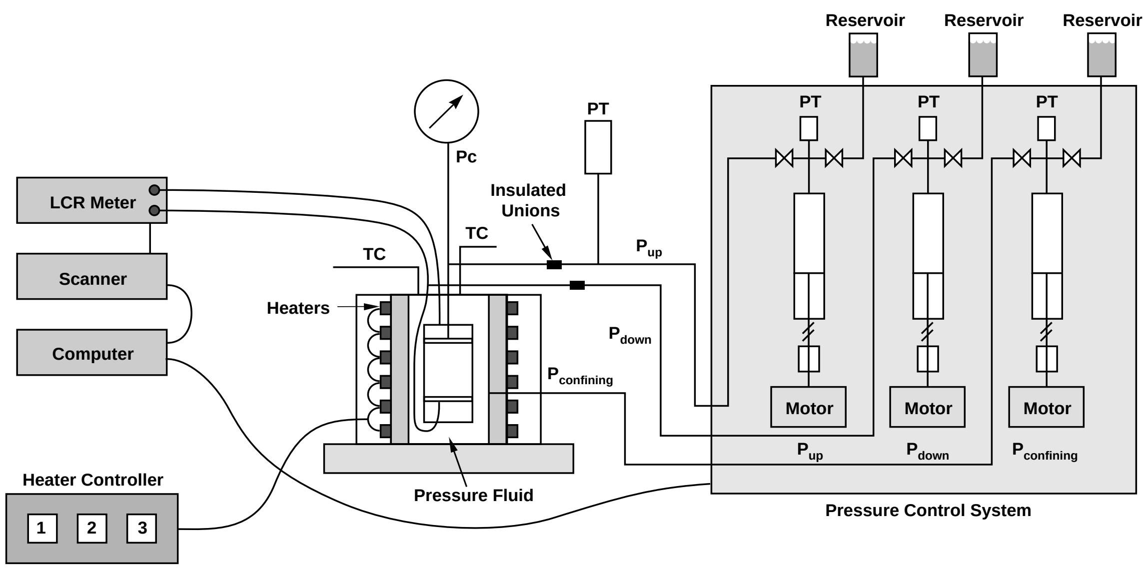


**Figure 1.** Schematic of the new experimental apparatus, showing pressure vessel, sample configuration, pumping systems, and data acquisition and control electronics.

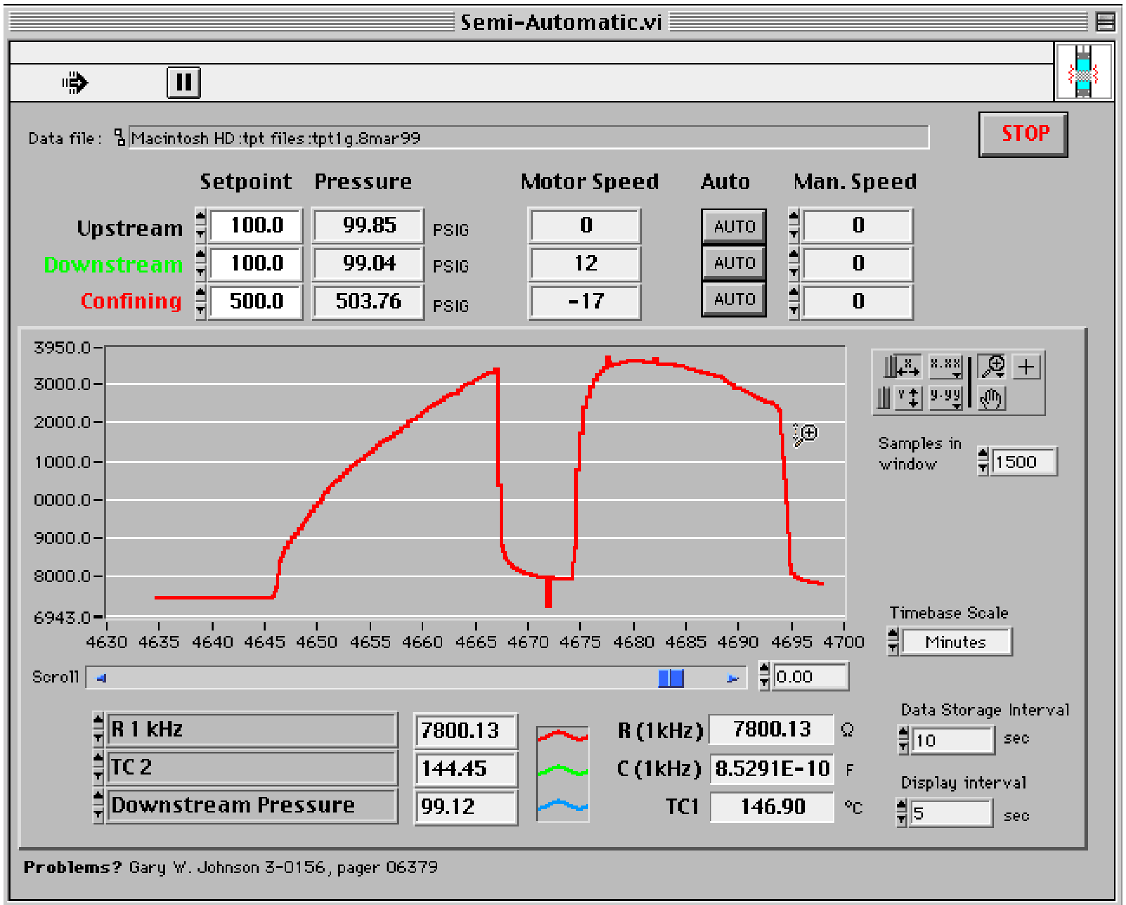


**Figure 2.** Computer panel display showing data and experimental parameters at the end of boiling events initiated by lowering pore pressure to ~20 psi. Thirty minutes of continuous data are shown. See text for details.

## CONTACTS

Jeff Roberts
Lawrence Livermore National Laboratory
P.O. Box 808, L-201
Livermore, CA 94551-0808
Phone: (925) 422-7108
Fax: (925) 423-1057
Email: roberts17@llnl.gov

Paul Kasameyer
Lawrence Livermore National Laboratory
P.O. Box 808, L-203
Livermore, CA 94551-0808
Phone: (925) 422-6487
Fax: (925) 422-3925
Email: kasameyer@llnl.gov

Marshall Reed
Office of Geothermal Technologies, EE-12
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-8076
Fax: (202) 586-8185
Email: Marshall.Reed@hq.doe.gov

Peggy Brookshier
Office of Program Management
U.S. Department of Energy
Idaho Operations Office
785 DOE Place, MS 1220
Idaho Falls, ID 83402
Phone: (208) 526-1403
Fax: (208) 526-6249
Email: BROOKSPA@INEL.GOV

# CONVECTIVE PLUME SEPARATION IN HYPERSALINE GEOTHERMAL SYSTEMS

Curtis M. Oldenburg and Karsten Pruess
Lawrence Berkeley National Laboratory

## KEY WORDS

thermohaline convection, thermal retardation, double-diffusive convection, double-advective convection, hypersaline geothermal systems

## PROJECT BACKGROUND AND STATUS

This project is an extension of our prior studies of thermohaline convection in hypersaline geothermal systems wherein we determined that layered convection is likely in anisotropic porous media (Oldenburg and Pruess, 1998). Over the course of that earlier project, we observed thermal retardation effects. However, it was not until this year that we were able to focus attention on these effects and investigate the resulting process of plume separation. The results of our current work have been published in Oldenburg and Pruess (1999).

## PROJECT OBJECTIVES

The objective of the project is to investigate the role of thermal retardation in controlling natural convection in idealized thermohaline systems.

### *Technical Objectives*

- Use numerical simulation to investigate transient thermohaline free convection flow.

### *Expected Outcomes*

- Bring to the attention of researchers the importance to natural convection of intergranular heat exchange with the flowing fluid.

- Publish a research paper in a peer-reviewed journal.

- Present results at American Geophysical Union 1999 Fall Meeting (San Francisco, CA, December 13–17, 1999) and at the 25$^{th}$ Geothermal Reservoir Engineering Workshop (Stanford, CA, January 24–26, 2000).

## APPROACH

To carry out this study, we built on our prior work in simulating hypersaline systems (Oldenburg and Pruess, 1998) and using higher-order differencing schemes (Oldenburg and Pruess, 2000). We developed simple idealized two-dimensional flow systems based broadly on hypersaline geothermal systems (Figure 1) and carried out numerical experiments with the reservoir simulator TOUGH2 (Pruess *et al.*, 1999) of transient thermohaline convection where the flows are upward, downward, and subhorizontal. The resulting flow, temperature, brine mass fraction, and density fields reveal the properties of the various convective flows.

## RESEARCH RESULTS

Our numerical experiments show the strong tendency for the brine plume to separate from the thermal plume in transient thermohaline convection. This occurs because the thermal plume travels at approximately the Darcy velocity due to intergranular heat exchange with the fluid, while the brine plume travels at the pore velocity. For ascending plumes, the brine advances ahead of the thermal plume but cannot move upward due to the higher density of the brine, and forms what we call a "density lid" (Figure 2). For descending plumes, the advancing brine plume moves easily downward ahead of the thermal plume and efficiently separates from it (Figure 3). For lateral flows, such as would occur in a geothermal outflow region, the brine plume advances ahead of the thermal plume, and then moves downward due to the higher density of the brine.

## FUTURE PLANS

Our studies will continue to investigate the role of thermal retardation in the evolution of sharp brine interfaces in hypersaline geothermal systems. This research is of particular interest for companies developing geothermal resources at the Salton Sea, southern California.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Improved understanding of brine and temperature distributions in hypersaline geothermal systems is relevant to energy production from liquid-dominated geothermal systems.

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## CONTACTS

Marshall Reed
Office of Geothermal and Wind Technologies Division
U.S. Department of Energy EE-122
Washington, D.C. 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

Curtis Oldenburg Phone: (510) 486-7419 cmoldenburg@lbl.gov
Karsten Pruess Phone: (510) 486-6732 k_pruess@lbl.gov
Earth Sciences Division
bldg 90-1116
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
FAX: (510) 486-5686

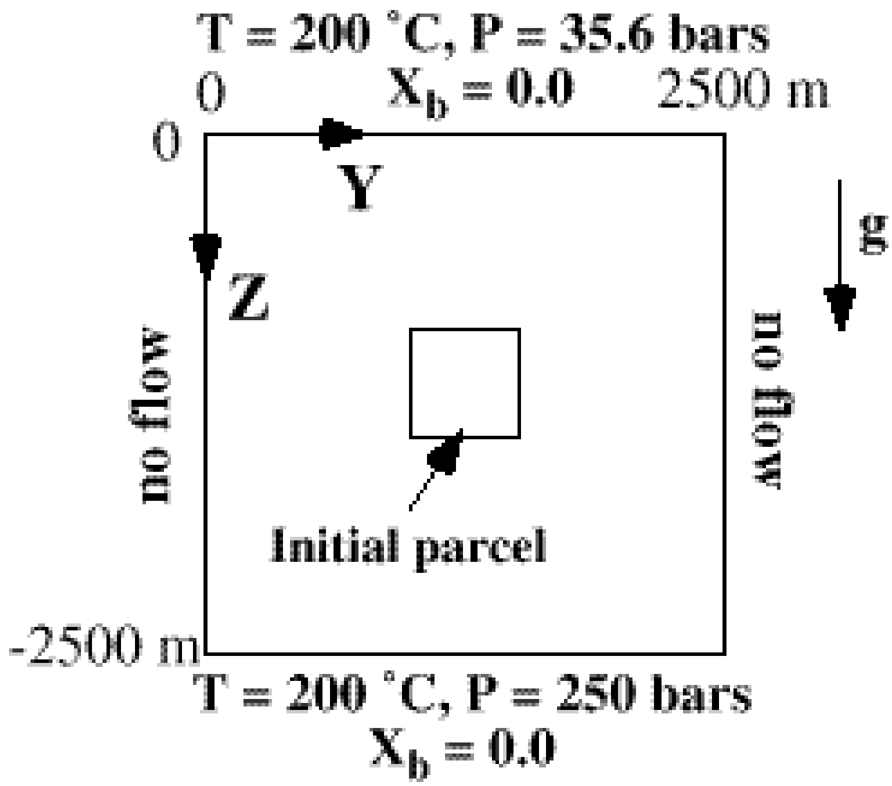


**Figure 1.** Boundary and initial conditions for two-dimensional thermohaline convection.

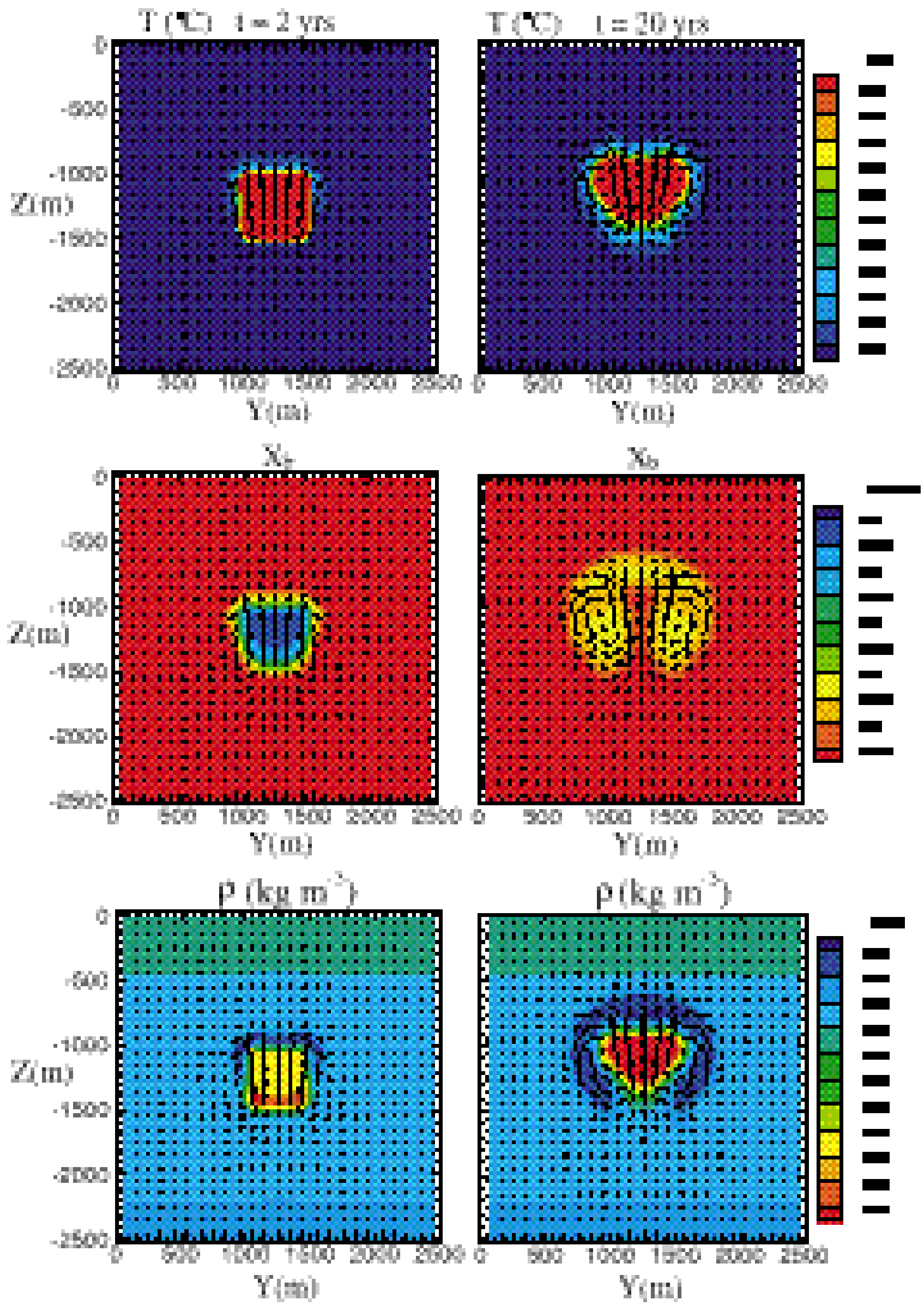


**Figure 2.** Temperature, brine mass fraction, and density at *t* = 2 and 20 years for the case of 5% positive initial buoyancy. Note the density lid and separation of the brine and thermal plumes.

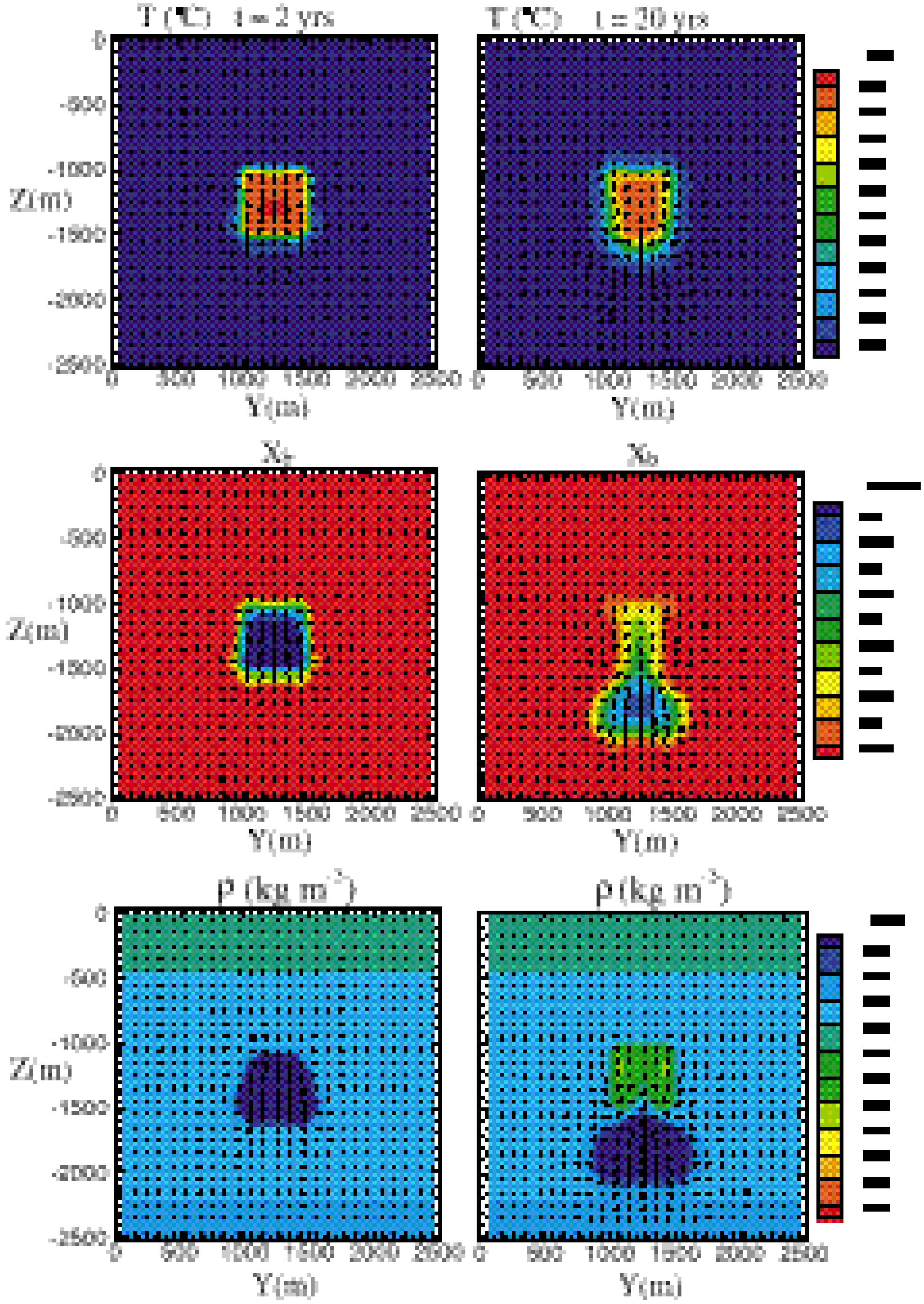


**Figure 3.** Temperature, brine mass fraction, and density at *t* = 2 and 20 years for the case of 5% negative initial buoyancy. Note the complete separation of the brine and thermal plumes.

# TOUGH2, VERSION 2.0: A GENERAL-PURPOSE GEOTHERMAL RESERVOIR SIMULATOR

Karsten Pruess, Curt Oldenburg, and George Moridis
E. O. Lawrence Berkeley National Laboratory

## KEY WORDS

numerical modeling, coupled wellbore flow, multicomponent fluid mixtures, tracer transport, saline brines, heterogeneous reservoirs, preconditioned conjugate gradient solvers

## PROJECT BACKGROUND AND STATUS

Numerical reservoir simulation has matured to the point where it is now standard engineering practice in the assessment, development, and management of geothermal resources. Advances continue to be made to improve the description of reservoir fluids and processes, enhance numerical efficiency and enable solution of larger problems on smaller computers, and to increase the power of simulators as practical engineering tools.

## PROJECT OBJECTIVES

The general objective of this research is to improve the realism, power and utility of geothermal reservoir simulation as a robust and accurate engineering tool, by developing enhanced process simulation capabilities, novel applications to reservoir problems, and improved user features. Recent work has focussed on assembling and documenting a new version of our general-purpose reservoir simulator TOUGH2. Among the specific objectives of version 2.0 are the following, (1) add significant capabilities for simulating flow and transport processes, that will be useful for engineering and geoscience applications; (2) add features to improve usability of the code, but avoid encumbering users with "feature creep;" (3) keep code changes to the minimum required to achieve desired capabilities; (4) remain as much as possible upward compatible with the earlier version; (5) stay with FORTRAN77 and publish source code; (6) facilitate code maintenance by minimizing the number of independent modules and "minor" variations among them; (7) increasingly emphasize solved problems and internal documentation as a way of communicating code features and use.

***Technical Objectives***

- Develop more comprehensive and accurate description of reservoir fluids and processes.
- Improve numerical algorithms, portability, and usability of reservoir simulators.
- Demonstrate novel applications of interest to the geothermal community.
- Accomplish technology transfer and provide technical support for users of the TOUGH/MULKOM family of codes.

***Expected Outcomes***

- Continue to release updated and fully documented versions of the widely used TOUGH2 simulator.
- More versatile and realistic descriptions of fluid mixtures containing dissolved solids and non-condensable gases, including water-soluble and volatile tracers.

- Improved modeling of fluid and heat flow in highly heterogeneous systems.
- Capabilities for coupled modeling of reservoir and wellbore flow.

## APPROACH

TOUGH2 program modules developed for various research projects are being integrated into the overall program structure. User documentation is being developed, including templates for typical application problems and improved user features. Additional code enhancements and novel applications to difficult reservoir problems are ongoing. Technical information is disseminated through laboratory reports and journal papers, at conferences (e.g., Pruess, 1998), and on the TOUGH2 homepage on the WorldWideWeb, at URL: http://www-esd.lbl.gov/TOUGH2/.

## RESEARCH RESULTS

- Coding and documentation for the new version 2.0 of our general-purpose reservoir simulator TOUGH2 has been completed (Pruess et al., 1999). The code has been transferred to DOE's Energy Science and Technology Software Center (ESTSC) for distribution to the public.
- TOUGH2, Version 2.0 includes several new fluid property modules that provide new capabilities for treating dissolved solids and non-condensable gases, and phase-partitioning tracers, such as noble gases and halogenated hydrocarbons. It also includes a capability for fully coupled simulation of reservoir and wellbore flow (Pruess et al., 1998), and a package of robust and efficient preconditioned conjugate gradient solvers (Moridis and Pruess, 1998).
- Simulations of thermohaline convection have demonstrated mechanisms for the separation of thermal and salinity plumes in hypersaline systems (Oldenburg and Pruess, 1999; see also a separate project summary).
- A systematic approach to local grid refinement was developed (Pruess and Garcia, 2000).
- Simulation of phase-partitioning tracers has demonstrated effects and phenomena seen in tracer testing at The Geysers (Pruess et al., 2000).
- Powerful techniques for automated model calibration (history match) with TOUGH2 have been developed. These are implemented in the publicly available iTOUGH2 code (Finsterle, 1999), and are described in a separate project summary.

## FUTURE PLANS

We continue to improve process modeling capabilities and user features of TOUGH2. There is increasing emphasis on tracer transport, chemically reactive flows (Xu and Pruess, 2000), multi-scale phenomena relating to flows in faults and fractures, and on the prediction of geophysical observables.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The TOUGH and TOUGH2 reservoir simulation programs are currently in use in approximately 200 organizations in 27 countries. We receive many requests for information from TOUGH2 users and prospective users worldwide, and continuously provide technical support to the user community. We maintain a TOUGH2 homepage on the web (http://www-esd.lbl.gov/TOUGH2/) with technical information and resources for TOUGH2 users. We are also providing advice to private companies who are developing novel applications and enhancements for TOUGH2. A short course on multiphase flow simulation with TOUGH2 was held in October 1999 at the International Groundwater Modeling Center (IGWMC), Colorado School of Mines. IGWMC has adopted TOUGH2 as a teaching tool.

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## CONTACTS

Marshall Reed
Office of Geothermal and Wind Technologies
U.S. Department of Energy EE-12
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-8076
Fax: (202) 586-8185

Karsten Pruess
Lawrence Berkeley National Laboratory
Earth Sciences Division
One Cyclotron Road, Mail Stop 90-1116

Berkeley, CA 94720
e-mail: K_Pruess@lbl.gov
Phone: (510) 486-6732
Fax: (510) 486-5686

Energy Science and Technology Software Center
P.O. Box 1020
Oak Ridge, Tennessee 37831
phone (423) 576-2606
fax: (423) 576-2865
email: estsc@adonis.osti.gov
WorldWideWeb: http://www.osti.gov/estsc/

# TRACER MATCHING AND PRODUCTION/INJECTION STRATEGIES FOR FAULT DOMINATED GEOTHERMAL RESERVOIRS

Daniel Swenson, Brian Hardeman
Mechanical Engineering Department
Kansas State University, Manhattan, KS 66506
785-532-2320, swenson@ksu.edu

## KEY WORDS

Geothermal Reservoirs, Modeling, Flow, Tracers, Faults, Fractures, Finite Element

## PROJECT BACKGROUND AND STATUS

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 on fractures can cause short-circuits and prematurely cool the produced fluid. In addition, there is increasing recognition that fractures will often be encountered at commercial reservoir scales and that these fractures will significantly affect flow. Realistic fracture models can help both in designing re-injection strategies and in operation of fractured reservoirs.

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.

The project includes numerical model development at Kansas State University, tracer and reservoir analyses at the Energy & Geoscience Institute at the University of Utah, and oversight and industrial collaboration with Oxbow Power Services. The three year project started March 1 of 1998, and was half complete at the end of fiscal year 1999.

## PROJECT OBJECTIVES

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.

### *Technical Objectives*

The specific objectives of this project are to:

- Develop capability for modeling fluid flow on 3D planar fractures. The model will provide a simultaneous solution of planar flow in fractures, porous flow through rock, deformation of the rock and fractures, and heat transfer through the reservoir, including all coupling effects.

- Include tracer simulation with thermal degradation and adsorption.

- Implement the model in a modern interactive user interface that will allow the user to work at the reservoir feature level (boundaries, fractures, wells, etc.) when developing a model.

- Apply the model to the Dixie Valley reservoir. The development of this model will be an iterative process. By the end of the project, a fully coupled fluid flow/heat transfer/rock deformation analysis will be performed. This will include the effects of thermal cool-down on reservoir permeability.

***Expected Outcomes***

Expected outcomes of the project include:

- The delivery of an analysis tool that will allow realistic modeling of flow in fractured reservoirs. Such analysis capability will be useful because of the increasing recognition of the importance of fractures both on production and during re-injection.

- Demonstration of a geometric framework for developing reservoir models using the features of the reservoirs, rather than focusing on the meshing used for the numerical solution. This more natural interface offers the possibility of extension to provide an interface to other reservoir simulators, such as TOUGH2 and TETRAD.

- Demonstration of the use of the model on an actual reservoir at Dixie Valley, including tracer and flow analyses.

## APPROACH

There are two primary aspects to our modeling approach: a description of the problem using a geometric database and the method used to solve the physics of the simulation.

Geocrack3D uses a vertex-use based, non-manifold topological database as the modeling framework for representation of the problem domain (Martha, 1989). Topology provides a rigorous framework for geometry description. The topology used in Geocrack3D includes vertices, edges, faces, and volumes, and makes it possible to describe the reservoir independent of any particular method to be used to solve the problem.

The finite element method is used to discretize the problem and solve equations for fluid flow, heat transfer, and rock deformation. We are using object-oriented software methods to design a finite element program framework applicable to the coupled hydro-thermal-structure problem, while allowing extension and application to other problems. A design document has been completed and is being followed as we write the actual code to implement the solution.

## RESEARCH RESULTS

### *Fluid Flow and Tracer Analysis*

The major accomplishment this fiscal year was the completion of all the basic capability needed to model flow on fractures with tracers. The capabilities include:

- Interactively defining a reservoir, including fractures and wells.
- Automatically meshing the fracture surfaces and wellbores.
- Defining pressure boundary conditions on the wells.
- Defining tracer boundary conditions on the wells.
- Solving the fluid flow problem using finite elements.
- Displaying the pressures, flow rates, and tracer results.

Pete Rose at the Energy & Geoscience Institute University of Utah has begun developing a Geocrack3D model of Dixie Valley. At this stage the model is very simple, with a minimum number of fractures. The flow results of initial calculations are shown in Figure 1. The model has also been used to perform tracer calculations. Figure 2 shows the resulting tracer streamlines on the fractures. At this time, the model is being refined to obtain better correlation with the experimental data.

### *Implementation of Heat Transfer*

We completed the finite element implementation of steady-state and transient coupled flow and heat transfer in a planar fracture. This includes planar triangle and quadrilateral elements for the fracture surface and volume tetrahedral elements for heat conduction in the solid.

One of the verification problems represented flow in a fracture, with a film coefficient to model heat transfer between the rock and the fluid. Heat transport occurs in the fluid as a result of the fluid flow. Conduction is included in the rock. The comparison between the analytic and 3D finite element solution is shown in Figure 3. As can be seen, the finite element solution is accurate.

### *Meshing of 3D Volumes*

To complete the heat transfer solution, it is necessary to have automatic meshing of the 3D rock volume. This is the area of current focus. We are fortunate that Joaquim Bento Cavalcante, presently at Universidade Federal do Ceara, Brazil is making available his implementation of 3D meshing. We have placed his C code in a small C++ wrapper. Figure 4 shows a first volume mesh made using his code. The next step is to test more complex geometries. His algorithm fits naturally into our implementation, since the previously meshed fracture surfaces form the boundaries required for volume meshing.

### *Updated Web Site*

The Geocrack web site (www.mne.ksu.edu/~geocrack) has been updated. It includes some new 3D example problems and an improved user interface. One can now download our quarterly progress reports from that site.

## FUTURE PLANS

Significant work remains to implement 3D meshing and merge the volume heat transfer with the previously completed fluid flow model. This task will be completed in the current year of the project. Rock deformation will be the focus of the final year of the project.

We are increasing our focus on refining the Dixie Valley model and comparing calculated results to measured tracer data.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Oxbow Power Services | Providing Dixie Valley data and oversight |
| Energy & Geoscience Inst. | Using Geocrack3D for analysis |
| GeothermEx | Interested in analysis approach |
| Maxwell Technologies | Interested in analysis approach |

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## CONTACTS

Daniel Swenson
Mechanical and Nuclear Engg. Dept.
Rathbone Hall, Room 302
Kansas State University
Manhattan, KS 66506
(785)532-2320, (785)532-7057 Fax
swenson@ksu.edu

Joel Renner
Program Manager
Lockheed Martin Idaho Technologies Co.
P.O. Box 1625, MS - 3830
Idaho Falls, Idaho 83401-1563
(208)526-9821
rennerjl@inel.gov

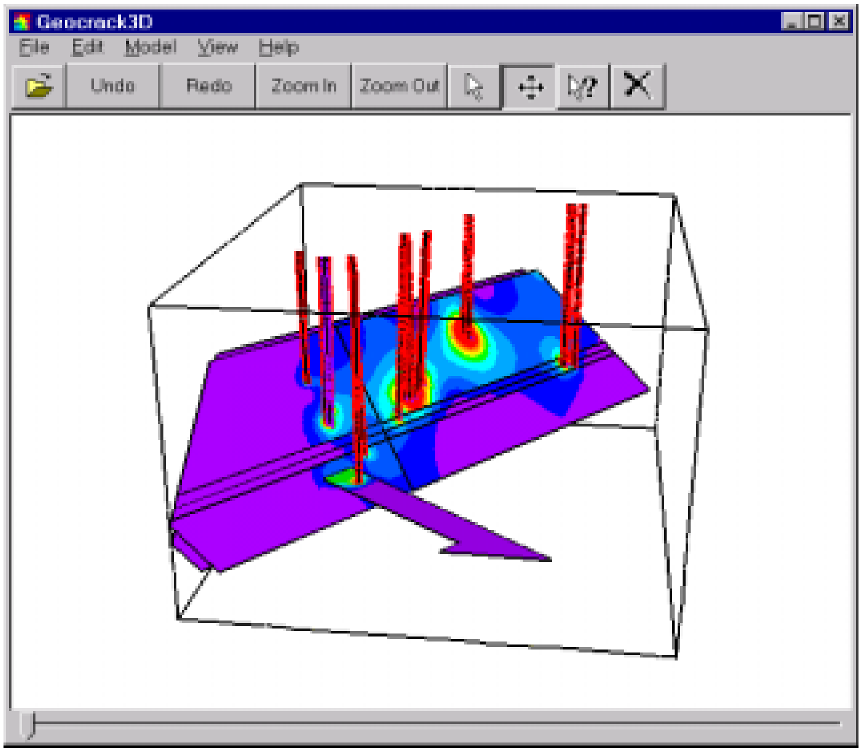


**Figure 1.** Dixie Valley model showing flow rates in fracture.

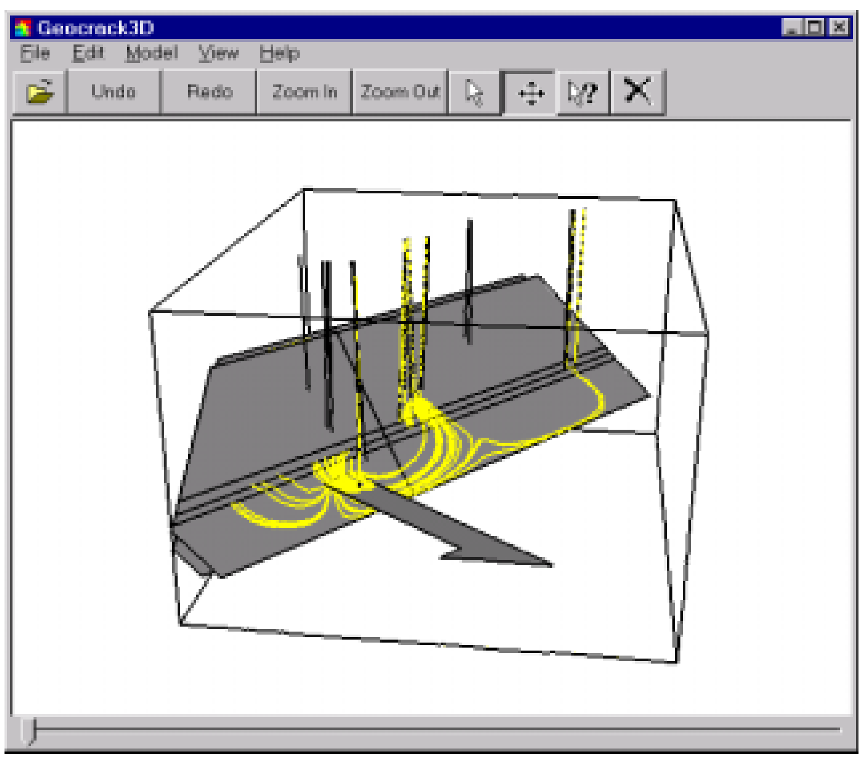


**Figure 2.** Tracer calculations in Dixie Valley model.

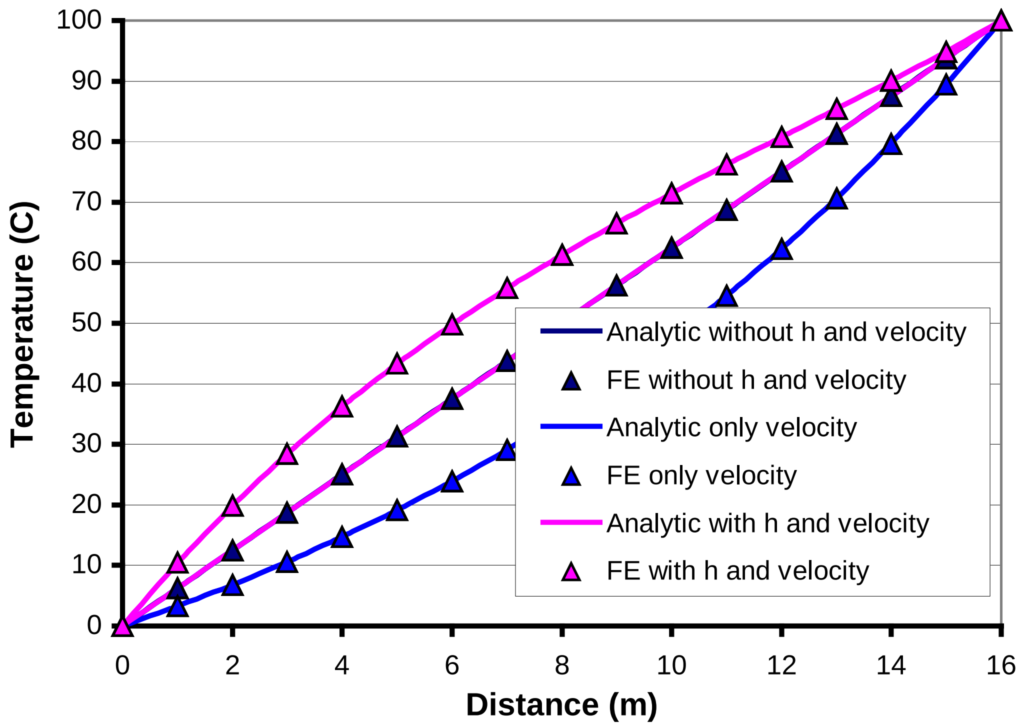


**Figure 3.** Verification problem for flow in fracture.

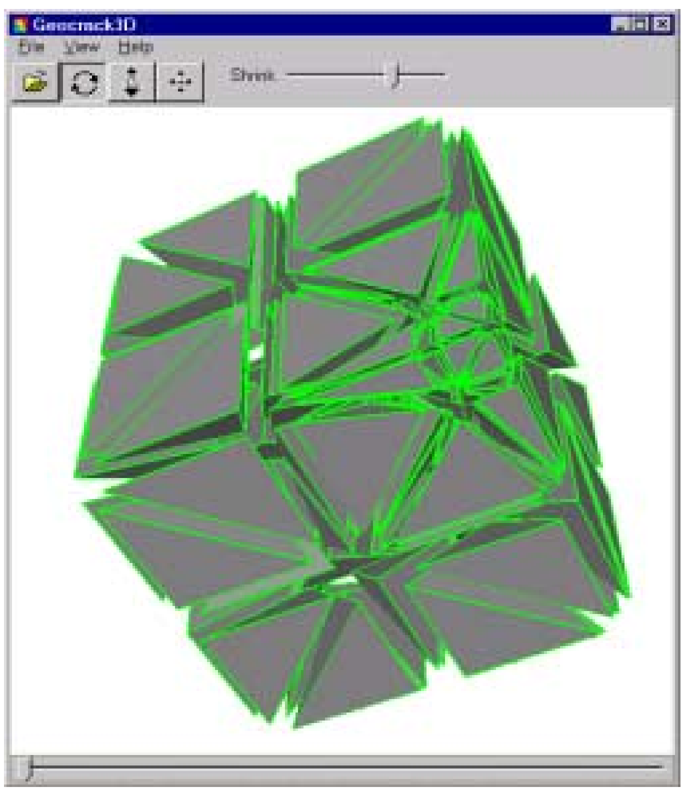


**Figure 4.** Volume mesh showing internal elements

# FLUID TRACERS AND RESERVOIR EVOLUTION

Juske Horita, David R. Cole and Lee R. Riciputi
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory

## KEY WORDS

Isotope, partitioning, ion probe, fluids, minerals, tracers, geothermometer

## PROJECT BACKGROUND AND STATUS

The stable isotope distributions of oxygen, hydrogen, and other light elements (e.g., C, S), are widely applied in geothermal systems in order to delineate the sources and fluxes of reservoir fluids, the contribution of injection fluids to production, the extent of boiling and mineral deposition from the fluids, and the time-temperature evolution of alteration mineralization that effects the porosity-permeability relationships. The chemical and isotopic signals of these processes are recorded in the minerals on a very fine scale (<10 to 100's of micrometers), and different phases typically exhibit complex intergrowths. This requires *in situ*, microanalytical techniques in order to obtain chemical and isotopic information on different phases. Secondary ion mass spectrometry (SIMS) can be used for relatively rapid, high precision analysis, *in situ*, of both trace elements and stable isotopes, with high spatial resolutions of 5 – 30 micrometers. The analysis of modern fluids and fluid inclusions in minerals can provide both chemical and isotopic compositions of fluids responsible for secondary mineral formation. The microsampling capability of SIMS, coupled with fluid analysis, provides unparalleled opportunity to quantify the temporal evolution of fluid-rock interaction leading to an understanding of the changes in the secondary porosity in geothermal systems.

Knowledge of isotope partitioning in mineral-brine-gas systems at elevated temperatures is essential to proper understanding of the isotopic data of geothermal systems. There are currently insufficient experimental data or theoretical models to predict isotopic partitioning at elevated temperatures. The presence of dissolved salts in fluids can lead to large errors in calculated temperatures and gross misinterpretation of fluid sources and fluxes, particularly in highly saline geothermal systems such as the Salton Sea. In addition, recent theoretical works predicted that pressure may affect significantly isotope partitioning between water and coexisting phases at geothermal conditions. Experimental verification of these isotope salt and pressure effects is needed.

The current project started together with complementary experimental programs at Oak Ridge National Laboratory, funded by DOE’s Office of Basic Energy Sciences/Geosciences program. Recently, substantial progress has been made on experimental studies on the isotope salt and pressure effects at elevated temperatures. With these new, accurate experimental data of isotope partitioning, we have recently initiated studied on two geothermal systems (Awibengkok, Indonesia and Salton Sea, California).

## PROJECT OBJECTIVES

The objectives of this project are to: (1) quantitatively assess the micro-scale distributions of light stable isotopes (O, H, C, S) and trace elements in order to understand the sources of fluids and the processes responsible for the evolution of porosity and permeability in the Awibengkok geothermal system, (2) investigate the isotopic evolution of metal-rich, hypersaline brines from the Salton Sea geothermal system, and (3) conduct hydrothermal experimental studies of isotope partitioning among phases (e.g., water, volatiles, minerals) of direct relevance to the interpretation of isotope behavior in the Awibengkok and Salton Sea systems. An improved understanding of the water-rock interaction through the study of

Awibengkok drill core and Salton Sea brines will be useful in exploitation of existing reserves and exploration for additional resource.

***Technical Objectives***

- Evaluate the micro-scale (5-30 micrometers) distribution of stable isotopes (O, H, C, S) and trace elements in minerals (quartz, calcite, epidote, pyrite, etc.) from select portions of the Awibenkok core 1-2 by means of advanced ion microprobe and laser-fluorination techniques.

- Investigate oxygen and hydrogen isotope compositions of a suite of hot (>200$^{o}$C), hypersaline (> 30 wt%) brines collected from Salton Sea geothermal system, California, by means of analytical techniques specifically developed for high-salinity brines.

- Determine experimentally the effects of common dissolved salts (NaCl, KCl, $CaCl_2$, etc.) and pressure on oxygen and hydrogen isotope partitioning in the systems water liquid-vapor and mineral-water at temperatures to 600$^{o}$C, and establish simple, empirical equations for calculating the isotope salt and pressure effects.

***Expected Outcomes***

- Improved understanding of temporal and spatial history of the sources, fluxes, compositions, and temperature of reservoir fluids in Awibenkok geothermal system, which can be used for efficient exploitation and exploration of geothermal energy resources.

- Better understanding of the sources, fluxes, and history (boiling-condensation, water-rock interactions) of hot, metal-rich and hypersaline fluids in Salton Sea geothermal system, in order to improve the efficiency of geothermal plant operations and metal recovery.

- A set of internally consistent, precise experimental results on the partitioning of oxygen and hydrogen isotopes among geothermal materials (waters, brines, steam, gases, and minerals) at elevated temperatures as a function of pressure and fluid composition, that can be directly used to better characterize geothermal reservoirs (temperatures, origin and residence time of fluids, phase separation, and water-rock interaction) and to trace injected fluids to production sites for estimating the quantity of production that is derived from injection.

## APPROACH

We will use our modified Cameca 4f ion microprobe, in concert with other capabilities in our group (e.g., fluid inclusion extraction, $CO_2$ laser fluorination/gas source mass spectrometry, cathodoluminescence) to document and interpret the nature of the micro-scale isotopic record and mass transport during fluid-rock interaction in the Awibengkok geothermal system. We will quantify the isotopic and trace element systematics in the drill core provided by EGI as they relate to (a) temperature and pressure as a function of depth, (b) the host rock, (c) fluid composition, (d) geometry and intensity of fracturing and/or brecciation, and (e) the presence of hot water entries. We will focus most of our effort on isotopic and trace element behavior of alteration phases, reported to include quartz, adularia, calcite, epidote, chlorite, hematite, anhydrite, and pyrite. We will also conduct isotopic analysis of brines recovered from wells in the Salton Sea geothermal system, provided by CalEnergy. In support of this effort on natural systems, we will conduct hydrothermal isotope exchange experiments that quantify the temperature, pressure, and composition dependencies of oxygen and hydrogen isotope partitioning between in brine-gas-mineral (calcite, brucite, chlorite, hematite) systems at elevated temperatures.

## RESEARCH RESULTS AND VARIANCES

Oxygen isotope ratios were measured by SIMS on twenty-two individual spots on a large (~1cmx8mm), euhedral quartz grain sampled from a fracture at 5539.2 ft depth in Awi-1 core. Precision for each analysis is better than ±1‰. $\delta^{18}O$ values for individual analyses ranged from +5 to +14‰, with an average value of +8.5±2.0‰ (1σ). There appears to be a general trend to lower isotope values from core to rim in the quartz grain. Analyses from the very center of the grain have an average $\delta^{18}O$ value of +9.5±2.0‰ (n=5). Analyses of spots in the interior of the grain (between the center and the rim) have an average $\delta^{18}O$ value of +8.0±1.3‰ (n=8), which is similar to the isotope values of analyses taken along the rim of the grain (+8.3±2.0‰, n=9). Using quartz-water fractionation curves from Matsuhisa et al. (1979), potential fluid compositions can be calculated, and potential causes for the isotopic variation modeled. If we assume that fluid temperature was constant at present-day borehole values (~250°C), the calculated fluid compositions range from -4 to +5‰, with an average value indistinguishable from seawater (-0.4‰). Given the elevation of the site, this value is slightly higher than the expected meteoritic composition (around -4‰), which could indicate possible mixing between lighter meteoric and heavier magmatic fluids. Mixing between reservoirs could also explain the variability in $\delta^{18}O$ values within the quartz crystal. Another potential mechanism that could account for the oxygen isotope variability in the quartz is differing fluid temperatures. Assuming that the fluid had a constant value of -4‰, explaining the variation in quartz $\delta^{18}O$ values solely through temperature requires that fluid temperatures fluctuated from ~140 to ~250°C, over 100°C.

Ion microprobe analysis of oxygen isotope ratios in a large vein-filling calcite from the 4371 ft were conducted on 8 individual spots. $\delta^{18}O_{V\text{-}SMOW}$ values ranged from +2.7 to +11‰, with an average value of +6.9±2.6‰. There is a suggestion of isotopic zonation in the crystal, as rim analyses are generally slightly heavier than analyses from the interior of the grain. However, it is difficult to assign a temporal history to this possible zonation, as the growth history of the crystal is difficult to determine with a normal optical microscope. Assuming that the temperature of the fluid from which the calcite precipitated was constant and identical to present-day borehole values (~250°C), the calculated isotopic compositions of the fluid in equilibrium with the calcite range from range from -4.6 to +3.7‰, with an average $\delta^{18}O$ value of -0.4‰. If we assume that the isotopic composition of the fluid was constant, the variation in $\delta^{18}O$ values measured in the calcite requires a fluid temperature fluctuation of ~120 to 140°C.

A series of hydrothermal experiments were conducted in order to investigate pressure effect on isotope partitioning in the system brucite [$Mg(OH)_2$]-water at: (1) 300°C and at 100, 500, 2000, and 3000 bars, and (2) 500°C and at 500, 800, 1750, and 3000 bars. 10-20 mg of a fine-grained brucite and 50-200 mg of pure water were loaded into gold capsules, which were then brought up to the experimental conditions inside a cold-seal vessel. The experiments lasted 4 to 120 days. The brucite grains coarsened significantly and as a results, the isotopic exchange proceeded over 90% toward equilibrium. Since isotopic exchange between brucite and water was not complete, an equilibrium fractionation factor was calculated from a set of four experiments with isotopically different waters, using the partial exchange technique developed by Northrop and Clayton (1966). At 300°C, the measured D/H fractionation between brucite and water, $10^3\ln\alpha$, where $\alpha=(D/H)_{brucite}/(D/H)_{water}$, systematically increased from -31.8±1.6 ‰ at 100 bars to -26.2±1.6 ‰ at 3000 bars. At 500°C, D/H fractionation factor also systematically increased from -27.0±2.1‰ at 500 bars to -20.3±1.6‰ at 3000 bars. The increases are rapid at low pressures (<1000 bars) and slow at high pressures (>1000 bars). Our results are very consistent with results obtained at 300° and 500°C, both at 1000 bars, by Satake and Matsuo (1984). When the D/H fractionations are plotted against the density of water at the experimental conditions (0.71-0.92 g/cm$^3$ at 300°C and 0.26-0.77 g/cm$^3$ at 500°C), good linear relations were observed. These results are consistent with our results previously obtained at 380°C and 15-8000 bars, and all of these results clearly demonstrate that pressure has a significant effect on mineral-water isotope partitioning in a wide range of temperature.

The observed pressure effects on brucite-water D/H fractionation factor at 300-500°C are a combined pressure effect on the mineral brucite and water, and experiments alone cannot separate the effects on the two phases. Driesner (1997) calculated pressure effect on D/H partitioning of water based on spectroscopic measurements of O-H and O-D stretching frequencies of $H_2O$ and HDO, respectively, at elevated temperatures. Our experimental results of pressure effects on D/H partitioning between brucite and water at 300-500°C yielded the same trend as calculations by Driesner (1997), but their magnitudes are smaller by one-half to two-thirds. The observed linear relation of the brucite-water D/H fractionation with the density of water at a given temperature is also consistent with Driesner's calculations. In collaboration with Dr. Polyakov of Vernadsky Institute of Analytical Chemistry and Geochemistry in Russia, we calculated pressure effects on D/H partitioning in brucite on the basis of the thermodynamics. The calculations show that D/H partition function ratio of brucite increases linearly with increasing pressure at a rate of 0.99‰/kb at 300°C to 0.66 ‰/kb at 500°C. The magnitude of pressure effects on brucite is much (by a factor of 2 to 5) smaller than the measured pressure effects. Furthermore, the calculated effects are linear with pressure, not with water density. It is likely that the observed pressure effects on brucite-water D/H fractionation at 300-500°C are due largely to pressure effects on water, rather than those on brucite, but further experimental and theoretical studies are needed.

We have discussed with the personnel of CalEnergy on a sampling protocol for isotopic analysis of brines to be collected from wells at Salton Sea geothermal system, California. Due to high silica, metals, and salt concentrations in the brines, amorphous silica and NaCl will precipitate and metals will oxidize rapidly upon sampling. In order to prevent these, brine samples are commonly diluted with or without acidification, and added of a reducing agent, such as formate or ascorbate. For the isotope analysis of brines, the precipitation and oxidation of dissolved compounds do not cause problems. On the other hand, the dilution of samples will alter the isotopic composition of brines. We suggested that samples for isotopic analysis should be split and stored in a glass bottle with a tight cap without dilution and addition of chemicals. Recently, CalEnergy has initiated sampling of injection fluids, and will start on the production wells in the first quarter of 2000.

## FUTURE PLANS

Preliminary oxygen isotope results from the ion microprobe studies of quartz and calcite suggest that fluid compositions may have varied by many per mil during the evolution of the Awi system due to either extensive exchange with the country rocks and/or mixing of multiple fluid types. Work in the next funding period will focus on samples where there are multiple phases/generations with clear paragenetic relations that can be correlated with specific temperatures of formation from fluid inclusion studies. The effort will be concentrated on isotopic and trace element behavior of select alteration phases, including quartz, adularia, calcite, epidote, chlorite, hematite, anhydrite, and pyrite. This activity will be closely coordinated with the petrological and fluid inclusion studies currently being conducted by researchers at EGI. Data from these studies will be integrated to quantify: (a) temperature history of the system, (b) sources and timing of fluid events, (c) the nature and extent of mass transport associated with flow, and (d) the influence of local rock chemistry/structure on the isotope signatures of alteration phases observed on the microscale.

Measurements of oxygen and hydrogen isotope partitioning between vapor and liquid water will be resumed and continued for the system Na-K-Mg-Ca-Cl-$SO_4$ to 350°C, including several mixed salt solutions resembling natural geothermal brines (i.e., Salton Sea). Recently, hot (500°C), hypersaline (40 wt% salinity) brines rich in $FeCl_2$ were recovered from Kakkonda Geothermal field in Japan. It is very likely that $FeCl_2$ also has large isotope effects. Highly concentrated acid waters are encountered in mine drainages, crater lakes, volcanic emanations, and some andesitic geothermal systems. It is known that HCl and $H_2SO_4$ have large oxygen isotope effects at room temperature, and we plan to examine the effect of these acids at elevated temperatures.

We will complete hydrothermal experiments for investigating the effect of pressure on D/H partitioning between brucite and water at 200-600°C and at 200-3000 (or 8000). Pressure effects on $^{18}O/^{16}O$ partitioning between brucite and water will also be investigated, using the run products from the experiments already conducted for D/H partitioning. Experiments of mineral-water isotope exchange in the presence of salts (NaCl, $CaCl_2$) will be extended, in order to investigate and differentiate the effects of pressure and dissolved salts on isotope partitioning at elevated temperatures. We plan to conduct a few experiments in the system calcite ($CaCO_3$)-water-salt to gain knowledge on the isotope salt and pressure effects at select T-P-X conditions. Possible pressure effects on oxygen isotope partitioning will also be investigated with these minerals. Aside from the isotope salt and possible pressure effects on isotope partitioning between water and other phases, fractionation factors for a number of important phases are simply lacking. The temperature dependency of stable isotope partitioning provides geochemists with a particularly large number of geothermometers, but most of the reliable equilibrium fractionation factors have been obtained experimentally at temperatures well above those appropriate for geothermal systems. We plan to investigate the equilibrium oxygen and hydrogen isotope partitioning between common hydrous minerals (e.g., kaolinite, chlorite, epidote) and iron oxides (magnetite and hematite), and water.

Upon receiving samples of injection fluids and brines from the production wells at Salton Sea geothermal system, we will initiate oxygen and hydrogen isotope analysis of these waters. We plan to employ $H_2$- and $CO_2$-water equilibration methods, which are very suitable for high-salinity brines.

## INDUSTRIAL INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| CalEnergy | Collaboration on brine analysis from the Salton Sea |
| UNOCAL | Using our results to monitor injection |
| EGI, Univ. of Utah | Using our results for the interpretation of geochemical data from The Geysers |
| JMC (Japan) | Discussing on isotopic data of hot, hypersaline brines from Kakkonda geothermal field in Japan |

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## CONTACTS

Marshall Reed
Geothermal Division, CE-122
U. S. Department of Energy
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-5124

David R. Cole Phone: (865) 574-5473
Juske Horita Phone: (865) 576-2750
Lee R. Riciputi Phone: (865) 576-4839
J. Michael Simonson Phone: (865) 574-4962
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
P.O. Box 2008, Bldg. 4500S, MS 6110
Oak Ridge, TN 37831-6110
FAX: (865) 574-4961

# FURTHER DEVELOPMENTS AND APPLICATIONS OF INVERSE MODELING

Stefan Finsterle and Karsten Pruess
Earth Sciences Division
Lawrence Berkeley National Laboratory
University of California, Berkeley

## KEY WORDS

inverse modeling, parameter estimation, history matching, iTOUGH2

## PROJECT BACKGROUND AND STATUS

The project aims at developing, improving, and applying parameter-estimation techniques by automatically matching the results of a numerical model to laboratory or field data from geothermal reservoirs. Inverse modeling provides optimized, case-specific, and model-related parameters on the scale of interest, making the subsequent model predictions more reliable.

The iTOUGH2 code (Finsterle, 1999a, b, c) provides inverse modeling capabilities for the general-purpose multiphase reservoir simulator TOUGH2 (Pruess, 1991). Any TOUGH2 input parameter can be estimated in a joint inversion using any type of data for which a corresponding TOUGH2 output can be calculated. The accuracy and transferability of the estimated parameters depends on the appropriateness of the conceptual model; it must be able to represent the salient features and processes of the geothermal domain/system being modeled. Moreover, adequate and sensitive data of high quality must be available to enable independent and accurate estimation of the key parameters affecting the system. Finally, the necessary computer resources must be available to efficiently run the many forward simulations required for the solution of the inverse problem.

iTOUGH2 has been extensively tested, is fully documented, and released to the public through DOE's Energy Science and Technology Software Center. At the same time, the code is continually being revised and enhanced to incorporate improvements and extensions of the underlying TOUGH2 simulator. The efficiency and robustness of the optimization algorithms are also being enhanced, and new diagnostic analyses of inverse modeling results are being added.

## PROJECT OBJECTIVES

The general objective of this research is to adapt iTOUGH2 to the needs of specific geothermal applications, and to demonstrate its usefulness for the determination of hydrogeologic and thermal properties of geothermal systems.

### *Technical Objectives*

- Apply iTOUGH2 to field data from fractured geothermal reservoir to examine strengths and weaknesses of a formalized model calibration procedure.
- Incorporate new iterative and direct solvers from TOUGH2 (Version 2) into iTOUGH2.
- Develop technique to generate correlated random permeability fields and to estimate geostatistical parameters.

- Implement Monte Carlo method to study impact of uncertain, correlated parameters on model predictions.

***Expected Outcomes***

- Fully documented and tested version of iTOUGH2 to be released to the public through DOE's Energy Science and Technology Software Center.

- Report/paper demonstrating benefit of automatic history matching of actual field data from fractured geothermal reservoir.

- Improved uncertainty propagation analysis.

- Improved efficiency and robustness through incorporation of novel solvers.

## APPROACH

A new version of the multiphase reservoir simulator TOUGH2 has become available (Pruess et al., 1999). The new code has been compared to the previously released version, and significant modifications have been transferred and implemented into iTOUGH2, specifically the new package of linear equation solvers.

Empirical Orthogonal Functions (Kitterød and Gottschalk, 1997) was identified as a suitable method to include parameter correlations into Monte Carlo sampling for evaluation of model-prediction uncertainties.

Pressure and enthalpy data from a geothermal well have been selected for analysis with iTOUGH2. Different conceptual models have been developed and matched against the data, demonstrating the importance of the model structure and its impact on the estimated parameters.

Spatially correlated, heterogeneous permeability fields can be generated using the GSLIB geostatistical simulation package (Deutsch and Journel, 1992). Of that package, the method of Sequential Indicator Simulation was adapted and implemented into iTOUGH2.

## RESEARCH RESULTS

The method of Empirical Orthogonal Functions (Kitterød and Gottschalk, 1997) has been implemented into iTOUGH2 and used to examine prediction uncertainty as a result of the uncertainty in strongly correlated parameters (Finsterle, 1999d).

The new linear equation solvers (Moridis and Pruess, 1998; Pruess et al., 1999) and faster subroutines for the calculation of thermodynamic properties of water have been implemented into iTOUGH2.

Geostatistical methods to generate heterogeneous permeability fields have been evaluated and implemented into iTOUGH2, allowing generation of spatially correlated permeability fields and the estimation of geostatistical parameters. The new capability has been employed in a study described in Finsterle (1999d).

Inverse modeling was applied to field data in an attempt to better understand the production characteristics of a well in a fractured geothermal reservoir. The joint multiphase inversion of pressure and enthalpy data (see Figure 1) demonstrated the need to accurately represent fracture flow, as well as fracture-matrix heat-exchange mechanisms using a double-porosity approach, to match the measured well data. Details about the inversion can be found in Finsterle et al. (1999).

## FUTURE PLANS

We continue to improve process modeling capabilities, inversion algorithms, and user features of iTOUGH2. We attempt to incorporate simplified geophysical models to allow joint inversions of geophysical and hydrogeological data. iTOUGH2 will be applied for the analysis of laboratory flashing experiments (in collaboration with the Stanford Geothermal Program).

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

iTOUGH2 has been fully documented and tested for use on Unix workstations and PCs. The code has been transferred to the Department of Energy's Energy Science and Technology Software Center (ESTSC), Oak Ridge. To request iTOUGH2, send e-mail to estsc@adonis.osti.gov. Additional information about iTOUGH2 can be found at http://www-esd.lbl.gov/iTOUGH2.

| Organization | Type and Extent of Interest |
|---|---|
| Stanford University | Analysis of laboratory experiments |
| DOE/YMP | Calibration and analysis for nuclear waste isolation program |
| Auckland University | Calibration of geothermal reservoir models, parallelization |
| Orkustofnun, Iceland | Analysis of well test data, calibration of geothermal reservoir models |

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## CONTACTS

Marshall Reed
Office of Geothermal and
Wind Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-8076
Fax: (202) 586-8185

Stefan Finsterle and Karsten Pruess
Lawrence Berkeley National Laboratory
Earth Sciences Division
One Cyclotron Road, Mail Stop 90-1116
Berkeley, CA 94720
Phone: (510) 486-5205
Fax: (510) 486-5686
E-mail: SAFinsterle@lbl.gov, K_Pruess@lbl.gov
WWW: http://www-esd.lbl.gov/iTOUGH2

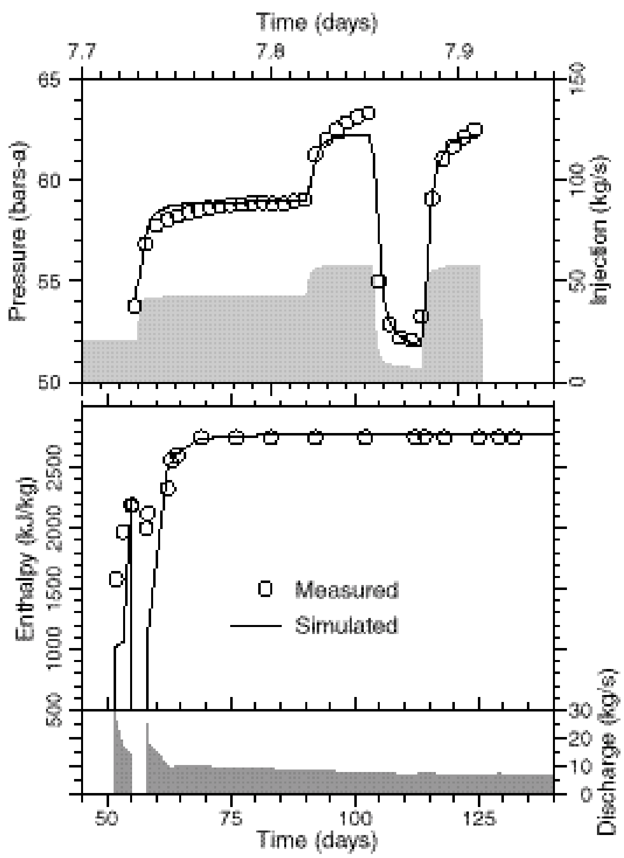


**Figure 1.** Measured and simulated pressures (top) and enthalpies (bottom) using the best-estimate parameter set. The shaded curves show the injection and production rates.

# OPTIMIZING INJECTION USING TRACERS

G. Michel Shook
Idaho National Engineering and Environmental Laboratory

## KEY WORDS

tracers, injection, swept volume, moment analysis, thermal breakthrough

## PROJECT BACKGROUND AND STATUS

Injection of spent geothermal fluids has become a standard reservoir management tool over the past decade. Injection serves not only to maintain reservoir pressure, but also to increase energy extraction efficiency over the productive life of the resource. Because the injected fluid is frequently much cooler than in-situ fluid, these benefits depend strongly on locating injection wells in such a fashion so as to delay the breakthrough of the cooler injectate. Proper design of injection requires knowledge of the volume of rock and pore space that the fluids contact in moving between injection and extraction wells. This volume can be estimated through an appropriately designed and analyzed tracer test. However, even when injection wells are optimally located, thermal breakthrough from injectate can only be delayed, not eliminated. Therefore, operators need to predict the time at which thermal breakthrough is expected. These data, both the pore volume that is swept by an injection well and the time at which thermal breakthrough is expected, can be used to design an optimal injection strategy.

Work continued in FY-1999 to develop the analytical methods necessary to estimate pore volume and thermal velocities from tracer test data. The methods developed previously have been extended to more complex conditions that include the effects of significant permeability contrasts (e.g., layering). Work was also begun in extending these methods to multi-phase conditions.

## PROJECT OBJECTIVES

The overall goal of this project is to develop the tools necessary to optimize an injection strategy. Because tracer testing has become a standard tool for tracing flow paths in geothermal reservoirs, the work has been focused on analysis of tracer test results (effluent analysis). The tools being developed include measurement of reservoir pore volume swept by a tracer and the prediction of thermal breakthrough through tracer test analysis. Work was previously restricted to single phase porous media. Extension to multi-phase conditions was begun in FY-99. Specific details of these objectives are given below.

### *Technical Objectives*

- Develop a tracer test analysis method to estimate reservoir pore volume from a tracer test.
- Predict the propagation of a thermal front arising from injection of cooler fluids.
- Extend conventional geothermal tracer test analysis to multi-phase regimes, and investigate the potential to estimate in-situ saturation from tracer tests.

### *Expected Outcomes*

The successful conclusion to this project will allow the geothermal operator to design and implement a tracer test and use the results of the test to:

- Estimate the volume of reservoir associated with a given well pair. This can help identify thief zones or primary flow paths that result in short-circuiting of injected fluids, and is useful in developing injection schemes, sizing power plants, and estimating the life of a project.

- Use tracer test analysis to predict the timing of thermal breakthrough arising from injection. This allows the operator lead time to either modify the injection strategy or drill makeup wells.

- Calculate mass in place, from combined pore volume and saturation estimates.

## APPROACH

The approach taken in this project is to first develop the theory that governs estimating the desired quantity (pore volume or thermal breakthrough time), and then to compare predictions with numerical simulation results. We have begun intentionally with the simplest reservoir description and excluded second order effects from the analysis. Good agreement between theory and simulation has been used as the measure of success. From the simpler reservoir description, we have extended the analysis to include more complex geometries and initial conditions. In late FY-2000, we anticipate soliciting interest in a field demonstration of the method.

## RESEARCH RESULTS

A conventional slug tracer test can be analyzed and pore volume measured using the mean residence time of the tracer. The first temporal moment (mean residence time) of a tracer in single phase flow is given as (Shook, 1998):

$$\bar{t} = \frac{\int_0^\infty C t\,dt}{\int_0^\infty C\,dt} - \frac{t_s}{2}$$

where C is tracer concentration in the effluent, t is time, and $t_s$ is the tracer injection time. Pore volume swept by that tracer is calculated from the injection rate, q, and the first moment as shown below.

$$V_p = q\bar{t}$$

Thus, a conventional tracer test can be conducted and the reservoir pore volume readily calculated from analysis of the effluent.

The velocity of a thermal front, $v_T$, can be estimated from the combined mass and energy conservation equations (Shook, 1999). The ratio of the velocity of isotherms relative to fluid velocity, $v_w$, is given as:

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

where $\varphi$ is porosity, $\rho$ is density (r = rock, w = liquid), and Cp is thermal heat capacity. Therefore, if one can estimate the fluid velocity, one can then predict the onset of cooling. The fluid velocity is given from the mean residence time above. In order to make use of the tracer data, however, we require variable transforms so that tracer data and temperature data exhibit similar behavior. The following variable transformations provide convenient comparison between the two data types.

For the predicted temperature history, plot normalized tracer recovery (predicted dimensionless temperature, $T_P$) vs. pseudotime ($t^*$):

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

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

The utility of these variable transforms can be visualized in the following way. One can imagine an infinite number of streamtubes of varied length, all originating at an injection well and terminating at a production well. Each streamtube carries a fraction of the injected tracer; the variable transform for the predicted temperature history is simply the fraction of streamtubes that have delivered the tracer, and will begin to show thermal decline at any given point in time. Pseudotime is merely time that has been translated to account for thermal inertia.

***Effects of thermal conductivity***

The thermal velocity given above assumes that thermal conductivity can be neglected as a second order effect. This assumption is usually good in porous media, but there are conditions in which this leads to underpredicting thermal breakthrough times. Such conditions tend be prevail where there exist large contrasts in permeability (e.g., layered media), or in heterogeneous media that exhibits significant permeability streaks (e.g., highly correlated permeability). Under those conditions the thermal velocity is affected by conduction as well as convection, which tends to smear the otherwise sharp front. Thermal conduction can be explicitly included in the thermal velocity estimates by estimating a thermal Peclet number and modifying the equations given above. However, even in significantly heterogeneous media, ignoring conduction usually results in less than 10% error in thermal breakthrough times (Shook, 2000). Given the uncertainties in other parameters (e.g., porosity), this appears to be an acceptable error.

***Extension to saturated conditions***

Efforts to extend these methods to two-phase conditions have begun. From our initial analyses, several important observations can be made. First, there exist only three temperature states in the reservoir. These are related to the initial temperature, the temperature at the fluid interface (which is related to the production pressure), and the injected temperature. The velocity of the first temperature wave is proportional to the initial saturation and production pressure. The second temperature wave has a velocity as given by the single phase equations given above. This preliminary analysis is a continued portion of this project.

## FUTURE PLANS

Work to date on this project has been restricted to heterogeneous, porous media. Efforts have been made in the last year to include effects of layering, and to extend the method to multi-phase conditions. The extension to multi-phase flow will be completed in FY-2000, and work will begin in extending the work to fractured reservoirs. After development of the appropriate analysis methods, interest in a field demonstration will be solicited from the geothermal community.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Presentations have been made at the Geothermal Resources Council annual meeting (Shook 1998) and the Stanford workshop (Shook, 1999). Additional discussions have been held with Oxbow Geothermal, USGS, and EGI colleagues. A field test of these methods will be solicited in late FY-2000.

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Shook G.M., "Prediction of Thermal Breakthrough from Tracer Tests," Proceedings, Twenty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan. 1999, pp 24-30.

Shook, G.M., "Reservoir Pore Volume and Thermal Velocity as Estimated from Tracer Test Analysis," submitted to Geothermics, in review.

## CONTACTS

G. Michael Shook
INEEL
PO Box 1625
Idaho Falls, ID 83415-2107
(208) 526-6945
(208) 526-9822 FAX
ook@inel.gov

Peggy Brookshier
DOE Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
(208) 526-1403
(208) 526-6249 FAX
brookspa@id.doe.gov

Joel L. Renner
INEEL
PO Box 1625
Idaho Falls, ID 83415-3830
(208) 526-9824
(208) 526-0969 FAX
rennerjl@inel.gov

Marshall Reed
DOE-HQ, Geothermal Division
CE-122
1000 Independence Ave. SW
Washington DC 20585
(202) 586-8076
(202) 586-5124 FAX
Marshall.Reed@hq.doe.gov

# TECHNOLOGY FOR INCREASING GEOTHERMAL ENERGY PRODUCTIVITY

P.I., Nancy Mϕller; Co P.I., John H. Weare
Chemistry Department (0340), University of California at San Diego, La Jolla, CA 92093

## KEYWORDS

breakout, brine chemistry, computer models, EOS, phase coexistence, reservoir, scaling, simulations, solubility, heat content, thermodynamic properties

## PROJECT BACKGROUND AND STATUS

A major cause of the limited exploitation of geothermal resources is the lack of technology available to increase the efficiency and reduce the costs associated with exploration and energy production. Our current grant (DE-FG07-99ID13745) from the DOE Geothermal Program started 3/18/99 and ends 3/17/04. In this project period, we are developing computer model technologies that can help overcome important chemical problems associated with both present-day near surface and future deep high T,P geothermal energy operations. With previous DOE funding, we have demonstrated (e.g., see Mϕller et al. (1998); Duan et al. (1995)) that semi-empirical equilibrium models can reliably reproduce reservoir and production chemistry - scaling, breakout, steam fractions, heat content, gas emission, phase co-existence, miscibility, pH, formation temperatures, downhole brine concentrations - for a wide range of PTVX variables. For conditions with few data available, we have developed new simulation technology to generate needed thermodynamic information from first principle theory. Comprehensive user interfaces have been developed so that completed models can be incorporated into PC application packages. Substantial progress has been made on two packages: TEQUIL (rock/water interactions, such as scaling and reservoir chemistry, as a function of composition for temperatures below 300°C) and GEOFLUIDS (multiple phase processes, such as flashing and miscibility, to very high T, P conditions). Some progress has been made on two other packages: GEOHEAT (heat characteristics, such as enthalpies, of complex mixtures) and GEOPHASES (internet-based phase behavior visualization tools). Considerable progress has been made establishing a web site for use of our modeling codes.

## PROJECT OBJECTIVES

- To improve the productivity of geothermal operations and exploration by providing user-friendly computer models of the thermochemical/physical properties of geothermal brines and their associated noncondensible phases as well as reservoir behavior.

- To develop methods to optimize the transfer of technology.

***Technical Objectives:***

- To construct thermodynamic models for predicting the energetic and chemical characteristics of reservoirs, hydrothermal brines and injectates as well as behaviors encountered during the extraction of energy from geothermal fluids under a wide range of XTP conditions.

- To develop new theoretically based modeling technologies that reduce the dependency on experimental data and increase the understanding of rock/water interactions.

- To develop application and visualization software which facilitate the use of our models and the understanding of geothermal chemistry.
- To develop a web site for accessing modeling codes and for user feedback.

***Expected Outcomes***

- Pitzer-type models for liquid brine density systems that can predict scaling, support abatement strategies (such as pH modification and chemical inhibition) and characterize reservoir rock-water interactions.
- New equation of state models that can treat compressible phases and the chemical behavior occurring in very high T, P resources, including the effects of injectates on deep, low permeability reservoirs.
- Enthalpy and specific heat models based on the above models.
- User-friendly modeling code application packages for PC's.
- A web site for online use and downloading of modeling codes and for user comments.
- Molecular simulation technology and analyses of theoretically-based extrapolation techniques to reduce the dependence on experimental data.
- A summary of many geochemical data through model parameterizations.

## APPROACH

**Liquid Density Brine Models, T <300°C.** Our models describing the equilibrium behavior of solid-brine-gas systems to high concentration and temperature (T <300°C) via their free energy incorporate the semi-empirical Pitzer (1987) equations. In this approach, only binary and ternary data are necessary to fully parameterize a model for complicated, many-component systems. Gas phases are easy to add because they act nearly ideally near 1 atm. Pressure corrections for low concentration applications can be calculated from the limiting partial molal volumes. These data are available. For higher concentrations, partial molal volumes as a function of composition are needed.

**Equation of State Models to High T, P for Systems with Compressible Phases.** New problems are expected to arise in the future development of very high T, P resources. The density can change dramatically in going from the liquid to vapor phase, and in the supercritical region it is a strong function of pressure. To describe multiple phase geothermal processes, such as flashing and miscibility, and to accurately reproduce XPVT properties under high T, P conditions, new equation of state (EOS) descriptions must be generated to: (1) yield free energies that are correct at both the liquid and vapor densities and (2) treat the large changes in composition that can occur in two phase processes, where highly saline brines can be produced from fluids originally of low concentration. Methods will need to be developed to treat the very difficult critical region.

**Heat Models.** With appropriate reference state information, models of heat properties can be produced from both the Pitzer and alternative EOS models.

**Molecular Simulation Studies and Theoretical Extrapolation Models.** To generate needed thermodynamic "data" for empirical model construction in TPX regions where few experimental data are available and to construct more theoretically based descriptions of geothermal fluids, we carry out first principles simulations (e.g., molecular dynamics).

**Technology Transfer:** As our models are developed and validated, they are included in PC application packages for distribution via diskettes or the internet.

## RESEARCH RESULTS AND VARIANCES

**Liquid Density Brine Models, T <300°C.** Acid/base reactions influence the outcome of many important processes occurring in different stages of geothermal energy production. Carbonate, silica and hydroxide scaling, $CO_2$ and $H_2S$ breakout, aluminum, carbonate and silica speciation, corrosion are well known phenomena affected by brine pH. This year substantial progress was made in improving the TEQUIL scaling model's acid/base description, which was defined previously only by data in the HCl and NaOH systems.

In TEQUIL, $H^+$ interactions were based on the HCl electrochemical data of Greeley et al. (1960), which suffer from the increased solubility of AgCl in the electrode at high temperatures. Using the more recent osmotic and activity data of Holmes/Mesmer and co-workers, new temperature functions were established for the HCl binary parameters. Temperature functions for the mixing parameters in the NaCl-HCl-$H_2O$ and KCl-HCl-$H_2O$ systems were then determined using the low concentration activity coefficient data of Mesmer and Holmes (1992) and solubility data to 7m HCl. TEQUIL $H^+$ interactions were expanding by adding the sulphuric acid system. A new model for the Na-H-$HSO_4$-$SO_4$-$H_2O$ system was established by fitting osmotic data from 0°C to 225°C (Holmes and Mesmer (1992, 93, 94), Rard (1989, 1992), Clegg et al. (1994)) and literature solubility data (0°C to 120°C). Since the sodium sufate-bisulfate acid salts were not included in TEQUIL, new chemical potential temperature functions were also established for these salts. Work started on parameterizing the K-H-$HSO_4$-$SO_4$-$H_2O$ system to high temperature. Solubility data found for this system range only from 0°C to 75°C and the amount of osmotic data is considerably less than in the sodium system.

To improve the base description of TEQUIL, we developed a model for the Na-K-OH-Cl-$SO_4$-$H_2O$ system to high concentration and temperature. Osmotic data from 0°C to 250°C (Hammer and Wu; Simonson et al.; Holmes and Mesmer) were used to establish the temperature functions for the NaOH-$H_2O$ binary parameters to 6-8m. Osmotic and emf data from 0°C to 170°C (Hammer and Wu; Mikulin; Holmes and Mesmer; Harned and Cook; Akerlof and Bender) were used to evaluate the functions for the KOH-$H_2O$ binary parameters to 6-8m. The mixing parameters, $\theta_{OH,Cl}$ and $\psi_{OH,Cl,Na}$, were established from halite solubility data in the NaOH-NaCl-$H_2O$ system to 10 m NaOH from 0°C to 200°C. The potassium ternary parameter, $\psi_{OH,Cl,K}$, was established from sylvite saturation data from 0°C to 180°C in the KOH-KCl-$H_2O$ system up to 8m KOH. The temperature functions for $\theta_{OH,SO4}$ and $\psi_{OH,SO4,Na}$ were determined from mirabilite and thenardite solubility data in the NaOH-$Na_2SO_4$-$H_2O$ system from 0°C to 250°C and to 8m NaOH. Correlations (up to 8m KOH) with the 0°C to 75°C arcanite solubility data in the KOH-$K_2$SO4-$H_2O$ system indicated that the temperature function for $\psi_{OH,SO4,Na}$ could be used successfully for the potassium parameter. Values of $\psi_{OH,Na,K}$ were set equal to zero.

**Equation of State Models to High T, P for Systems with Compressible Phases.** We are constructing a model for the important natural fluid NaCl-KCl-$MgCl_2$-$CaCl_2$-$CO_2$-$CH_4$-$H_2O$ (HPTSW) system which will be based on accurate models of the subsystems (NaCl-$CO_2$-$H_2O$, $CaCl_2$-$H_2O$, etc). This year we continued to improve the thermodynamic descriptions of the $MgCl_2$–$H_2O$, KCl-$H_2O$ and $CaCl_2$-$H_2O$ binaries. Mineral stability predictions as a function of T, P and composition are compared to the data of Aranovich and Newton in Fig. 1. In these experiments, the mineral coexistence of periclase (MgO) and brucite ($Mg(OH)_2$) provides a direct measure of the activity of water in the KCl-$H_2O$ solution. (There is very little $MgCl_2$ in the solution phase.) Below 15 molar, the results of the KCl-$H_20$ model (dashed lines) agree well with the experimental data (solid lines). This is remarkable since most of the data used to parameterize the model came from the relatively low pressure liquid/vapor coexistence region. Since our phenomenology inadequately treats the entire composition range for this system, we are developing new modeling methods to more succinctly represent natural waters (see below).

Few mixing property measurements exist for the HPTSW system. Since there are data in the NaCl-KCl-$H_2O$ system, we hope to use this system to develop an efficient mixing approach for the full system. NaCl-$H_2O$ and KCl-H2O binary models based on thermodynamic perturbation theory were constructed. Both models give good representations of the data from 300$^oC$ to about 800$^oC$ and pressures from water saturation to about 5000 bar. Reasonable agreement with the limited data is found up to pressures of 15,000 bar. Interpolating between the end member binaries and adjusting the parameters in the interpolation formulas with data in the mixed NaCl-KCl-$H_2O$ system, we developed a mixture model that appears to be accurate for temperatures up to 700$^oC$ and pressures up to 15,000 bar. The results agree with the limited liquid/solid coexistence data in the mixed system.

Description of the critical region is important in analyzing the thermal history of geothermal systems from fluid inclusion data. Because of the nonanalytic functionality of the free energy in the critical region, agreement between experiment and model predictions is often not satisfactory. This problem is illustrated (Fig. 2) by comparing measured and GEOFLUIDS predicted (dashed line) liquid/vapor phase coexistence points for the $H_2O$-$CO_2$ system at temperatures close to the critical temperature of water. GEOFLUIDS predicts that the point X=.3, T=548K and P >1000 bar is in a two phase region, whereas measurements show this to be single phase region. The GEOFLUIDS model was based on an empirical equation of state. This year, we developed a new more theoretically based model using thermodynamic perturbation theory. Improved prediction resulted but qualitative errors similar to those shown in Fig.2 remained, indicating that a better form for the equation of state needed to be developed (see below). In the interim, we have developed a fitting method that enables correct phase coexistence prediction in the critical region (solid line Fig. 2, maximum deviation from the experimental data is .03 in mole fraction). However, since the free energy is not available from this fitting approach, other thermodynamics properties, such as the densities of the coexisting liquid and vapor phases, cannot be calculated.

**Molecular Simulation Studies and Theoretical Extrapolation Models.** Aluminum/silicate species are major components of reservoir rocks. Hydrolysis plays an important role in the behavior of aluminum in aqueous solutions. With hydrolysis of $Al^{3+}$ to $Al(OH)_4^-$ (the dominant Al solution species even in slightly basic waters), the coordination number changes from six to four. This behavior is different from other ions which retain their coordination number with loss of protons (e.g., $Fe^{3+}$ has a $Fe(OH)^-_4(H_2O)_2$ species in basic solutions). Attempts to reproduce this behavior using MD simulation were carried out last year and continued this year. Reproduction of the $Al^{3+}$ coordination number change is a demanding test of whether or not the correct balance of electronic and ionic forces can be achieved in these calculations. We showed that the predicted structure of the resulting aluminum anion is close to that calculated in quantum chemistry calculations.

The problems with the critical region predictions of our EOS models based on perturbation theory (illustrated in Fig. 2) led us to believe that we need better reference system descriptions. First, we developed a direct simulation method for the most complex endmember, water, in the $H_2O$-$CO_2$ system using the hard sphere dipole representation that we used in our thermodynamic perturbation methods. These simulations worked well at high TP, but not in the critical region. Therefore, we developed simulation methods based on more realistic water-water interactions. Replacing the hard sphere repulsive interactions by soft Lennard Jones (LJ) potentials and the dipole representation by separated charges, resulted in interaction potentials that are closer to those in the real system. Preliminary simulations of the vapor/liquid coexistence curve compare well with experiment. For example, the predicted vapor pressure of water at T=600 K is 105 bar, compared with the experimental value of 121 bar. The predicted critical temperature is 650 K vs 647 K for the experimental value.

We also began to directly simulate partial molar properties of high TP fluids. These quantities provide a convenient way to represent thermodynamic data for many geochemical applications. For example, the partial molar volume can be used to predict the change in solubilities of scales as a function of pressure. Using Monte Carlo methods and the Kirkwood Buff theory of solutions, we began these simulation studies using mixtures of molecules interacting via LJ interactions. The agreement of calculated and measured behavior is quite good. For example, at 1300 K the predicted partial molar of $H_2O$ is 49cc/mole and the experimental is 47cc/mole. Differences in volume are probably caused by the lack of hydrogen bonding structure in the LJ fluid.

**User Interfaces and Web Site Improvements:** This year substantial improvements were made to our http://geotherm.ucsd.edu web site. A preliminary implementation of our GEOFLUIDS application package was added to the site, which previously offered only the TEQUIL package. Since the graphics for the PC version of GEOFLUIDS were done in Visual Basic, they had to be completely redone for use on the web site. A CGI/Perl front end was developed to interface with the Fortran simulation engine on the webserver. In addition to online applications for both TEQUIL and GEOFLUIDS, the site now has download and feedback utilities for both TEQUIL and GEOFLUIDS.

The entire web site was completely redesigned to improve the aesthetics as well as navigation, access and user interaction. Extensive HTML development was required. New images, logos and links were created. The new links make it easier to find all of the data and utilities contained within the pages and to move throughout the pages. A user registration procedure, funding and research credits and a reference list have also been added. Some time was also spent developing trouble-shooting mechanisms.

## FUTURE PLANS

We will continue expanding the compositional flexibility of our rock/water Pitzer-type models (T< 300°C). Aluminum hydroxide, silicate and sulfide systems and pressure variability will be added as well as important thermochemical assessment tools, such as heat content, pH prediction. We will complete a model for the $NaCl-KCl-CaCl_2-MgCl_2-H_2O$ system, targeted for 300°-1000°C and to 6000 bars, for characterizing the chemistry of very high T,P reservoirs and describing important geothermal processes such as flashing, phase co-existence and miscibility. Heat property models of supercritical conditions will be developed. We will also explore more theoretically based modeling approaches in order to develop analytical forms for brine activity expressions (T < 300°C) and free energy descriptions which are accurate through the critical range from subcritical to supercritical conditions. Our TEQUIL, GEOFLUIDS and GEOHEAT application packages will be expanded as described above. A new package, GEOTHERM, containing geothermometry software will be developed. Our web site will continued to be improved. Incorporation of postprocessing visualization tools will be introduced.

## TECHNOLOGY TRANSFER

**Contacts, FY99**

BRITISH GEOLOGICAL SURVEY, United Kingdom: Jon Naden requested TEQUIL, GEOFLUIDS and GEOHEAT.

GEOTHERMAL FIELD, Izmir, Turkey: Niyazi Aksoy requested information about models for space heating applications.

GEOTHERMEX, INC., San Francisco, CA: Christopher Klein requested GEOFLUIDS and TEQUIL.

INSTITUTO TECNOLOGICO GEOMINERA DE ESPANA: Fernandos Tornos requested GEOFLUIDS.

LLNL, Livermore, CA: Carol Bruton requested information about downloading TEQUIL from the web site and about silica solubility.

MCGILL U., Ctr. Climate & Global Change: Christopher Omelon requested TEQUIL and GEOFLUIDS.

NREL, Colorado: Consultants Gene Fritzler and Martin Vorum requested TEQUIL and GEOFLUIDS.

PENNSYLVANIA STATE UNIVERSITY, Dept. Geosciences: James Kubicki requested information about our aluminum speciation simulation studies.

SUNY COLLEGE, Cortland, NY, Dept. Geology: Bob Darling requested GEOFLUIDS.

TECHNISCHE U. HAMBURG-HARBURG, Ger: M. Kuehn requested silica and sulfide parameters.

UN. NEUCHATEL, Centre Hydrogeologie, Switzerland: F-D. Vuataz requested TEQUIL.

USGS, Woods Hole, MA: James Booth requested GEOFLUIDS for methane studies.

VIRGINIA TECH., Dept. Geological Sciences: Robert Bodnar requested our EOS for methane -water.

**Technical Meetings, FY99**

Cal. Tech., Materials and Process Simulation Center Research Seminar, March 18-19, 1999.

U.C. Irvine, Workshop on Density Functional Methods, March 26-28, 1999.

U.C. Berkeley, Earth Sciences Division, April 9, 1999.

DOE Geothermal Program Review XVII, Berkeley, CA, May 18-20, 1999.

NSF/DOE Workshop on Molecular Energy and Environmental Science, Rosemont, IL, May 26-27, 1999.

**Technical papers, FY99**

Duan, Z. Mϕller, N. and Weare, J. "Accurate Prediction of the Thermodynamic Properties of Fluids in the System $H_2O$-$CO_2$-$CH_4$-$N_2$ up to 2000°K and 100kbar from a Corresponding States/One Fluid Equation of State." Accepted, September, 1999.

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## CONTACTS

Marshall Reed, CE-122
U.S. Department of Energy
Washington, D.C. 20585
Phone: 202-586-8076
Email: MARSHALL.REED@ee.doe.gov

Nancy Moller and John H. Weare
Dept. Chemistry & Biochemistry
University of California, San Diego 92093
Phone: 858-534-6374; 858-534-3286
Email: nweare@ucsd.edu; jweare@ucsd.edu

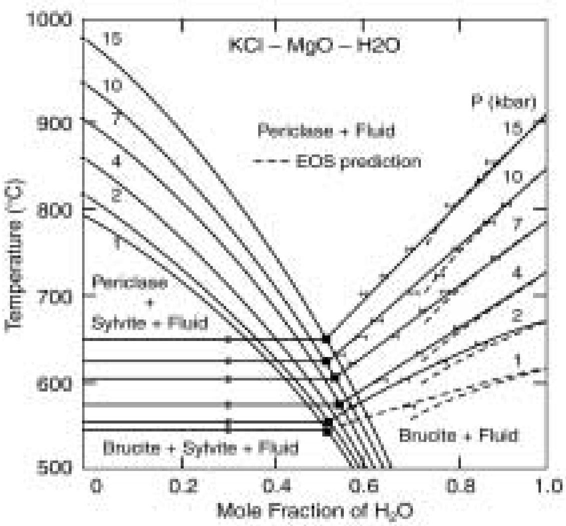


**Figure 1.** Mineral co-existence in the presence of KCl-$H_2O$ solutions (see text).

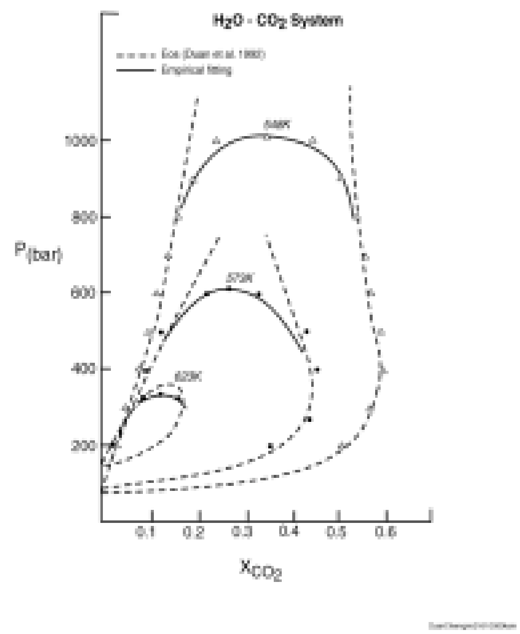


**Figure 2.** Vapor-liquid equilibria in the $CO_2$ – $H_2O$ system (see text).

# INDEXING AND ARCHIVING U.S. HOT DRY ROCK QUANTITATIVE DATA AND OTHER TECHNICAL INFORMATION

Lynn McLarty, Cliff Carwile
Princeton Energy Resources International, LLC

## KEY WORDS

hot dry rock, Fenton Hill, data indexing, data archival

## PROJECT BACKGROUND AND STATUS

DOE sponsored several activities as part of the closeout of the Fenton Hill hot dry rock experimental site near Los Alamos, New Mexico. These activities included decommissioning the site, preparing a comprehensive history of the project, conducting a peer review and data review of the project, and preparing an index of technical information resulting from the project. Of the first two activities, both undertaken by Los Alamos National Laboratory (LANL), decommissioning is complete and the project history is in progress. The last three activities, all of which are complete, were conducted by Princeton Energy Resources International and its subcontractor, GeothermEX.

The purpose of the work described here is to serve as a guide to what happened at the Fenton Hill HDR project, promote easy reference and access to much of the literature that describes that research, and to provide recommendations about preserving quantitative data from the project. This work focuses on indexing the 524 related technical literature pieces published by Los Alamos National Laboratory and the 115 experimental activities conducted at the site. It also identifies the more important quantitative data sets resulting from the research and provides recommendations for archiving them and making them accessible.

This work is part of a larger effort to create an archival and indexing system to preserve all of the important quantitative data and technical literature resulting from the LANL HDR research. LANL has established a fairly comprehensive archive of the technical literature in its library. In addition, much of the literature is also found in the permanent collections at the Geothermal Resources Council (Davis, CA), Princeton Energy Resources International (Rockville, MD), and the Office of Scientific and Technical Information (Oak Ridge, TN).

Much of the quantitative data are still stored at LANL. However, most of the data are not considered archived because there is no system in place for their organization, retrieval, or long term storage and preservation. For this reason, references to the quantitative data sets were not included in the index.

European researchers provided much of the impetus for creating a dedicated HDR project archival and indexing system. They developed such a system for preserving the results of the completed Rosemanowes HDR project at Cornwall, UK, and are developing a similar system for the ongoing HDR project at Soultz-sous-Forets, France. The Europeans recommended a similar system be developed for the Fenton Hill Project under the auspices of Annex III of the Geothermal Implementing Agreement (GIA), to which the U.S. Department of Energy is a signatory. The GIA, which is sponsored by the International Energy Agency, is an international framework for cooperative research in geothermal energy.

## PROJECT OBJECTIVES

The principal objective of this project was to begin the process of indexing and archiving the most important technical information and quantitative data resulting from the hot dry rock experimental project at Fenton Hill, New Mexico. The Fenton Hill project was conducted by Los Alamos National Laboratory from 1970 to 1995. This initial effort focused on identifying and recommending formal archiving of the most important quantitative data sets and creating a database relating the technical reports published by LANL, the quantitative data sets, and the individual experiments conducted at the site.

***Technical Objectives***

- Identify and recommend archiving for the most important data from the Fenton Hill HDR project.
- Develop a database identifying and relating the experimental activities, data, and technical reports published by LANL.

***Expected Outcomes***

- The expected outcome is that the work will serve as a catalyst for preserving and making accessible the information and data generated over 25 years and at a cost of approximately $180 million.

## APPROACH

The approach included the integration of three important sources of information 1) the "Data Review of the Hot Dry Rock Project at Fenton Hill, New Mexico" which was undertaken by the same investigators concurrently with the work described herein, 2) A geothermal bibliography of over 800 citations (mostly related to HDR) provided by Grant Heiken (LANL), 3) personal interviews with industry and research personnel.

Based on recommendations from European researchers, we used the relational database system developed by Polydynamics Engineering, a Swiss firm. International researchers are using the same software for similar purposes in Europe, Japan, and Australia. After testing the software, we decided to use it for two reasons. First, it seemed adequate and appropriate and its use would preclude expending considerable funds to develop a separate system. Second, a common system would facilitate the exchange of data and information among the various international researchers involved in similar research.

## RESEARCH RESULTS

The project resulted in the development of an electronic Project Data Index (PDI) and recommendations for archiving and preserving specific sets of quantitative data. The PDI references and relates the experimental activities at the project and 520 technical reports published by LANL over the 22-year period. Unfortunately, much of the quantitative data are uncertain in regards to their exact location, content, format, and storage media. This precluded the inclusion of this detailed information in the PDI.

The data identified as being the most important and which we recommend be preserved in archives are:

1. Seismic Data
    a. Phase I experiments 203, 195 and 204 (hydraulic fracturing and flow testing of well EE-1) and the Stress Unlocking Experiment at the end of Run Segment 5 (Experiment 217)
    b. Phase II seismic data collected during hydraulic fracturing
2. Phase II Hydraulic Fracturing Data

3. Phase II Flow Test Data

4. Select Phase I and II Tracer Test Data

5. Select Phase I and Phase II Well Log Data

Further details of these recommendations can be found in the final report "Indexing and Archiving U.S. Hot Dry Rock Quantitative Data and Other Technical Information."

## FUTURE PLANS

There are currently no plans for continuing this work.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This work is of limited interest to the geothermal industry. It is of interest primarily to U.S. and international researchers involved in similar research.

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## CONTACTS

Lynn McLarty
Princeton Energy Resources International, LLC
1700 Rockville Pike, Suite 550
Rockville, MD 20582
(301) 468-8442
(301) 230-1232
LmcLarty@perihq.com

Dr. Allan Jelacic
U.S. Department of Energy
Office of Geothermal and Wind Technologies
1000 Independence Ave., SW
Washington DC 20585
(202) 586-6054
FAX: (202) 586-8185
allan.jelacic@hq.doe.gov

Bob Creed, Project Manager
Laboratory Development Office
U.S. Department of Energy
Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
(208) 526-9063
FAX: (208) 526-5964
creedrj@id.doe.gov

# A REVIEW OF GEOTHERMAL WELL STIMULATION EXPERIMENTS IN THE UNITED STATES

Daniel J. Entingh
Princeton Energy Resources International, LLC

## KEY WORDS

well stimulation, hydraulic fracturing, acid treatment, permeability, enhanced geothermal systems

## PROJECT BACKGROUND AND STATUS

This review was undertaken to support technical planning for research in enhanced geothermal systems. Enhanced geothermal systems are those in which advanced technology is required to extract energy from the earth's crust in areas with higher than average heat flow but where the natural permeability and/or fluid content are limited. Such areas are commonly found within or adjacent to commercially operated geothermal fields in the U.S. and elsewhere. Improving permeability through well stimulation methods is of interest to improve success ratios for hydrothermal wells and to extract heat energy that would otherwise be inaccessible.

The review was completed in 1999.

## PROJECT OBJECTIVES

The principal objective of this project was to support technical planning for research in enhanced geothermal systems. It is intended this review will serve as a catalyst for a future baseline study of the state of the art of rock fracturing and other well stimulation technologies, one of several baseline studies outlined in the Enhanced Geothermal Systems Roadmap.

### *Technical Objectives*

- Review the methods and results of the ten geothermal well stimulation experiments sponsored by the U.S. DOE from 1979 through 1984.

### *Expected Outcomes*

- A brief compendium of geothermal well stimulation research to inform planners of research for enhanced geothermal systems.

## APPROACH

The approach included both reviews of technical literature and personal interviews.

## RESEARCH RESULTS

This review focused on ten stimulation experiments in geothermal hydrothermal wells sponsored by the Department of Energy from 1979 through 1984. The Department's Geothermal Reservoir Well Stimulation Program (GRWSP) sponsored eight of the ten experiments. These eight studied the application of conventional petroleum industry well stimulation technologies to geothermal wells. Two additional experiments involved explosive fracturing and high energy gas fracturing.

The GRWSP included literature reviews, laboratory studies, field tests of hydraulic fracturing and acidization treatments. The literature reviews focused on identifying conventional oil and gas well stimulation technologies for possible applications in geothermal wells. The laboratory work studied high temperature behavior of stimulation materials as well as their chemical interactions with formation rocks and fluids. Of eight field experiments conducted, five involved hydraulic fracturing, two involved acidization, and one involved both hydraulic fracturing and acidization. Two of these field experiments were conducted at Raft River, Idaho in 1979; two at East Mesa, California, in 1980; two at Baca, New Mexico, in 1981; one at The Geysers, California, in 1981; and one at Beowawe, Nevada, in 1983.

The results of the GRWSP field experiments were mixed. The best results were achieved in the sedimentary environment at East Mesa where two hydraulic fracturing operations in the same well, each at different intervals, resulted in a 114 % improvement in the productivity of the well. In the metamorphic environments of the other sites the experiments were less successful. The two fracturing treatments at both Raft River and Baca succeeded in obtaining significant production from previously nonproductive intervals, but in each case the production was not commercial quality because of deficiencies in flow rates and/or temperatures. The acid etching experiment at The Geysers resulted in no change in well productivity. At Beowawe, the acid etching operation resulted in a 230% improvement in injectivity of the treated well but measurements of possible productivity improvements were precluded by mechanical problems with the well.

Los Alamos National Laboratory conducted two explosive fracturing operations in a single well at The Geysers in 1981. The experiments resulted in a 35% reduction in permeability-thickness and steam flow rate. Researchers speculated that rubble from the explosions partially blocked two deep steam entry zones.

Experiments by Sandia National Laboratories with high energy gas fracturing (HEGF) in five boreholes at the DOE Nevada Test Site demonstrated that multiple fractures could be created to link a borehole with other fractures. That experiment offered some hope that stimulation can create fractures parallel to the least principal stress in rocks, providing a greater chance of intersecting pre-existing natural fractures, which generally run perpendicular to the least principal stress. However, a subsequent HGEF experiment in a geothermal well at The Geysers failed due to premature ignition of the propellant.

## FUTURE PLANS

Future plans include a review of geothermal well stimulation experiments in Italy and Japan and a study of the current state-of-the-art of well stimulation, including recommendations for geothermal well stimulation R&D.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This work is of interest to geothermal development companies interested in technologies that will enable them to convert non-commercial wells into commercial producers or injectors. The review has been published in two places, the first to reach U.S. geothermal specialists and the second to reach a broader audience.

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## CONTACTS

Dr. Daniel Entingh
Princeton Energy Resources International, LLC
1700 Rockville Pike, Suite 550
Rockville, MD 20582
(301) 468-8418
(301) 230-1232
dentingh@perihq.com

Dr. Allan Jelacic
U.S. Department of Energy
Office of Geothermal and Wind Technologies
1000 Independence Ave., SW
Washington DC 20585
(202) 586-6054
FAX: (202) 586-8185
allan.jelacic@hq.doe.gov

Bob Creed, Project Manager
Laboratory Development Office
U.S. Department of Energy
Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
(208) 526-9063
FAX: (208) 526-5964
creedrj@id.doe.gov

# Assessment of the State-of-the-Art of Numerical Simulation of Enhanced Geothermal Systems

Lynn McLarty
Princeton Energy Resources International, LLC

## KEY WORDS

enhanced Geothermal System, Reservoir Simulation, Reservoir Simulator, Reservoir Model

## PROJECT BACKGROUND AND STATUS

Although GeothermEx, Inc. conducted the reservoir simulation study described here, it has not reviewed this paper.

The strategy for Enhanced Geothermal Systems (EGS) research includes a number of technology baseline studies to determine the status of pertinent technologies and make recommendations for further research in these technologies in order to rationally plan EGS research. One of the principals behind this strategy is to identify possible advances in technologies applicable for EGS research but which might be unknown to geothermal researchers.

This paper briefly reports on a baseline study of reservoir simulators. A number of hydrothermal reservoir simulation models have been developed, some of which continue to be used for commercial or research purposes. Of these, this study examined TOUGH2, TETRAD, STAR AND FEHM. The study also examined simulators designed specifically for hot dry rock reservoirs. These included FRACTure, GEOTH3D, FRACSIM-3D, and Geocrack2D. Besides these geothermal reservoir simulators, the study also examined nuclear-waste-isolation simulators including FLAC and FLAC3D, FracMan and MAFIC, FTRANS, HYDREF, CHEF, VIPLEF, MAGNUM2D, MOTIF, NAPSAC, ROCMAS, SWIFT98, UDEC. Also, the study included several other simulators which might have useful aspects but which did not include a representation of fluid flow in fractures.

This project was begun and completed in federal fiscal 1999.

## PROJECT OBJECTIVES

The general objective of the project was to assess geothermal and nuclear-waste-isolation simulators and make recommendations for further development of simulators applicable to enhanced geothermal systems.

### *Technical Objectives*

- Gain knowledge of geothermal and nuclear-waste-isolation simulators and evaluate them in the context of enhanced geothermal systems.

### *Expected Outcomes*

- A complete evaluation of the state-of-the-art of geothermal and nuclear-waste-isolation simulators.

- Recommendations for use of one or more of these simulators, or combinations of them, or efforts to combine salient aspects of some for simulation of enhanced geothermal systems.

- Recommendations for improving selected simulators or types of simulators for EGS applications.

## APPROACH

The general approach involved evaluating simulators for hydrothermal and hot dry rock reservoirs as well as those developed for studying nuclear-waste-isolation. The nuclear-waste-isolation simulators were included for two reasons: 1) most of them simulate fluid flow in fractured media, and 2) there has been considerable funding for the development of these simulators over the last decade. We first developed a framework for comparison and then evaluated each of the simulators within that framework. The framework consisted of identifying and defining the critical features necessary for simulators of artificially fractured systems. We then evaluated each of the simulators, and compared each with the others, within this framework. Our reviews included literature reviews, reviews of simulator user manuals, operation of simulators, and interviews with the developers and experienced users of simulators.

## RESEARCH RESULTS

We found that none of the simulators reviewed possessed all the capabilities considered necessary for simulating artificially fractured reservoirs. However, it is not necessary for a single simulator to possess all these capabilities at this time because a single simulator or suite of simulators can probably be applied depending on the problem. The table below lists the capabilities of the simulators deemed to be more suitable to EGS applications.

Experience with EGS reservoirs is limited enough that it is not realistic to recommend a particular simulator or simulation approach. A single type of simulator may not be suitable for all EGS projects or at every stage of a given project. Fracture-based models are applicable, but the simulation of discrete fractures is speculative until a model can be validated by operational data.

Currently, further development of existing simulators is more useful than developing a single, all-purpose simulator for EGS. This is particularly true considering that near-term EGS development in the U.S. is likely to occur in hot, low-permeability areas in or adjacent to commercially developed hydrothermal fields. It is likely that the use of a simulator in such instances will be to predict the effect of the EGS development on the conditions in the main part of the hydrothermal reservoir. In the future, EGS development might require a dedicated EGS simulator that combines the capabilities of HDR and hydrothermal simulators, and possibly some of the features of the more complex nuclear-waste-isolation simulators to rigorously model flow in discrete fractures.

Experience with existing simulation tools in real EGS reservoirs is necessary to determine which modeling approaches and capabilities are best suited for differing reservoirs and project phases. We recommend federal funding for active simulation of real EGS reservoirs. Preferably, this research could involve several teams, each modeling the same reservoir with fundamentally different simulators. This approach would demonstrate which simulators were more appropriate at different stages of reservoir development and operation and what additional capabilities might need to be added.

We also recommend that further research should target improving both fracture-network simulators and discrete-fracture simulators for EGS use. Potential areas of improvement include the ability to: 1) handle two-phase flow (including experimentation to adapt the cubic law for two-phase conditions); 2) simulate the formation of a hydraulically stimulated fracture network, given appropriate stress information; and 3) modify fracture aperture as a function of both effective and shear stress.

For hydrothermal simulators, the ability to handle deformation could be added, which would enable them to be used to model the effect on fracture aperture of: 1) thermal contraction of matrix blocks; 2) changes in effective stress; and 3) changes in shear stress. Furthermore, although the approximation of fractures used in the porous-medium simulators has worked well to model highly fractured geothermal reservoirs, it is cumbersome to implement the specific hydraulic connections associated with a large number of specific fractures. The use of these models to represent discrete, hydraulically active fractures could be investigated further, perhaps by adapting a fracture network generator to the porous-medium solver. The link already developed between FracMan (fracture network mesh generator) and TOUGH2 or FEHM (solvers) could be investigated to determine its utility in EGS evaluations.

## FUTURE PLANS

No follow-on work is currently planned.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This work is of interest to developers and operators of hydrothermal reservoirs as well as to potential developers of EGS systems.

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## CONTACTS

Lynn McLarty
Princeton Energy Resources International, LLC
1700 Rockville Pike, Suite 550
Rockville, MD 20582
(301) 468-8442
(301) 230-1232
LmcLarty@perihq.com

Dr. Allan Jelacic
U.S. Department of Energy
Office of Geothermal and Wind Technologies
1000 Independence Ave., SW
Washington DC 20585
(202) 586-6054
(202) 586-8185 (fax)
allan.jelacic@hq.doe.gov

Bob Creed, Project Manager
Laboratory Development Office
U.S. Department of Energy
Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
(208) 526-9063
(208) 526-5964 (fax)
creedrj@id.doe.gov

# GEOCHEMICAL MONITORING AND TRACER TESTING AT THE COVE FORT-SULPHURDALE GEOTHERMAL SYSTEM, UTAH

Joseph N. Moore[1], Michael C. Adams[1], K. Kit Bloomfield[2]
1. Energy & Geoscience Institute, 423 Wakara Way, Salt Lake City UT 84108 U.S.A
2. Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID 83415 U.S.A.

## KEY WORDS

Fluid and gas geochemistry, Tracers, Fluorescein, R-134a, Numerical Simulation

## PROJECT BACKGROUND AND STATUS

The Cove Fort-Sulphurdale geothermal system is one of two fields in Utah currently generating electricity. The field is unusual because it produces dry steam from a parasitic steam cap and liquid from the underlying liquid-dominated resource. The field and power plant are jointly owned by the Utah Municipal Power Agency (UMPA) and Provo City. The plant came on line in 1985 and is currently generating 6-7 MWe from a combination of condensing and binary units.

In 1995, a geochemical monitoring program was initiated by the Energy & Geoscience Institute to determine how production was effecting the resource. Since that time, samples from the five producing dry steam wells have been collected at least biannually, and frequently more often. The dry steam samples were analyzed for their major gases and gas/steam ratios and their stable isotope compositions. $^3He/^4He$ ratios of the steam wells presented by Tonani et al. (1998) indicated that the noble gases were crustal in origin. In mid 1996, well P-91-4, which produces only liquid, was brought on line and injection was initiated. Data on the composition of the reservoir liquid was also presented by Tonani et al. (1998).

In order to understand the potential effects on injection on this system, a numerical model of the reservoir was constructed and a simulated tracer test was performed (Fig. 1; Bloomfield, 1998). A successful production history match was achieved. The results of this study indicted that injection was providing pressure support to the field and that movement of the injectate plume into the bore field was very slow.

A tracer test was performed in January, 1999 to quantity the effects of injection and to obtain additional reservoir information. This test is the first time tracers have been specifically injected to track the movement of the liquid and vapor phases simultaneously. The results of the tracer testing and geochemical monitoring are described in this summary.

## PROJECT OBJECTIVES

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. Thus, the Cove Fort-Sulphurdale geothermal resource provides a unique opportunity to develop a better understanding of the behavior and relationships between naturally formed liquid and vapor-dominated portions of the same reservoir. This information will be of general use to a wide sector of the geothermal community. The work performed here will also provide an improved understanding of the reservoir boundaries, communication between injector and production wells, and interaction between the liquid zone and steam cap. This will help the resource developer optimize production and future expansion of the field.

### *Technical Objectives*

- Develop and test liquid and vapor-phase tracers for geothermal applications.
- Develop a better understanding of the interactions between liquid-and vapor-dominated portions of the same resource.
- Determine how changes in reservoir processes are reflected in the chemistries of the reservoir fluids.
- Develop methods to evaluate tracer testing to acquire reservoir properties.
- Incorporate reservoir properties into numerical simulation techniques that consider both liquid- and vapor-dominated components of a reservoir.
- Train resource operators to incorporate tracer testing in reservoir management.

### *Expected Outcomes*

- Develop better methods of predicting reservoir processes from changes in the compositions of the vapor-dominated portions of the system.
- Quantification of reservoir parameters and processes from vapor-phase tracer testing.
- Identification of key parameters that reduce the risk and expense of expanding exploitation of the Cove Fort-Sulphurdale geothermal resources.
- Development of computationally efficient field scale models to validate project benefits.
- Improved understanding of the behavior of liquid-dominated systems with exploitable vapor-dominated caps.

## APPROACH

The project consists of the integration of three major tasks. They include: 1) establishing the chemical composition of the reservoir fluids and monitoring changes as a function of time; 2) developing appropriate numerical simulations of the geothermal reservoir; and 3) tracer testing and monitoring tracer returns over time

### Chemistry of the Reservoir Fluids

Chemical monitoring of the of the Cove Fort-Sulphurdale geothermal system has included compilation of all fluid analyses into a geochemical database and, and since 1995, routine sampling of the steam and water wells. Comparison of the analyses will provide information on long term chemical changes in the reservoir fluids that will help in predicting future reservoir behavior. Frequent sampling on a quarterly basis prior to injection has been used to assess short-term variations. The sampling and analysis conducted between 1995 and mid 1999 was supported by DOE. Subsequent sampling will be conducted by UMPA. The field operators have been trained in the sampling procedures.

Numerical Modeling

A preliminary numerical model of the Cove Fort-Sulphurdale geothermal system was developed prior to tracer testing. The geometry of this model was based on existing reservoir geologic, geophysical, pressure and production data. The model had an areal size of 7000 feet by 7000 feet with a 20 by 20 grid. In developing the reservoir model, it was assumed that production was primarily from aquifer influx. Calculated temperature and pressure gradients matched the observed data.

Tracer Testing

One of the principal difficulties in designing a tracer test is determining the quantity of tracer that must be injected. In this test, 200 kg each of liquid tracer fluorescein and the vapor-phase tracer R-134a were injected simultaneously into well 42-7 on January 14, 1999. These tracers were selected because of their stabilities, low detection limits, and the results of the numerical modeling which indicated that movement of the tracers from the injection to production wells would be slow, and that significant tracer returns might not occur for at least a year. The wells were sampled on the day of injection, then once per week for four months and at least monthly thereafter.

## RESEARCH RESULTS

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 from both a parasitic vapor cap and the underlying liquid reservoir. A comparison of the analytical data indicate that the compositions of the steam and liquid have remained relatively stable since production began in 1985, but that the steam wells recorded a transient pulse of increased gas shortly after injection was initiated in mid 1996. Recent sampling indicates that these ratios have returned to preinjection levels.

The tracer test has yielded positive results. R-134a, which was injected to trace the movement of the vapor-phase, was detected in all of the steam wells two weeks after injection and as of January 2000, tracer concentrations are still increasing. Mass balance calculations indicate that less than 1% of the R-134a has been recovered. This behavior is in contrast to tracer profiles from the vapor-dominated system at The Geysers, which typically show short duration spikes in tracer returns and high recoveries. (Fig 1). These results are consistent with the numerical modeling and suggest that the early tracer returns have come from a location where the reservoir taps a small fraction of the slowly-moving, liquid injection plume close to the injection well. It is possible that the rest of the tracer may arrive later, and by a different route. The results of the numerical simulation are shown for three months and one year after the start of the tracer test (Fig 2 & 3).

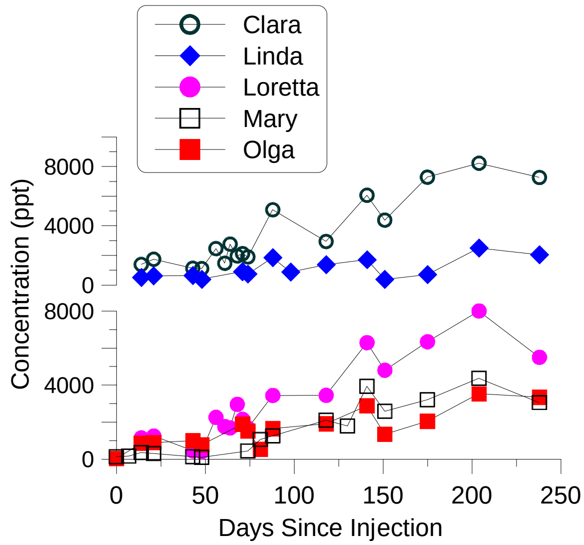


**Figure 1.** Steam well recovery curves for R-134a

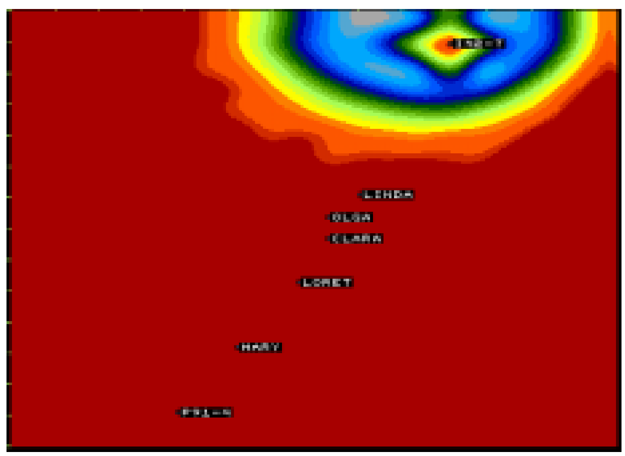


**Figure 2.** Three months after start of tracer test

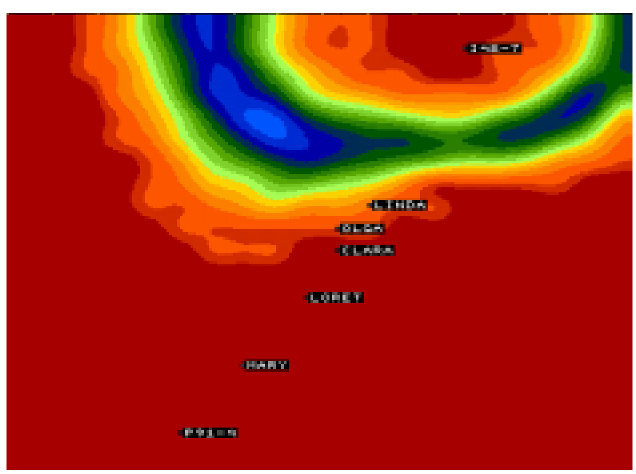


**Figure 3.** One year after start of tracer test

## FUTURE PLANS

We plan to continue the model study and develop and implement techniques to characterize geothermal resources using tracers. We will:

- Identify methods of relaxing the boundary conditions to incorporate what is happening outside the study area.
- Incorporate tracer test results into the numerical simulation.
- Continue monitoring tracer returns
- Continue monitoring the gas compositions of the production wells;
- Characterize changes in gas composition over time and determine the reservoir conditions responsible for them;
- Incorporate these changing reservoir conditions into the numerical simulations being developed;
- Present the results to the geothermal industry

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

There is significant interest in this project from both UMPA and the industry in general because of the similarities between the Cove Fort-Sulphurdale geothermal systems and other systems with parasitic vapor caps. The initial numerical simulations and tracer status report were presented at the annual Stanford Geothermal Workshop and have been provided to UMPA.

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## CONTACTS

DOE Program Manager:
Marshall Reed
U. S. Department of Energy
Geothermal Division, EE-122
1000 Independence Ave., SW
Washington, D. C. 20585
Tel: (202) 586-8076
Fax: (202) 586-8185

DOE Idaho Operations Office Program Manager:
Peggy Brookshier
U. S. Department of Energy
Idaho Operations Office
795 DOE Place, MS 1220
Idaho Falls, ID 83401-1563
Tel: (208) 526-1403
Fax: (208) 526-5964

Principal Investigator:
Joseph N. Moore
Energy & Geoscience Institute
423 Wakara Way
Salt Lake City, UT 84108
Tel: (801) 585-6931
Fax: (801) 585-3540

# EFFECTS OF COLD WATER INJECTION: CERRO PRIETO CASE STUDY

Marcelo J. Lippmann
Lawrence Berkeley National Laboratory

Alfred H. Truesdell
Consultant

## KEY WORDS

Cerro Prieto, liquid-dominated geothermal systems, injection effects, field case study

## PROJECT BACKGROUND AND STATUS

The Lawrence Berkeley National Laboratory has studied the liquid-dominated Cerro Prieto field of northern Baja California, some 30 km south of the California-Mexico border, since the late 1970s. This work is done in close cooperation with the Comisión Federal de Electricidad (CFE), operator of the field. Until about 1989, all separated brines and excess condensate produced at Cerro Prieto were discharged into a large man-made pond located west of the wellfield. During the summer the climatic conditions of the region are ideal for evaporating the brine stored in the pond, however in winter the water level tends to rise, sometimes filling the pond to capacity.

As the installed electrical generation capacity at the field rose, fluid production rate as well as waste brine volumes increased, especially after 1986-87 when two large (220 MWe) power plants were put on line. At that time, CFE began to build facilities to inject the pond brine back into the reservoir to avoid possible brine infiltration into the alluvium of the Mexicali Valley.

Long-term injection experiments started in wells drilled on the western edge of the geothermal field in April 1989 (Gutiérrez Puente and Ribó Muñóz, 1994). Since then, the number of wells and the amount of injected fluid has varied, reaching a maximum of 24 % of the total mass extracted in 1993 (Truesdell et al., 1997); at present, around 20 % is injected. The bulk of the fluid injected is cold (i.e., brine from the evaporation pond). To date, only minor amounts of hot separated brines have been injected taking advantage of the wellhead separation pressures.

It is important to note that at the beginning, the main goal of CFE's injection project was the disposal of brine to reduce the volume stored in the evaporation pond. As the beneficial effects of injection on nearby production wells became evident, the emphasis of the operation shifted to finding the optimum injection/production scheme for recharging the geothermal system without premature thermal breakthrough in production wells.

## PROJECT OBJECTIVES

The overall purpose of the project was to study the effects of injecting cold brine from the evaporation pond on nearby production wells in the western part of the field (Cerro Prieto I area; CP-I).

### *Technical Objectives*

- Determine and quantify the changes (if any) in the chemistry, enthalpy of the produced geothermal fluids, and output of production wells that resulted from the injection of cold brines.

- Identify the processes affecting the chemistry of the waste geothermal brines as they are temporarily stored and then injected back into the reservoir.

***Expected Outcomes***

- Conference paper describing the effects of injection on Cerro Prieto production wells, and associated chemical and physical processes.

## APPROACH

Production, injection and chemistry data provided by CFE, as well as information from published reports, conference articles and journal papers are analyzed to (1) identify physical and geochemical processes that occur during the storage, evaporation and injection of waste geothermal brines, and (2) quantify changes in producing wells resulting from the injection of cold brines into the reservoir.

## RESEARCH RESULTS

As described by Truesdell et al. (1999), the study determined that,

- The waste geothermal brines stored in the evaporation pond have lost silica, which lowered the possibility of mineral precipitation that may reduce well injectivities.

- Silica in the pond brine decreased to near equilibrium with amorphous silica, and re-equilibrates with quartz in the reservoir after injection.

- Several production wells in the western part of the Cerro Prieto field (CP-I area) showed beneficial effects from injection (i.e., sustained well production capacity).

- Some cooling of the reservoir has occurred near the deeper CP-I well E-55 which produces the highest proportion of injected brine. Chemical front breakthrough was identified in this well on the basis of the chloride content in the produced fluid, however thermal breakthrough was not evident.

Considering the positive results to date, we conclude that the injection of cooled waste geothermal brines should continue along the western boundary of the Cerro Prieto field, and we recommend that injection of hot separated brines in other areas should be contemplated by CFE.

## FUTURE PLANS

The analysis of Cerro Prieto production and injection data will continue as part of the on-going field case study. The information being gathered continues to provide insights on the behavior of geothermal systems under exploitation Even though Cerro Prieto has a predominantly porous medium reservoir (fractures only seem to be prevalent at deeper levels), many of the physical and chemical phenomena observed, or inferred from field data, are also occurring in other geothermal areas.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

U.S. companies interested in the development of the Salton Trough geothermal resources on both sides of the California-Baja California border, will benefit in the results of the Cerro Prieto case study. The data and the results of the study will be useful in their exploration, evaluation and development efforts.

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## CONTACTS

Marshall Reed
Office of Geothermal and Wind Technologies
U.S. Department of Energy, EE-12
Washington, DC 20585
Phone: (202) 586-8076
Fax: (202) 586-8185
e-mail: marshall.reed@hq.doe.gov

Marcelo J. Lippmann
Earth Sciences Division, MS 90-1116
E.O. Lawrence Berkeley Natl. Laboratory
Berkeley, CA 94720
Phone: (510) 486-5035
Fax: (510) 486-5686
e-mail: mjlippmann@lbl.gov

Alfred H. Truesdell
700 Hermosa Way
Menlo Park, CA 94025
Phone: (650) 322-6135
Fax: (650) 324-4009
e-mail: ahtruesdell@lbl.gov

# FIELD STUDIES OF GEOTHERMAL RESERVOIRS RIO GRANDE RIFT, NEW MEXICO

James C. Witcher
Southwest Technology Development Institute, New Mexico State University

## KEY WORDS

Rio Grande rift, alteration, geologic mapping, Jemez Pueblo, Hillsboro, Rincon, San Diego Mountain, geochemistry, hydrothermal history, hydrogeologic models

## PROJECT BACKGROUND AND STATUS

The Rio Grande rift provides an excellent field laboratory to study the nature of geothermal systems in an extensional environment. Much of the geologic complexity that is found in the Basin and Range is absent because the rift is located on cratonic crust with a thin and relatively well understood Phanerozoic stratigraphy. On the other hand, the Neogene thermo-tectonic history of the rift has many parallels with the Basin and Range to the west (Chapin and Seager, 1975; Seager and others, 1984).

The geology of the southern Rio Grande rift is among the best characterized rift systems in the world. Also, the Quaternary geologic framework of rift study areas is exceptionally well characterized (Gile and others, 1981; Seager and others, 1982; Seager and others, 1987; Seager and Hawley, 1973; and Seager and others, 1971).

Pleistocene to Holocene entrenchment of the Rio Grande and tributaries unroofs the alteration signatures and permeability attributes of paleo outflow plumes and upflow zones, associated with present-day, but hidden or "blind," hydrothermal systems at Rincon and San Diego Mountain (Witcher, 1991a, and 1998). These areas are important because both the hanging wall and footwall expressions of major controlling structures are exposed. Alteration aureoles, intercalated paleo hot spring deposits, and domains of fault- and geothermal-related fracturing exposed in badlands topography allow a "four" dimensional view of these systems. A view of the fourth dimension, time, for these geothermal systems is possible because the stratigraphy, tephrochronology and paleomagnetic signature of host Pleistocene sediments is very well characterized (Mack and others, 1998; Mack and others, 1996; Mack and others, 1993; and Mack and James, 1986). In addition, hydrothermal alteration and paleo spring deposits provide additional datable material. In many cases, paleo hot spring deposits are draped across geomorphic surfaces (terraces and straths) associated with an entrenching ancestral Rio Grande (post 700 ka) (Jarvis and others, 1998).

This project also has a near-term economic development goal to spur geothermal use at Jemez Pueblo in order to provide much needed revenue and employment opportunities. Available resource data suggest that geothermal production for direct-use may have among the lowest capital and operating cost potential of the resources in New Mexico due to the shallow reservoir depth and artesian head of the fluids (Witcher, 1991b).

This project, which began in the Summer of 1998, will be completed in 2000.

## PROJECT OBJECTIVES

Recognition of geohydrologic windows through the use regional subcrop map compilations appears to provide a first-order geologic model to predict resource occurrence on regional and intermediate scales (Witcher, 1988). However, the actual nature of the flow paths, recharge sources, depth of circulation, relation to Neogene tectonism and magmatism, and behavior of the systems through time is unknown or very poorly defined for Rio Grande rift geothermal systems outside of the Valles Caldera area in Jemez Mountains of New Mexico. This research project is directed at defining the main geologic and hydrogeologic characteristics of higher temperature geothermal systems in the Rio Grande rift outside of the Valles Caldera.

***Technical Objectives***

- Identify and map primary and secondary structural and stratigraphic controls on system upflow and lateral outflow.
- Characterize the geochemical and stable isotopic signatures associated with the upflow and lateral outflow alteration and fracture mineralization.
- Describe the paragenetic sequence of alteration minerals and events.
- Map the extent of petrologic and geochemical signatures of hydrothermal processes and events.
- Determine paleo temperatures and salinity where suitable fluid inclusion information may be obtained from alteration and fracture mineral phases.
- Define the lateral extent of the shallow geothermal resource at Jemez Pueblo.

***Expected Objectives***

- Document the temporal and spatial evolution and development of geohydrologic windows for rift hydrothermal systems with respect to architectural elements of the rift and complementary normal faults and stratigraphy.
- Document the nature and importance of older deeply-penetrating pre-rift structures for fracture permeability and reservoir hosts.
- Detail the hydrothermal history and relate this history to the Neogene timelines of regional geologic evolution and climate.
- A dipole-dipole resistivity survey will determine the extent of the shallow geothermal resource at Jemez Pueblo and lead to near-term utilization.
- Direct-use and/or small-scale binary electrical power geothermal development is expected at Rincon, Hillsboro, and San Diego Mountain in the near future.

The first three expected objectives of the field case studies developed by this project will greatly assist efforts to successfully explore and wisely develop "blind" Basin and Range or rift-related and fracture-dominated geothermal systems.

## APPROACH

Detailed geologic mapping is delineating the structural permeability of these systems and the alteration types and distribution. Major stratigraphic units include fluvial channel deposits of sand and gravel, opal beds (siliceous sinter), overbank silt and clay and other beds as necessary to describe the outflow plume alteration and hydrostratigraphy. Stratigraphically coherent sampling for alteration and geochemistry is performed in conjunction with the mapping. Alteration studies include petrographic study of thin-sections and X-ray diffraction. Geochemical analysis includes whole-rock major and trace element analyses of altered and unaltered lithologies. Paleo fluid temperature and salinity will be determined where alteration and fracture mineral phases provide suitable primary fluid inclusions.

Stable oxygen, carbon, and sulfur isotope analysis of solid phases provides important clues on the recharge, flow paths and the magnitude of geochemical interaction between geothermal fluids and reservoir rocks. Also, selected materials will be age dated to extract detailed information on timing and duration of specific hydrothermal events or processes.

A detailed petrographic and geochemical analysis of core from the Rincon SLH#1 corehole is also being conducted. This borehole, 371 m depth, was funded by the State of New Mexico (Witcher, 1998).

Finally, a dipole-dipole electrical resistivity survey in conjunction with Dr. Howard Ross, Energy and Geoscience Institute (EGI), University of Utah will complete the geothermal resource evaluation of Jemez Pueblo tribal lands prior to actual production drilling and commercial geothermal use.

## RESEARCH RESULTS

The Rincon and San Diego Mountain geothermal systems are associated with Neogene inversion tectonics within the rift. Both areas represent basement terranes or horst blocks that are actively piercing upward from an older Miocene graben floor through Oligocene to Late Miocene volcanics and basin fill. The hanging walls on both uplifted terranes contain fracture and breccia zone barite and minor fluorite mineralization. Uplift of Precambrian granite to the surface at San Diego Mountain may exceed 2 km since 9.6 Ma, the age of the Seldon basalt flow (Seager and others, 1984) that was extruded on to the floor of the Miocene Rincon basin near the end of basin deposition. An apatite fission track age on the San Diego Mountain granite in the footwall indicates uplift through the 120 $^{o}$C isotherm at 6.5 +/- 2.2 Ma (Kelley and Chapin, 1997).

Footwall barite mineralization in these areas has several important implications. First, this mineralization may document reservoir conditions of present-day geothermal systems in the rift because the low salinity and moderate homogenization temperatures of fluid inclusions are compatible with salinity and maximum geothermometers of many higher temperature systems such as Rincon (Witcher, 1991a and McLemore and others, 1998). Pleistocene barite mineralization is also observed in fractures of core from the Rincon SLH1 borehole. Second, the life span of these systems may exceed 6.5 million years and be a hydrogeologic consequence or expression of the tectonism.

At Rincon, mapping shows that the north striking East Rincon Hills fault segments and jogs left lateral in the area of highest temperature gradients and most anomalous SP survey areas discussed in Ross and Witcher (1998). As fault tips are approached at the lateral offset, the fault zone damage increases in intensity and breadth and is characterized by a widening zone of erosion resistant silicified breccia. Hanging wall strata show a "half dome" upwarp geometry around the fault "dog leg." A set of high-angle fractures cuts the hanging wall region of fault tips or segment termination. These fractures are oblique to fault strike and are filled with banded opal. Core from the Rincon SLH1 borehole indicate that the fracture fills change systematically with depth (Witcher, 1998). Only opal is present above 122 m depth, opal is absent below 183 m depth. Drusy quartz is present below 143 m depth along with pyrite and some barite. While fractures are largely filled above 122 m depth, the fractures are partially to fully open at greater depth.

Rift accommodation or transfer zones are emerging from this research as extremely important generators of fracture permeability and for the evolution of hydrogeologic windows for shallow geothermal resources in fault footwalls and horst blocks in the rift. Also, the local architecture of faults such as "jog" or "dog leg" transfer zones show enhanced open fracture permeability along the fault plane and in the adjacent hanging wall ramp zones.

## FUTURE PLANS

Current emphasis is on detailed petrographic study of alteration and mineralization and geochemical systematics.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| | |
|---|---|
| Jemez Pueblo | geothermal as a vehicle for tribal economic development |
| lease holders | binary electrical power production |
| startup business | large-scale (~10 acre) geothermal greenhouse development |
| NMGS | led 110 members of New Mexico Geological Society on field trip to Rincon geothermal area to view exposure of Pleistocene geothermal system in November 1998 (Witcher, 1998 and Mack and others, 1998) |

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## CONTACTS

James C. Witcher, Principal Investigator
Southwest Technology Development Institute
New Mexico State University
Box 30001, MSC 3SOL
Las Cruces, NM 88003
505/646-3949
505/646-2960 FAX
jwitcher@nmsu.edu

Robert Creed, Jr., Project Manager
U. S. Department of Energy
Idaho Operations Office
850 Energy Drive, MS-1220
Idaho Falls, Idaho 83401-1563
208/526-9063
208/526-5964 FAX
creedrj@inel.gov

Marshall J. Reed
Program Manager
U. S. Department of Energy
Office of Geothermal Technologies, EE-12
1000 Independence Avenue, SW
Washington, DC 20585
202/586-8076
202/586-8186 FAX
marshall.reed@hq.doe.gov

# TRACING FLUID FLOW IN GEOTHERMAL RESERVOIRS

Peter E. Rose
Energy & Geoscience Institute
University of Utah

## KEY WORDS

geothermal tracers, tracer tests, ground water tracers, fluorescein, polyaromatic sulfonates, laser-induced fluorescence

## PROJECT BACKGROUND AND STATUS

Injection of produced fluids is essential to prudent geothermal reservoir-management strategies, both as a means of disposing of an environmental pollutant as well as a method of maintaining reservoir pressures. The location of the injection wells within the three-dimensional network of fractures that forms the reservoir is crucial to the successful exploitation of the field. Proper well location leads to increased power production due to enhanced pressures, less reservoir scaling from boiling around the production wells, and reduced thermal breakthrough. Introduction of tracers into the injection-production loops is the fastest and most effective method of obtaining data that reveal the flow patterns of injected fluids.

At the inception of the tracer development program in 1982, there were very few tracers in use by the geothermal industry. In addition, an insufficient knowledge of the thermal stability of these known tracers produced a lack of confidence in the results of tracer field tests. Surveys of the geothermal industry by the DOE indicated a strong belief that tracer research and development would be very valuable if stable geothermal tracers could be developed. It was on this basis that the tracer development project was founded. Several tracers have subsequently been developed and field-tested (Adams and Davis, 1991; Adams *et al.*, 1992; Rose and Adams, 1994; Rose and McPherson, 1997; Rose *et al.*, 1998; Rose, 1998; Rose *et al.*, 1999; Rose *et al.*, 2000). Laboratory and field testing continues in an effort to develop additional tracers in order to facilitate the prodigious task of tracing the flow paths of injected geothermal fluids through hydrothermal systems.

## PROJECT OBJECTIVE

The primary objective of this research project is to identify and test candidate compounds for use as tracers in geothermal reservoirs. An ideal tracer is nontoxic, environmentally benign, thermally stable (or possessing a quantifiable and reasonably slow rate of decay under geothermal conditions), detectable at very low concentrations, non-reactive with the reservoir rock and relatively inexpensive. As many of these compounds as possible should be identified because of the need for identifying individual injector/producer flow paths in reservoirs containing multiple injection wells.

### *Technical Objectives*

- To prove the stability of several candidate compounds for use as tracers in high-temperature geothermal reservoirs. Use both laboratory and field-tests to provide the evidence of stability. As many of these compounds as possible should be identified because of the need for the simultaneous use of multiple tracers in reservoirs containing many injection wells and, as a result, multiple injection-production flow paths.

- To demonstrate the greatly enhanced detectability of fluorescent compounds using the emerging technologies of laser-induced fluorescence, fiber optics and charge-coupled device (CCD) spectrometry. Using this approach the detection limit of fluorescent compounds can be reduced by a factor of 1000 to the low parts-per-quadrillion range. This allows not only for a huge reduction in the amount of tracer required for a tracer test, but also for the use of many fluorescent compounds that are not available in bulk quantities.

***Expected Outcomes***

- To provide a minimum of seven affordable, easily detectable tracers that are stable in geothermal reservoirs with temperatures exceeding 300$^{o}$C.

- To demonstrate a reduction in the detection limit of fluorescent compounds by a factor of 1000 from the current low parts-per-trillion range to the low parts-per-quadrillion range.

## APPROACH

Our approach to the development of new tracers for use in high-temperature geothermal reservoirs has been, first, to search the literature for promising candidates. Next, standard methods of chemical analysis are employed in order to determine whether the candidate compounds are sufficiently detectable to render them affordable for industrial application. The surviving candidates are then subjected to a series of laboratory experiments using high-pressure autoclaves to create an environment of temperature, pressure, and solution matrix that simulates the reservoir environment. Upon completion of the laboratory phase, the candidate tracers are field-tested in geothermal reservoirs. The results of the full-scale field tests are then compared to the results of the laboratory tests in order to refine the laboratory-derived parameters. Finally, the results of the laboratory experiments and field tests are published in the open literature. These methods provide for rapid evaluation of candidate compounds and immediate, up-to-date access of our results to the geothermal community.

Our approach to the development of greatly increased detectability of fluorescent tracers has focused on the emerging technologies of laser-induced fluorescence, fiber optics and CCD spectrometry. Significant improvement in detectability means that the quantity of tracer required in a field test will likewise be greatly reduced, with a concomitant reduction in cost to the geothermal operator. Small quantities also mean that many fluorescent compounds that are not currently manufactured in bulk will become available as tracers. Many of the technologies that we will demonstrate will have applicability in the development of rugged, affordable, on-line tracer detection at the well head, which geothermal operators have long desired.

## RESEARCH RESULTS AND VARIANCES

***Tracers for Use in High Temperature Geothermal Reservoirs***

In order for candidate tracers to qualify for use in the geothermal industry, they must be environmentally benign, affordable, detectable, thermally stable, and resistant to adsorption. Unfortunately, very few non-radioactive compounds are both very detectable and thermally stable under the rigors of a hydrothermal environment at 300$^{o}$C. We are continuing a systematic approach to the identification of viable tracers by looking within a class of fluorescent compounds that is known to possess these qualities--the sulfonate derivatives of polyaromatic hydrocarbons.

The polyaromatic sulfonates possess excellent thermal stability due to their condensed aromatic ring structure, which possesses significant double-bond character. Likewise, this condensed aromatic ring structure accounts for their fluorescence, which, in turn explains their excellent detectability. Figure 1 shows the various sulfonate derivatives of the 2- and 4-ring polyaromatic hydrocarbons that we have evaluated in the laboratory and in field studies during the past two years (Rose, 1998; Rose *et al*., 1998; Rose *et al*., 1999; Rose *et al*., 2000). Column 3 lists the extent of thermal decay observed for each compound upon exposure to laboratory-simulated geothermal reservoir conditions for one week at 300$^{o}$C. Since the experimental error was 5%, only Crisotan R5 evidenced any measurable decay.

In subsequent experiments, 1,5-naphthalene disulfonate and 1,3,6-naphthalene trisulfonate showed only 20% decay upon exposure to geothermal conditions for one week at 330$^{o}$C. Further studies of these compounds were conducted to determine their Arrhenius decay rate constants as functions of temperature over the range 310$^{o}$C to 330$^{o}$C (Rose *et al*., 1999; Rose *et al*., 2000). From these studies, it is evident that 1,5-naphthalene disulfonate and 1,3,6-naphthalene trisulfonate, which can be used in geothermal reservoirs with temperatures approaching 340$^{o}$C, are considerably more thermally stable than the xanthene dyes fluorescein and rhodamine WT, which are qualified for use as tracers in reservoirs with temperatures as high as 250$^{o}$C and 180$^{o}$C, respectively.

Whereas laboratory experimentation is required for testing candidate tracers under controlled conditions of time, temperature, pressure and solution chemistry, the tracer qualification process is incomplete without field-testing. 1,5-naphthalene disulfonate and 1,3,6-naphthalene trisulfonate were used in tracer tests at the Dixie Valley, Nevada, Ohaaki, New Zealand, and Awibengkok, Indonesia, geothermal reservoirs (Rose *et al*., 2000). All tests were successful; each tracer behaved conservatively and in accordance with laboratory predictions.

***Greatly Enhanced Detectability of Geothermal Tracers***

We designed, fabricated and tested an instrument for reducing the detection limit of fluorescent compounds by a factor of 1000 (see Figure 2). In addition, we evaluated a number of candidate fluorescent compounds that can be analyzed using this instrument. For those compounds that had the lowest detection limits, we have begun to characterize their decay kinetics parameters under laboratory conditions that simulate a geothermal reservoir.

## PLANS FOR CONTINUING WORK

Additional fluorescent candidate tracers from among the polyaromatic sulfonates will be tested for thermal stability and detectability in the laboratory under conditions that simulate high-temperature liquid-dominated geothermal reservoirs. The Arrhenius decay rate constants for 2-naphthalene sulfonate and 2,7-naphthalene disulfonate will be determined at appropriate temperatures. In addition, we will seek opportunities to test these tracers in high-temperature (300$^{o}$C or hotter) liquid-dominated hydrothermal systems. We will continue to evaluate the candidate fluorescein derivatives in order to select one for demonstrating the laser-induced fluorimetry approach and parts-per-quadrillion detection in a full-scale field test.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All of our field tests are designed to maximize the collection of reservoir information as well as data on tracer stability. Because of this balance between research and application, industry is willing to cost-share those tests. The following table lists the name of the company as well as the type and extent of interest that it has demonstrated:

| Organization | Type and Extent of Interest |
|---|---|
| CalEnergy Corporation | cost-shared tracer test at Coso, CA, geothermal reservoir |
| Calpine Corporation | cost-shared tracer test at The Geysers, CA, geothermal reservoir |
| Far West Capital Inc. | cost-shared tracer test at Steamboat Hills, NV, geothermal reservoir |
| Northern California Power Agency | cost-shared tracer test at The Geysers, CA, geothermal reservoir |
| Oxbow Power Services | cost-shared tracer test at Dixie Valley, NV, geothermal reservoir |
| Oxbow Power Services | cost-shared tracer test at Beowawe, NV, geothermal reservoir |
| Pacific Gas and Electric | cost-shared tracer test at The Geysers, CA, geothermal reservoir |
| Unocal Energy Resources | cost-shared tracer test at The Geysers, CA, geothermal reservoir |
| Unocal Geothermal of Indonesia | cost-shared tracer test at Awibengkok, Indonesia, geothermal reservoir |
| USGS and DOE | Cost-shared tracer test at INEEL, ID |

***Technology Transfer at the Idaho National Energy and Environmental Lab (INEEL)***

The polyaromatic sulfonate tracers that we are evaluating for tracing fluids in geothermal reservoirs are also useful in ground water tracing applications. In conjunction with the USGS, we conducted a cost-shared tracer test at DOE's INEEL facility near Idaho Falls, Idaho, at a site adjacent to INEEL's Radioactive Waste Management Complex (RWMC).

For the test, the geothermal tracer 1,5-naphthalene disulfonate was added to temporary lakes ("spreading areas") adjacent to the Radioactive Waste Management Complex (RWMC). These spreading areas are used for flood control during spring run-off. Water from the spreading areas flows into the subsurface, principally through fractured basalt deposits, and intersects unconsolidated sedimentary interbeds approximately 110 and 240 ft below the surface.

Tracer was detected in wells within the RWMC, indicating a high-conductivity pathway between the spreading areas and the RWMC via the sedimentary interbeds. Tracer was also detected in an aquifer below the water table. This test represents the first reported successful use of any of the polyaromatic sulfonates as ground water tracers. It has also stimulated a great deal of interest in the use of the polyaromatic sulfonates as tracers in other sites at INEEL.

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### CONTACTS

Peter E. Rose
Energy & Geoscience Institute
423 Wakara Way suite 300
Salt Lake City, UT 84108

Marshall Reed, CE-122
U. S. Department of Energy
Washington, D.C. 20585
Phone: (202) 586-8076

Robert Creed
U.S. Department of Energy
Idaho Operations Office
785 DOE Place
Idaho Falls ID 83402
Phone: (208) 526-9063

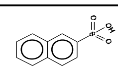
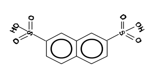
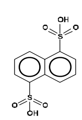
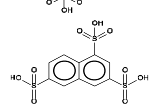
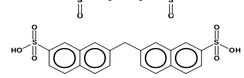
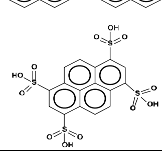
| Compound | Structure | % Decay | Ex/Em |
|---|---|---|---|
| 2-naphthalene sulfonic acid |  | < 5 | 220 / 336 |
| 2,7-naphthalene disulfonic acid |  | < 5 | 226 / 339 |
| 1,5-naphthalene disulfonic acid |  | < 5 | 218 / 334 |
| 1,3,6-naphthalene trisulfonic acid |  | < 5 | 228 / 342 |
| Crisotan R5 |  | < 15 | 228 / 340 |
| 1,3,6,8-pyrene tetrasulfonic acid |  | < 5 | 346 / 386 |

**Figure 1.** Chemical structures of the polyaromatic sulfonates tested in the laboratory and in the field. Column 3 shows the percent decay of each compound upon exposure to simulated reservoir conditions in laboratory batch reactors at 300°C for one week. Column 4 lists the excitation and emission maxima for each compound.

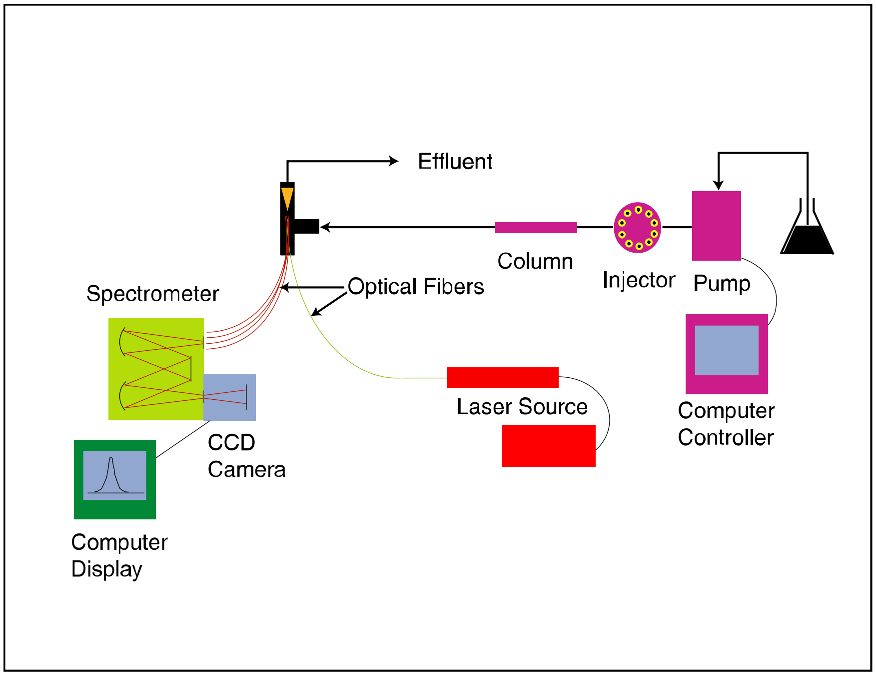



**Figure 2.** Schematic drawing of the laser-induced fluorescence equipment. A standard liquid chromatographic system physically separates analytes and delivers them to the flow cell. Light of an appropriate wavelength is delivered by an optical fiber to the flow cell. The fluorescent signal from the analyte is then backscattered and delivered via more optical fibers to the spectrometer and CCD camera, whereupon the signal is analyzed and interpreted by computer software.

# GEOLOGIC RESERVOIR CHARACTERIZATION OF THE MEDICINE LAKE VOLCANO GEOTHERMAL SYSTEM, CALIFORNIA

Jeffrey B. Hulen and Susan J. Lutz
Energy & Geoscience Institute, University of Utah

## KEY WORDS

Medicine Lake Volcano, geothermal system, California, volcanic stratigraphy, hydrothermal alteration, hydrothermal sealing, granitoid intrusions, Quaternary volcanism

## PROJECT BACKGROUND AND STATUS

Medicine Lake volcano (MLV) is a massive, Pleistocene-Holocene shield volcano situated just east of the Cascade range in northeastern California. The volcano hosts a large, active, high-temperature (up to 288$^{o}$C; Iovenitti and Hill, 1997), liquid-dominated geothermal system now being evaluated by CalEnergy and Calpine Corporations (Richard et al., 1998). The system is perhaps the most promising, currently undeveloped, electrical-grade geothermal resource in the contiguous United States. Numerous thermal-gradient boreholes and four deep production-scale wells have been completed in the MLV system. Three of the wells, in the CEC Telephone Flat region, are capable of commercial, electrical-grade, thermal-fluid production, and CEC has proposed accordingly to install and operate a 48 MW geothermal plant on the property (Iovenitti and Hill, 1997).

Although CEC and its predecessors at MLV have demonstrated the presence of a viable Telephone Flat geothermal resource, in the process assembling a voluminous geoscientific exploration database, additional work is desirable to develop an optimal geologic model of the system – a model to help guide future exploration and development efforts, and one which is tightly focused on elucidating the nature and configuration of the system's all-important porosity and permeability network. One means of accomplishing this task is through cooperative investigation with Department of Energy geothermal researchers. This approach has been highly beneficial at such geothermal systems as The Geysers (Hulen et al., 1995), California, and Awibengkok, West Java, Indonesia (Hulen and Anderson, 1998). Through implementation of such a program, industry gains the services of a dedicated research team of a size and breadth of knowledge which most geothermal companies find impractical to maintain internally. Researchers are correspondingly able to work with talented industry personnel on incomparable research materials which would otherwise remain exclusively proprietary.

EGI has obtained the key documents, data sets, and petrographic thin sections accumulated by CEC for its Medicine Lake/Telephone Flat geothermal exploration effort. Under the broader terms of a CEC-EGI technical data gathering agreement, these data, reports, and samples are considered confidential and proprietary, but can be used freely in support of EGI research projects. Results of these projects, by contractual obligation to the DOE Office of Geothermal Technologies, can be published with prior review by CEC.

CEC has proposed to complete a deep scientific coring effort at Telephone Flat, and has secured partial funding for that purpose from the California Energy Commission. Although funded, the project has been temporarily delayed until National Forest and other land-use issues are resolved. Because of the highly promising nature of this resource, and because a geothermal field would have minimal impact on the environment, we assume that the coring effort will get underway, and are preparing accordingly. In the meantime, the rich geological, geochemical, hydrological, and geophysical database for MLV is enabling EGI to prepare an unusually detailed three-dimensional picture of a large Holocene volcano and the vigorous, electrical-grade geothermal system which it hosts.

## PROJECT OBJECTIVES

### *Technical Objectives*

- Evaluate the existing Telephone Flat and MLV geological, geochemical, hydrological, and geophysical database, including information obtained directly by CEC and its predecessors at the site as well as published accounts, in particular the landmark contributions of the U.S. Geological Survey (e.g. Donnelly-Nolan et al., 1990; Bargar and Keith, 1999; Lowenstern et al., 1999).

- Examine the existing documentation (lithologic logs, geophysical logs, XRD analyses, petrographic descriptions, etc.) for cores and cutting retrieved to date from the Medicine Lake volcano. Determine what further characterization would be beneficial to the overall research effort. Complete this additional work (e.g. fluid-inclusion, stable-isotopic, age-dating, petrographic investigations).

- Build conceptual models portraying possible 3-D configurations for the explored and outlying portions of the Telephone Flat system.

- Select coring sites in the system most likely to yield the maximum amount of useful subsurface information about the circulating geothermal system and its permeability and porosity network.

- (Contingent on final approval for project): Hulen to participate in a Telephone Flat scientific coring effort in the capacity of Chief Scientist, discharging the duties of that position as for past such efforts including The Geysers Coring Project

### *Expected Outcomes*

- Improved understanding, in three dimensions, of the stratigraphic, structural, alteration, mineralization, and permeability configurations of the Medicine Lake volcano and Telephone Flat geothermal system as well as similar such volcanic-geothermal settings around the world.

- Selection of the best possible Telephone Flat coring site to obtain the maximum amount of useful information about the circulating geothermal system, its enveloping hydrologic seal, and its youthful volcano-tectonic setting.

## APPROACH

Phillips and Occidental Petroleum and Unocal Geothermal assembled a rich database on the geology, geochemistry, alteration, hydrology, and structural setting of Telephone Flat as an essential part of their extensive exploration effort commencing in the mid-1980's. The Phillips and Occidental data were inherited by Calpine Corporation, and the Unocal data were acquired by CEC in 1993. Since then, CEC and Calpine have significantly augmented the database through new exploration and evaluation. The combined database includes, but is not limited to, borehole logs of all types, petrographic descriptions, fluid-inclusion microthermometry, downhole stable-isotope analyses, whole-rock geochemistry, volcanic stratigraphy, magnetotelluric survey results, gravity, magnetics, and surface and subsurface water chemistry and isotopic composition. It is a wonderful resource, obviating the need for extensive additional such work in the near term. We are absorbing, cataloguing, and utilizing the data sets in alternative ways to obtain a thorough understanding of the system as known by the geothermal companies, and doing a limited amount of supplemental petrographic and XRD analytical work to bridge gaps where we perceive them. A three-dimensional model of the volcano and geothermal field has not heretofore been prepared. We have made good progress in completing this task, because we believe strongly such models aid immeasurably in the visualizing of the subsurface geologic setting necessary for optimum drill hole siting and ultimately geothermal production. With regard to the proposed scientific drilling efforts, we are of course in close contact with CEC geoscientists, who are the real experts on the Telephone Flat system, when the answers to specific questions are not immediately accessible from study of the database.

## RESEARCH RESULTS

During 1999, we completed lithologic, petrographic, and mineralogic assessments of five thermal-gradient wells and one deep productive geothermal well. This exemplary cross section will anchor completion of the 3-D model discussed above. Among the significant findings of this inaugural effort: (1) The active, productive portion of the geothermal system is hosted by commonly intensely propylitized, Pliocene to Pleistocene volcanic rocks ranging in composition from rhyolite to basalt, but dominated by the latter. Thick (>10 m) intervals of this sequence commonly contain >20% epidote, the key propylitic phase. (2) the productive propylitic zone is overlain by moderately to intensely argillized and sericitized volcanics of similar composition. These layer-silicate altered rocks provide a tight top-seal, or cap, on the underlying, convective geothermal system. The cap not only prevents the incursion of cool groundwaters downward into the system, it prevents the egress of hot hydrothermal fluids, thereby preserving overall system integrity. The caprock is overlain by a zone of only weakly altered Pleistocene to Holocene volcanics—a zone which corresponds to a pronounced, cool-isothermal interval on production-temperature logs. The cap itself is distinguished by a very steep conductive gradient. From the bottom of the cap to the base of the reservoir, temperatures measured so far in the MLV system are near-isothermal between about 230$^{o}$C and 260$^{o}$C—again, the maximum temperature measured in the field to date is 288$^{o}$C.

The lower reaches of two deep production-scale wells at MLV penetrate granitoid intrusions ranging in composition from granodiorite to granite. In one well, Glass Mountain Federal 31-17, the granodiorite is dominant, and is intensely potassically altered (secondary biotite after original mafics; secondary K-spar forming thick, irregular rims on primary plagioclase crystals. Highly saline secondary fluid inclusions are common in primary quartz, suggesting that the alteration may be of magmatic-hydrothermal origin. Lowenstern et al. (1999) have dated at least one phase of the granodiorite from 31-17 at about 230 ka. A younger age from argon-argon incremental-heating age-dating of K-feldspar (about 150 ka) likely reflects the strong potassic alteration. These intrusions are indicated by geophysical signatures to be both deep and broad. In view of their mid- to late Pleistocene age, the plutons are likely to be the still-cooling magmatic heat sources for the active MLV hydrothermal system.

## FUTURE PLANS

- Continue petrographic and mineralogic characterization of drill cutting and cores from MLV thermal-gradient boreholes and production-scale geothermal wells.
- Continue assimilation and synthesis of the existing MLV database. Refine that database with input from the first task, bulleted above.
- Continue preparation of field-wide stratigraphic, lithologic, structural, alteration, and mineralization models for MLV.
- Map and characterize in particular detail the deep granitoid intrusions beneath the MLV geothermal system.

- With detailed knowledge of those intrusions and overlying alteration zoning, collaborate with D.L. Norton to model mathematically the evolution of the hydrothermal system since initial igneous intrusion. Prepare conceptual models for targeting permeability “sweet spots” in the MLV system.

- Continue with preparations to assist CEC with a planned scientific corehole in the Telephone Flat portion of the MLV system.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Our MLV work, based as it is upon a voluminous sample and database supplied by CEC, will clearly benefit that company most directly. As the research is publically funded, however, it will also be of use to other geothermal companies with interest in or leaseholdings on the Medicine Lake volcano (e.g. Calpine Corporation). As always, many of our findings will be not only site-specifically beneficial, but will be useful in exploration for, and characterization and development of, all such high-temperature hydrothermal systems on a global basis.

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## CONTACTS

Jeffrey B Hulen
Energy & Geoscience Institute
423 Wakara Way
Salt Lake City, UT 84108
Phone: (801) 585-8497
Fax: (801) 585-3540
e-mail: jhulen@egi.utah.edu

# THE AWIBENGKOK, INDONESIA, GEOTHERMAL RESEARCH PROJECT

Jeffrey B. Hulen
Energy & Geoscience Institute
University of Utah

## KEY WORDS

Awibengkok, Salak, West Java, Indonesia, core, high-temperature, geothermal system, andesitic, volcanos, porosity, permeability, fractures, breccias, dissolution, fluid migration and storage

## PROJECT BACKGROUND AND STATUS

In March of 1998, the Energy & Geoscience Institute (EGI) took possession of 1.1 km of continuous core retrieved from the eastern and upper portion of the high-temperature, "andesitic" volcanic-hosted Awibengkok geothermal system, West Java, Indonesia. EGI geoscientists had been on site earlier during the actual drilling operations, to help assure careful retrieval and detailed description of the core immediately upon its retrieval to the surface. The core is the "cornerstone" for a multi-year, multidisciplinary research project involving National Laboratories, universities, various governmental agencies, and Unocal Geothermal Indonesia (UGI), operators of the Awibengkok geothermal field. The Awibengkok scientific consortium has made significant progress with its research efforts, initial results of which were reported at a special session of the 1999 Geothermal Resources Council Annual Meeting in Reno, Nevada.

## PROJECT OBJECTIVES

### *Technical Objectives*

- (*Governing)* – Through detailed study of the continuous Awi 1-2 core and ancillary data, significantly improve understanding of reservoir controls in a large but otherwise typical, island-arc composite-volcanic-hosted ("andesitic"), high-temperature geothermal system. Compare and contrast the new information obtained from this study with corresponding data from other such systems around the world, for example, the nearby Karaha-Telagabodas system, a portion of which is vapor-dominated, and the Medicine Lake Volcano geothermal system, in northeastern California.

- Determine the origins, measure and map the configurations, and establish the interrelationships of fractures, breccias, dissolution cavities, vesicles, and other voids which singly or in combination serve as geothermal fluid conduits or storage sites. Study the relative influence of regional vs local controls on development of these features. For example, to what extent are fractures and breccias formed in response to far-field stresses vs those of local origin (e.g. overpressured thermal fluids).

- Determine lithologic controls on configuration of the geothermal system's key components (e.g. caprock vs productive reservoir, aquifers and aquicludes in the reservoir proper). In so doing, establish a detailed volcanic stratigraphy potentially of use in indirect three-dimensional mapping of discordant conduits such as fractures and pebble dikes.

- Ascertain the effects of penetrated igneous intrusions on the geometry of the geothermal system, and on the compositions and textures of the reservoir rocks these igneous bodies invade.

- Map in detail hydrothermal alteration mineralogy and zoning, not only in a gross vertical sense with respect to the reservoir as a whole but also locally, for example selvages bordering veins as well as rims and rinds on clasts and phenocrysts. Examine this information for correlations with other rock and reservoir properties. For example, do certain alteration mineral assemblages and zoning sequences show a systematic relationship to active thermal-fluid-flow conduits? Are impermeable hydrothermal breccias differently altered than their permeable vuggy counterparts? Investigate the utility of secondary-mineral zoning and paragenetic sequences in targeting remotely, as well as mapping, potentially productive thermal-fluid conduits.

- Compare characteristics and controls of the Awibengkok system with those observed and inferred for several late Cenozoic volcanic-hosted precious-metal deposits in the immediate vicinity, especially the 2M oz, 8 Myr-old Pongkor deposit (Basuki et al., 1994) just a few kilometers to the northwest of Awi.

- Reconstruct the hydrothermal history of the portion of the Awibengkok geothermal system penetrated by the corehole. If possible, utilize this information to help predict changes in reservoir characteristics with time and progressive depletion. As a particularly important module of this work, investigate the possibility that a noncondensible gas cap had accumulated above this shallowest portion of the geothermal reservoir.

- Measure multiple physical and mineralogic properties of the penetrated rocks, not only under ambient conditions but also under simulated reservoir pressures and temperatures. Examine the utility of this information in constraining interpretations of surface- and borehole-based geophysical surveys of these and similar geothermal-reservoir rocks and the fluids they contain.

***Expected Outcomes***

- With the new information obtained from this investigation: (1) improve the odds of finding similar volcanic-hosted geothermal systems in other volcanic provinces; (2) help reduce operators' costs in exploiting those systems already secured, including Awi itself; and (3) enable those operators to prolong the systems' productive lives through more informed long-term development strategies.

- A detailed picture of the Awibengkok geothermal system's evolution since inception, especially: (1) the nature and timing of events specifically linked to the creation, enhancement, or occlusion of porosity and permeability; and (2) fluid sources, volumes, pathways, chemical transformations, and thermal histories.

## APPROACH

Acting as Chief Scientist for the Awibengkok project, J. Hulen first assembled a science team with a well-established collective record for addressing and solving the types of research problems outlined in the foregoing section. Many team members, for example, worked closely with Hulen on the Geysers Coring Project, which has yielded valuable new insights into the origin, evolution, permeability structure, and remaining water saturation of The Geysers vapor-dominated geothermal system, California. The approaches implemented by several of these scientists were directly applicable to the Awibengkok project. As an example, high-temperature adsorption experiments completed by Oak Ridge National Laboratory will become ever more germane as the Awibengkok field matures, as its upper reaches are predicted to develop production-induced steam caps, analogous in many respects to the natural vapor-dominated system at The Geysers. EGI's role in the Awibengkok project, as at The Geysers, is first of all maintaining close communication among the team members, and also ensuring, to the extent possible, that the investigators are working with the same carefully chosen representative sample suites. The information to be yielded from this collective approach far surpasses that produced by individual researchers working in functional isolation. J. Hulen has undertaken to complete petrographic, mineralogic, paragenetic, and geochemical characterization of all the study samples, to ensure uniformity in comparing various laboratory measurements with corresponding natural rock properties. This baseline geoscientific work is reviewed both internally and externally, so that bias and provincialism are cut to an irreducible minimum.

## RESEARCH RESULTS

At an inaugural EGI-based workshop for the Awibengkok geothermal research project (outlined in the 1999 "Research Summaries"), team members agreed to withhold publication of research results until the 1999 Annual Meeting of the Geothermal Resources Council. The Meeting was convened in Reno, Nevada, with EGI's Rick Allis as Technical Program Chairman, and J. Hulen as Chairman of a special session of oral and poster presentations on the Awibengkok project. The talks and poster sessions were accompanied by extended written documentation in the form of 6-8 page technical papers published in the 1999 GRC *Transactions* volume. Brief summaries of the presentations are as follows (See also the "References" section of this summary).

*Rick Allis* (1999), utilizing an extensive suite of drilling and reservoir-engineering data provided in support of the project by UGI, interpreted the complex contemporary hydrothermal conditions in the vicinity of the Awi 1-2 scientific corehole. Among his important findings: (1) The dissolved gas content, moderate temperatures (240-256$^{o}$), and dilute nature (8500 ppm NaCl) of reservoir fluids in this part of the field are consistent with overlying cooler waters mixing with the normally hotter and slightly more saline Awibengkok brines. (2) Single-phase liquid conditions prevail between about 1030 m and 1602 m depth (TD) in the Awi 1-2 corehole. Two-phase (boiling) conditions are present between the top of the corehole and 1030 m. It is this two-phase zone wherein research yielding information on vapor-dominated geothermal systems will be most applicable, as production likely will cause the two-phase zone both to expand and to "dry out", yielding higher-enthalpy reservoir fluids with time.

J. Hulen, *Fraser Goff*, and *Giday Woldegabriel*, the latter two scientists from Los Alamos National Laboratory, summarized the abundant hydrothermal breccias penetrated by the corehole. Some of these breccias were shown to be clearly intrusive, emplaced by upward-penetrating, overpressured thermal fluids. Others were interpreted as subaerial fallout aprons – lithic-rich phreatic breccia apron. Surprisingly and counterintuitively, this study has demonstrated that the breccias, although spectacular and commonly highly vuggy features of the core, are anti-correlated with modern major fluid entries. Although once highly porous and permeable by their very nature, the breccias must be tightly sealed on a scale larger than the core diameter. The clear implication of this finding is that the porosities and permeabilities of often gaudily-cemented and vuggy hydrothermal breccias (and equally attention-attracting open veins) cannot necessarily be extrapolated to reservoir scale. In fact, the vuggy veins and breccias are, at least in this case, more akin to vesicular volcanic rocks, with high but ineffective porosities – considerable but isolated open space.

*Greg Boitnott* and *Joel Johnson*, of New England Research, Vermont, reported upon their laboratory measurements of ultrasonic velocities in core as a function of changing effective confining pressures and fluid saturations. Their findings on the Awi 1-2 cores were similar to those for samples from The Geysers Coring Project. In particular, these investigators have shown conclusively that the dynamic shear modulus of the rock matrix weakens in the presence of water. These conclusions will have direct application to the interpreation of borehole-based sonic-velocity logs.

J. Hulen and *Susan Lutz*, both of EGI, described alteration mineralogy and zoning in the Awi 1-2 core. These features are quite typical for andesitic systems. An upper argillic alteration zone overlies and argillic-phyllic zone, which in turn overlies a thick propylitic zone; the latter hosts the bulk of the field's productive thermal-fluid entries. The argillic and argillic-phyllic zones serve principally as top-seals, or caprocks, on the underlying geothermal reservoir. One important finding, believed to be reported here for the first time: Several clay-rich horizons in the cap, particularly a 20-m intevarl at the very base of the argillic-phyllic zone, almost certainly were altered to clay first at the surface – they are in effect paleosols which become caprocks through progressive burial and further mineralogic transformations (e.g., smectite to illite/smectite). Many of these zones in the Awi 1-2 core have clay-mineral geothermometric signatures much too low for the modern temperatures, indicating that the zones were effectively sealed from further hot-water circulation when at a much lower temperature.

*Joe Moore* (EGI) and *Dave Norman* (New Mexico Institute of Mining and Technology) detailed their initial findings, developed from fluid-inclusion microthermometry and gas chemistry, concerning the thermal and chemical evolution of this eastern portion of the Awibengkok field. They found evidence of two principal thermal events – the first yielded a highly saline fluid (17% NaCl equiv.) which deposited calcite at temperatures near 270$^oC$; the second, apparently affiliated with (and evolving toward) the modern geothermal reservoir, produced lower salinity (<3.5% NaCl equic.) fluids at temperatures between 202$^oC$ and 320$^oC$. Variations in the temperatures, salinities, and gas contents of the fluids reflect mixing between a high-temperature, moderate-salinity geothermal brine and steam-heated meteoric waters. The early, highly-saline brine is probably of magmatic origin; it is spatially associated with a thick, highly altered sill of microdiorite.

*Greg Nash* (EGI) reported on his nontraditional Geographic Information System (GIS) for the Awi 1-2 core. The system enables, among other "user-friendly" applications, linkage of any core images (petrographic, electric-log, etc.) to a "map" of the actual core. In this fashion, a researcher can query any section of the core (or its entire length) to access all available information thereon. Heretofore, such an evaluation often meant a long trip to the core-archival facility together with lengthy communication with each of the affiliated researchers. Not only are the savings in time and money significant, but the potential depth of understanding for a given core and allied information has now reached hitherto unattainable levels.

Finally, *Jeff Roberts*, *Brian Bonner*, and *Al Duba* (Lawrence Livermore National Laboratory) outlined results of their research on electrical resistivity measurements on representative Awi cores saturated with brine and at simulated reservoir conditions. This work followed closely their superb similar research on samples from The Geysers Coring Project. Similar to that work, the Awi measurements have demonstrated that resistivity gradually increases when pore pressure is decreased below the phase-boundary pressure of free water. This is an indication that boiling is controlled not only by temperature and pressure, but also by pore-size distribution. This work well might lead to a new geophysical tool for delineating boiling zones in high-permeability areas of producing geothermal reservoirs.

Hulen also collaborated with *Jim Stimac* (Unocal Geothermal Philippines) and *Fransiskus Sugiaman* (UGI) to produce a paper on volcanic stratigraphy, plutonic geology, hydrothermal alteration, mineralization, and brecciation in Awi 1-2. The volcanic sequence penetrated in the corehole is explained in terms of a volcanic-facies model, and the mechanism of paleosol formation and consequent development of paleosol caprocks in tropical geothermal systems outlined. Stimac will present the paper at the World Geothermal Congress in Japan this year. He will also present a companion paper on overall stratigraphy and structure of the Awibengkok field.

## FUTURE PLANS

The research results outlined above are provocative but preliminary. They are being followed up by much more intensive studies expanded to include the entire core. The Awibengkok geothermal research project is scheduled for completion by October 2002. As the work progresses, results will be continuously compared and contrasted with those for similar settings on a global scale – for example, not only the nearby Karaha-Telagabodas system in West Java, but also the Medicine Lake Volcano geothermal system in northeastern California.

Hulen and Susan Lutz are nearing completion of a field-wide petrographic study of cuttings from throughout the Awi field. These results will be compared and contrasted with those for the core during the current research year. At this point, we can say that a variety of felsic- to intermediate-composition intrusives are likely to underlie the field at comparatively shallow depth.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

So far, the Awibengkok system has not proven to be atypical for “andesitic” high-temperature geothermal systems (although it is certainly larger, at >330 Mwe, than most). Our results accordingly will escape provincialism and be broadly applicable to such systems anywhere in the world. Of course, the field operator, UGI, will benefit most directly from this research project, but geothermal companies in similar terranes, for example, the Philippines and Central America, will also obtain information from the project potentially beneficial for reducing risks and costs in the exploration for and development of a type of system destined to provide an increasingly larger share of the world’s geothermal power.

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## CONTACTS

Jeffrey B Hulen
Energy & Geoscience Institute
423 Wakara Way
Salt Lake City, UT 84108
Phone: (801) 585-8497
Fax: (801) 585-3540
e-mail: jhulen@egi.utah.edu

# NATURAL STATE MODELS OF THE GEYSERS GEOTHERMAL SYSTEM, SONOMA COUNTY, CALIFORNIA

T. H. Brikowski
The University of Texas at Dallas
D. Norton
School of Thought, Stanley, ID
D. Blackwell
Southern Methodist University

## KEY WORDS

The Geysers, modeling, oxygen isotopes, alteration, finite element

## PROJECT BACKGROUND AND STATUS

This study is utilizes recently-summarized whole-rock oxygen isotope alteration data for The Geysers (Moore and Gunderson 1995; Walters and Moore, 1996) to generate accurate natural state models of the system. Work was begun in October 1998, and will continue until December 2000. Cross-sectional (2-dimensional) models have been completed for the pre-boiling system, two-phase (post-boiling) and 3-dimensional models will be carried out in 1999-2000.

Contrasting deep and shallow reservoirs are a common feature in deep magmatic geothermal systems (e.g. The Geysers, USA; Kakkonda, Japan). Typically these are attributed to presence of permeability variations. At sites where the prevalent circulation paths can be determined, for example using rock alteration, the fluid dynamics of such systems can be accurately modeled. These models demonstrate that dual, hydraulically-connected reservoirs are a natural consequence of fluid dynamics and fluid critical-point phenomena even in the presence of uniform permeability. Permeability variations exert final control on the distribution of shallow lower temperature and deep high temperature reservoirs in these systems, but fluid physics is the primary control.

Detailed modeling of fluid circulation and rock isotopic alteration at The Geysers geothermal system, USA offers a clear view of these phenomena. Since the liquid phase is most efficient at isotopic alteration, these models primarily treat the pre-boiling, natural state of The Geysers. The Geysers offer a unique opportunity in the U.S. to study an active hydrothermal system where the plutonic heat source is accessible. Natural state modeling of this system uses system-wide fluid mass and heat balances in space and time to derive a general view of system characteristics and lifetime. The benefits of such an approach at The Geysers are synthesis and advancement of our understanding of the nature and development of this important geothermal resource based on fundamental physical principles.

## PROJECT OBJECTIVES

The objective of the project is to develop a field-wide natural state model for The Geysers geothermal system, California. Our goal is to develop the best possible understanding and model representation of the development and early (liquid-dominated) history of The Geysers system, then to extend that model to include the vapor-dominated natural state that existed prior to commercial development of the field. The objective of this program is to provide a historical view of The Geysers geothermal system from magma intrusion to the beginning of production. This view of the evolution of the entire system can provide an improved context for local and system-wide production models at The Geysers, and hopefully allow pro-active management of the production declines associated with this resource. A second objective of the project is to demonstrate the application of these methods to obtain information that can be very useful for economic and production planning during initial geothermal development.

***Technical Objectives***

- Determine the primary controls on the distribution of rock isotopic alteration at The Geysers using a cross-sectional single-phase model of fluid circulation and isotopic alteration (completed, see Brikowski and Norton, 1999; Brikowski, 2000).

- Assess the impact of two-phase conditions (boiling) on the above cross-sectional analysis (in progress, Jan. 2000)

- Evaluate origins of horizontal segmentation of The Geysers using three-dimensional models, including two-phase conditions.

***Expected Outcomes***

- Integrated model of the development of The Geysers system, and rock alteration within it, in cross-section through Geysers Coring Project hole SB-15D

- Quantitative assessment of the relative influence of caprock, recharge distribution, and two-phase conditions on fluid circulation and rock alteration

- A flexible software tool for modeling fluid-rock oxygen-isotopic interaction in geothermal settings

## APPROACH

Natural state, production, and economic models of geothermal systems are based on the principles of energy, fluid mass and chemical mass conservation. In each model type, some initial state is assumed or measured, and the model is used to predict the evolution, response, or productivity of the system from that state using well-understood mathematical relationships. An historical model begins from a point where the energy and mass distributions within the system are well known. Since no natural state model has been made at The Geysers, production models are necessarily based on an incomplete understanding of this distribution. Our analysis will begin from a geologically known condition, the initial appearance of the heat source (magma intrusion). From this starting condition, the dissipation of the original thermal and chemical energy of the intrusion into its host rocks can be calculated by the models. Our project will take this approach, computing the temperature, pressure, fluid flow and chemical ($d^{18}O$) composition fields for The Geysers geothermal/hydrothermal system from the time of its inception (magma intrusion) to a time immediately prior to production. These models will be constrained (calibrated) using the current state of the system, including the temperature and pressure fields, distribution of chemical and isotopic alteration, and distribution of fractures and permeability. Two-dimensional models will be performed using a much-modified version of Mariah (Gartling and Hickox, 1982; Brikowski, 1995) to model heat, liquid and $^{18}O$ transport. Three-dimensional modeling plans to use a version of Tough2 modified for high temperature fluids, and using the water-rock interaction code extracted from the modified Mariah.

## RESEARCH RESULTS

Two-dimensional models of heat and fluid flow and $^{18}O$ transport were made using a finite element model over the cross-section depicted in Fig. 2. To allow for maximum solution stability, approximately 1000 quadratic triangular elements were used to discretize the system, with grid density concentrated where high advection and reaction rates were anticipated. The top boundary of the model was held at constant temperature and pressure, model sides and base were treated as impermeable and insulating. Repeated model runs were made, adjusting parameters until an adequate fit was achieved to observed $d^{18}O$ alteration, geothermometers, and general constraints on surficial heat flow in the system.

Model results demonstrate a number of fundamental features of The Geysers hydrothermal system. Perhaps of greatest significance are constraints on system lifetime. Purely conductive models of the geometry shown in Figure 3 indicate a maximum lifetime of 0.5 Ma, convective models using the indicated permeabilities reduce this lifetime to 0.35-0.5 Ma (Fig. 3, column 1). The youngest dates available for the felsite are 1-1.5 Ma (Dalrymple, 1992; Hulen *et al.*, 1997). This discrepancy indicates that The Geysers natural state system has had a considerably more complicated intrusive and hydrothermal history than is generally suspected.

Convection in the system is tightly constrained along the upward-sloping flanks of the felsite (vectors, Fig. 3). The lower boundary of this flow zone is controlled by the permeability contrast between reservoir and "basement felsite" rocks. The upper boundary of this zone is formed by localization of near-critical fluid properties. Recall that heat transport and fluid flow properties reach extrema near the fluid's critical point (374°C and 220 bar for pure water). These properties are computed in the model using an accurate numerical equation of state (Johnson and Norton, 1991). Heat capacity reaches near infinite values at the critical point, and is a useful indicator of near-critical conditions. The central column of Fig. 3 shows the development of a mantle of near-critical conditions in the host rock in the vicinity of the 375°C temperature contour. This contour moves outward from the felsite until around 125 thousand years (Ka), at the peak of hydrothermal activity, and then slowly retreats downward. By 240Ka critical conditions are within the deep, low-permeability felsite, and effective hydrothermal circulation ceases in the system. Hydrothermal circulation above the apex of the felsite is limited by the presence of the caprock, requiring divergent flow in that area, and by the failure of near-critical fluid conditions to develop within the greywacke reservoir there. Influx into the system is tightly channeled by these two phenomena, and is localized deep on the flanks of the intrusive.

To investigate the alteration impacts of this localized convection, the $^{18}O$ transport equation was solved simultaneously with the heat and fluid transport equations. A single reactant mineral was assumed. Average groundmass mineralogy of The Geysers host rock metagreywacke is approximately 40% quartz, 30% plagioclase (Moore and Gunderson, 1995). Lambert and Epstein (1992) note limited reaction of quartz grains in the greywacke, suggesting the primary reactant mineral is plagioclase. Volume fraction of plagioclase in rock was assumed to be 0.30, and volume fraction of mobile water in rock $\phi_f = 10^{-3}$. Isotopic parameters are the water-plagioclase isotope fractionation factor $A = 2.61 \times 10^6$ and $B = -3.7$ (Javoy and Bottinga, 1973), unaltered rock $\delta^{18}Or = 14^0/_{00}$ and maximum alteration $\delta^{18}Or = 6^0/_{00}$ (Moore and Gunderson, 1995).

Alteration in the system begins quickly, with notable rock alteration visible by 20Ka. By 50Ka, depleted fluids have penetrated much of the way up the flanks of the felsite (upper right image, Fig. 4). Because temperatures are high, rapid isotopic exchange is taking place, and the alteration progresses as a reaction front up the stream tube formed by the permeability contrast and critical-properties zone. As fluids approach the apex of the system, moving more sluggishly, they become enriched in $\delta^{18}O$ via exchange with the rock and no longer produce noticeable alteration. Had the caprock been permeable above the apex of the felsite, very strong convection would take place in that area, and a marked plume of $^{18}O$ -depleted fluids would alter the rocks in a vertical zone above the apex. The lack of such a pattern argues strongly for the presence of an unbroken caprock throughout the effective hydrothermal lifetime of The Geysers system. Although analysis of cores from well SB15d in this area support high fluid temperatures, this is not consistent with the lack of strong $^{18}O$ depletion in the shallow reservoir. Instead it seems that the SB15d veins record small zones of penetration of the caprock that were geologically short-lived.

## FUTURE PLANS

Future plans are to perform two-phase (steam-water) flow and alteration models in the cross-section described above, and to carry out simplified three-dimensional models of The Geysers system. Both efforts will require considerable computer code development and modification.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Results to date have been of great interest to present and former managers of The Geysers steamfield. In particular the results of this project are expected to provide a fundamental basis for development of production and management strategies at The Geysers.

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Project summaries, preprints and model results can be viewed at http://www.utdallas.edu/~brikowi/Publications/Geysers

**CONTACTS:**

Marshall Reed
U.S. Dept. of Energy
Geothermal Division, EE-122
1000 Independence Ave., SW
Washington, D.C.
Voice: (202) 586-8076
Fax: (202) 586-8185

Tom H. Brikowski
Geosciences, U. Texas-Dallas
P.O. Box 830688
Richardson, TX 75083-0688
Voice: (972) 883-6242
Fax: (972) 883-2537
Email: brikowi@utdallas.edu

Denis Norton
School of Thought
Box 310
Stanley, ID 83278
Voice/Fax: (208) 774-3735
Email: denis@ruralnetwork.net

David Blackwell
Geosciences, Southern Methodist University
Dallas, TX
Voice: (214) 768-2745
FAX: (214) 768-2701
Email: blackwel@passion.isem.smu.edu

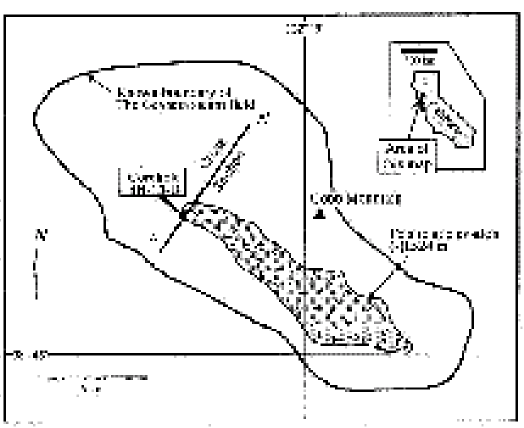

**Figure 1:** Location of The Geysers showing outline of the steam field and distribution of felsite at depth (after Hulen and Nielson, 1995). Coring project well SB15d and location of model cross-sections shown near center of steam field.

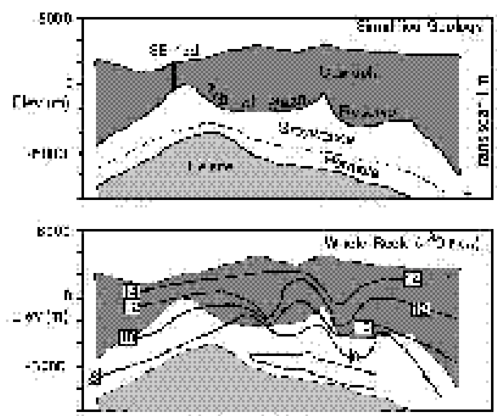

**Figure 2.** SW-NE cross-section of The Geysers, passing through well SB-15d, showing simplified geology and oxygen isotope alteration (after Hulen, et al., 1994). Location of well SB-15d and cross-section line shown in Fig. 1.

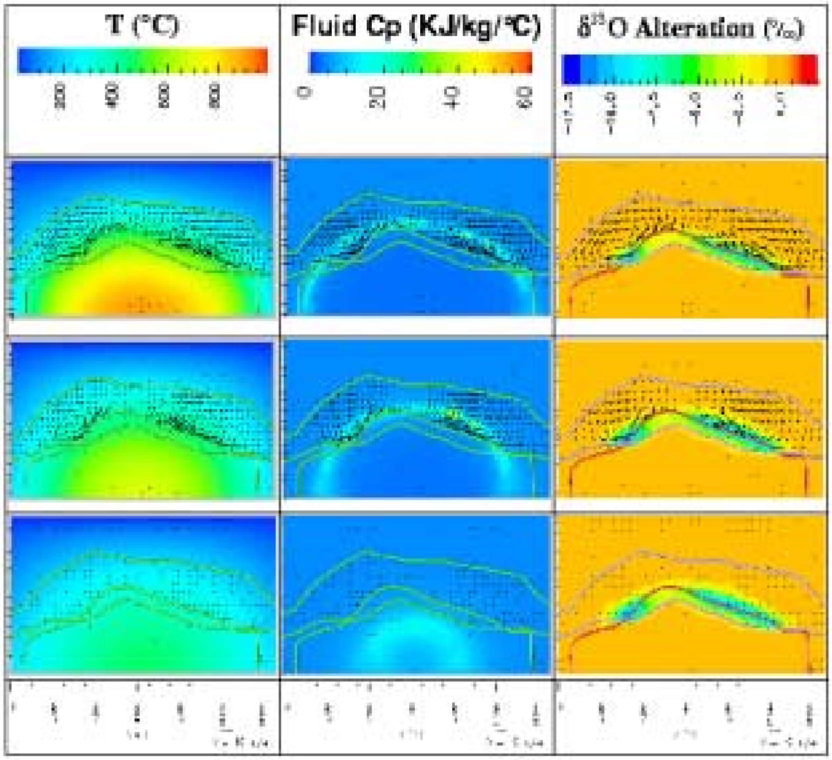


**Figure 3:** Temperature, heat capacity, and isotopic alteration results (columns) at 50Ka, 130Ka, and 240Ka (rows). Color scales given at top of columns. Black vectors show flow direction, length proportional to velocity (see scale arrow at base of columns). Horizontal scale given at base of columns, no vertical exaggeration, each panel is 5.4 km deep and 10.8 km wide. Felsite and reservoir boundaries shown by colored lines.

# THE STABILITY OF THE VAPOR-PHASE TRACER R-134a

Michael C. Adams
Energy & Geoscience Institute
University of Utah

## KEY WORDS

vapor-phase tracers, tracer tests, geothermal, R-134a, R-23, tetrafluoroethane, trifluoromethane, fluoroform, The Geysers

## PROJECT BACKGROUND AND STATUS

Vapor-phase tracers are useful in nearly all types of geothermal systems. They have been used in liquid-dominated (Upstill-Goddard and Wilkins, 1995), two-phase (Bixley et al., 1995; Moore et al., 2000), and vapor-dominated fields (Adams et al., 1991a; Beall et al., 1994; Beall et al., 1998). Vapor-phase tracers are of particular and immediate importance at The Geysers because vapor-dominated systems are water-poor and injection is a component vital to the longevity of the field. Artificial and natural tracers have been used at The Geysers to identify and track the flow of injected water and to evaluate the recovery of injectate. However, the natural tracers have become ineffective as the surface facilities were adapted to conserve steam for reinjection, and the most successful artificial tracers, chlorofluorocarbons, were taken off the market because of their deleterious effect on ozone concentrations in the upper atmosphere. R-134a and R-23, both hydrofluorocarbons, were proposed in 1997 as substitute geothermal tracers for the chlorofluorocarbons (Adams, 1997). Several successful field tests have now been performed using R-134a and R-23 (Adams, 1999; Beall et al., 1998). During the past year we have focused on laboratory tests to quantify the thermal stability of R-134a in pure water. These tests are now complete (Adams and Kilbourn, 2000).

R-134a is a replacement for some of the chlorofluorocarbons previously used in refrigeration, air conditioning, foam blowing, pharmaceutical inhalers, and fire suppressants. Like the chlorofluorocarbons, many of the hydrofluorocarbons are inflammable, non-toxic, and relatively inert. The toxicity of hydrofluorocarbons is generally even lower than that of corresponding brominated and chlorinated hydrocarbons because of the higher stability of the carbon-fluorine bond. R-134a has a very low acute and subchronic inhalation toxicity, has no chronic toxicity, and is neither a developmental toxicant nor genotoxic. Hydrofluorocarbons are, however, somewhat less stable at high temperatures than the chlorofluorocarbons. They are also less detectable using an electron capture detector, which was the preferred method for the chlorofluorocarbon tracers. However, an analytical method has been developed by Thermochem, Inc., which yields detection limits on the order of 10 to 100 parts per trillion. This method uses an enrichment procedure coupled with gas chromatography. A megabore porous polymer capillary column is used to separate the tracers from each other and from potentially interfering compounds. A modified Halogen-Specific Detector is used for detection.

Hydrofluorocarbons do not contribute to ozone depletion in the atmosphere because they do not contain chlorine or bromine atoms. Their vapor pressures are similar to their chlorofluorocarbon analogues, but they are considerably more soluble. A comprehensive list of hydrofluorocarbons and their properties can be found in Adams et al. (1991b).

## PROJECT OBJECTIVES

### *Technical Objectives*

- Evaluate the cost, availability, toxicity, detectability, and solubility of the hydrofluorocarbons.
- Test their stability in the laboratory at temperatures typical of geothermal systems.
- Test their interactions with rock and some common geothermal gases at temperatures typical of geothermal systems.
- Perform field tests in conjunction with industry to determine their efficacy under actual field conditions.
- Inject them simultaneously with tritium to evaluate their performance.
- Compare the results of tracer tests performed in identical locations but using tritium, chlorofluorocarbons, or hydrofluorocarbons separately.

### *Expected Outcomes*

- Provide as many proven vapor-phase tracers for The Geysers as possible. Only a few of these will be inexpensive enough to use routinely. The rest will be used for special cases when multiple tracers are needed. This will allow industry to:
  1. Plan and change injection-well flow rates and locations.
  2. Calculate injection recycling.
  3. Calculate increased power output or increased reserves due to effluent injection projects.
- Evaluate the effects of tracer volatility on the calculation of injection recovery.

## APPROACH

- Contact manufacturers and vendors to determine species, cost, and availability of volatile hydrofluorocarbons.
- Evaluate detectability in conjunction with commercial analytic laboratories to determine routine analysis procedures.
- Perform preliminary laboratory tests to determine thermal stability. The procedures used are described on our web site (http://www.egi.utah.edu: choose Geothermal Energy from the top page and then chemical tracer development from the text, last paragraph) and in our previous publications.
- Perform field tests to qualitatively determine stability under actual conditions.
- Perform detailed laboratory tests to quantitatively determine stability under conditions that include some geothermal gases and rock.

## RESEARCH RESULTS

Our search indicated that the most affordable species of hydrofluorocarbon is R-134a, or tetrafluoroethane. An analogous compound, R-23, or fluoroform, is more expensive but still economic for a tracer test at The Geysers. R-23 and R-134a are more soluble in water than their respective chlorofluorocarbons. At one bar of gas pressure the solubility of R-23 and R-134a are 0.1% and 0.15%, respectively. The detection limit has been determined to be in the lower parts per trillion in laboratory and field studies (Adams and Kilbourn, 2000). Our preliminary laboratory experiments predicted that R-134a would be stable enough to use in The Geysers normal reservoir.

Seven field tests of the hydrofluorocarbon were conducted at The Geysers during 1998 and two more during 1999 based on the results of our preliminary experiments. The first of these is discussed in (Beall et al., 1998) and the rest in (Adams et al., 1999). Eight of the nine tests were cost-shared by DOE and industry. The tests were considered a success by the industry participants. The criteria used to determine success were: 1) mass recovery of the tracer, 2) similarity with previous R-13 or tritium tests, and 3) similarity of tritium, R-134a, and R-23 curves in simultaneous injection experiments.

The results indicate that the decay of R-134a in pure water follows a pseudo-first order rate law, given by the relationship:

$$\frac{C}{C^o} = e^{-kt} \tag{1}$$

where C is the tracer concentration after heating, $C^0$ is the initial concentration, k is the rate constant, and t is time.

The temperature dependence of the decay rate is given by the Ahrrenius equation:

$$\ln k = -\frac{E_a}{R}\left(\frac{1}{T}\right) + \ln A_o \tag{2}$$

where k is the rate constant, $E_a$ is the activation energy, R is the Universal Gas Constant, T is temperature is degrees Kelvin, and $A_0$ is the collision frequency factor. The kinetic parameters were derived from the raw data using linear least squares regression. These constants and the fit statistics are listed in Table 1.

**Table 1.** Summary of kinetic parameters derived from the data in Table 3.

| |
|---|
| 270°C: k = 1.72 x $10^{-7}$ $s^{-1}$ |
| Coefficient of Determination, $r^2$ = 0.92 |
| 13 data points |
| 290°C: k = 4.97 x $10^{-7}$ $s^{-1}$ |
| Coefficient of Determination, $r^2$ = 0.90 |
| 15 data points |
| 310°C: k = 1.47 x $10^{-6}$$s^{-1}$ |
| Coefficient of Determination, $r^2$ = 0.90 |
| 15 data points |
| $E_a$ = 140,916 J/mol |
| ln (A) = 15.65 $s^{-1}$ |
| Coefficient of Determination, $r^2$ = 0.999 |
| 3 data points |

The constants in Table 4 can be combined into the simplified expression:

$$\ln(k) = 27.02 - \frac{16{,}969}{(T(c) + 273.15)} \quad (3)$$

where temperature is in degrees Celsius and **k is in days**$^{-1}$. The rate can then be used with equation 2 to calculate the amount of decay expected at a given temperature. A plot such as figure 3 can also be used to estimate the amount of decay during a tracer test at a given temperature. For example, a tracer test conducted in the normal reservoir at The Geysers (~240°C) lasting 50 days at a maximum temperature would result in approximately 12% decay of R-134a.

The same test conducted in the high-temperature reservoir (>300°C) would result in 90% decay. However, R-134a may still be useful at high temperatures because of its excellent detection limit.

The indications from our initial tests of R-23 are that it is as stable or more stable than R-134a. Consequently, the diagram in Figure 3 could be used for R-23 until better data are available.

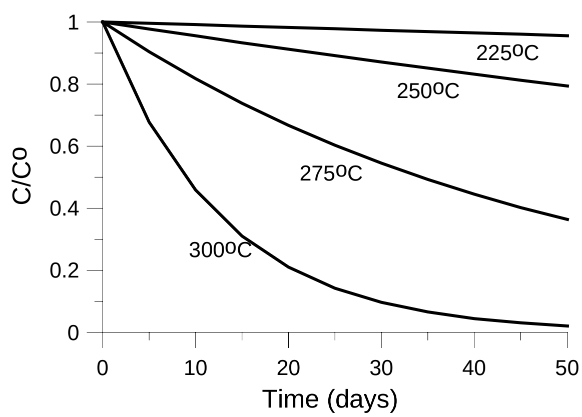


**Figure 3.** Time-decay plot for various temperatures. The plot was made using the kinetic parameters listed in Table 4.

## FUTURE PLANS

Our stability studies of R-134a and R-23 in the presence of rocks and geothermal gases will continue during FY2000. In addition, we will complete our thermal stability studies of R-23 in pure water. Potential tracers that are more soluble will be examined to try and develop steam-phase tracers that will boil at the same rate as water. For example, some of the alcohols would be suitable if a more sensitive analytical method were developed (Adams, 1995). The equation-of-state for the perfluorinated methylcycloalkanes currently being developed by Ryan Mcmurtrey under the direction of Robert Fox at INEEL will be used to examine the suitability of these compounds as geothermal steam or liquid tracers. Researchers using numerical models to simulate vapor-phase tracer tests have begun incorporating the stability and solubility of vapor-phase tracers into their modeling codes and are getting results that bear on the saturation and thermal draw down of vapor-dominated reservoirs (Preuss et al., 2000; Trew et al., 2000).

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Calpine Corporation | Cost-shared tracer tests at The Geysers CA |
| Unocal Geothermal Inc. | Cost-shared tracer tests at The Geysers CA |
| Northern California Power Agency | Cost-shared tracer tests at The Geysers CA |
| Utah Municipal Power Agency | Cost-shared tracer tests at Cove Fort |

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## CONTACTS

Marshall Reed, CE-122
U. S. Department of Energy
Washington, D.C. 20585

Michael C. Adams
Energy & Geoscience Institute
423 Wakara Way
Salt Lake City UT 84108
Phone: (801) 585-7784
Fax: (801) 585-3540
Email: madams@egi.utah.edu

# MICROSEISMIC MONITORING AT THE GEYSERS

A. Kirkpatrick, E.L. Majer and J.E. Peterson, Jr.
Lawrence Berkeley National Laboratory

## KEY WORDS

Microearthquakes, seismicity, seismic velocity, injection, geothermal monitoring

## PROJECT BACKGROUND AND STATUS

It has been demonstrated by several investigators that microearthquake occurrence at The Geysers geothermal area is associated with both water injection and steam extraction (e.g., Eberhart-Phillips and Oppenheimer, 1984). However, the relevant changes in subsurface conditions caused by these activities, and the mechanisms by which these changes cause microearthquakes (MEQs) remain unknown. If more were understood about the relationships between these processes, then MEQ occurrence and characteristics could possibly serve as indicators of reservoir conditions, and thus be used as a reservoir management tool. There have been two main changes in injection operations in the SE Geysers during the Lawrence Berkeley National Laboratory (LBNL) monitoring period, the 1994-95 DV-11 injection test and start of the Lake County water injection project in late 1997. Questions on the effect of the increased rate of injection from both the reservoir management and public acceptance viewpoints needed to be addressed.

In order to collect data to address these questions, LBNL installed a network of digital seismometers at the SE Geysers in 1993. The network operated from January 1994 through September 1995 and from August 1997 through March 1999. This network and results of several studies utilizing the data that were obtained, have been described in several papers (e.g., Kirkpatrick et al., 1995, 1996, 1997). In addition, Calpine operates a network of analog seismometers (formerly owned by Unocal Geothermal) over a larger area of The Geysers, and provides a catalog of MEQs hypocenters in the SE Geysers to LBNL. The locations of both networks are shown in Figure 1.

While the LBNL network is capable of locating events more accurately than the Calpine network, and can be used for more sophisticated source mechanism analysis, the Calpine network has operated for a long period of time with great reliability and is thus invaluable for studies of MEQ rate variations over time.

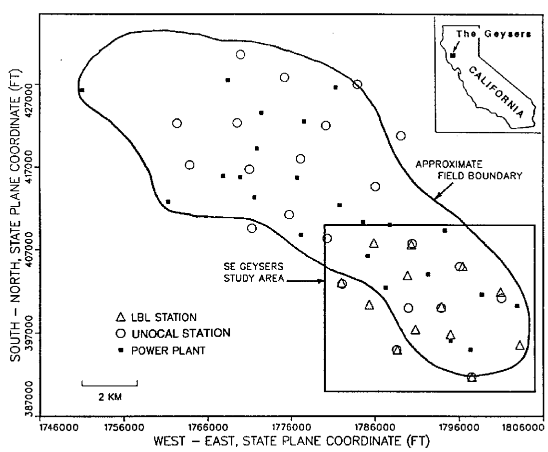


**Figure 1.** MEQ monitoring networks at The Geysers.

In 1999 the monitoring of the SE Geysers by LBNL stopped in March. It was felt that enough data had been acquired to examine the effect of the increased injection from the Lake County pipeline. Emphasis shifted to examining the temporal change in reservoir seismicity and the characteristics of the data.

## PROJECT OBJECTIVES

The general objective of the project is to evaluate the utility of high-resolution MEQ monitoring as a reservoir management tool. Understanding the relationship between reservoir production activities and MEQ generation and occurrence, may help elucidate the effects of these activities on the reservoir and provide information useful for optimal management of the geothermal resource.

### *Technical Objectives*

- Develop three-dimensional P- and S-wave seismic velocity and attenuation models for the SE Geysers.
- Locate hypocenters of MEQs occurring within the SE Geysers and characterize seismicity patterns.
- Determine MEQ source parameters such as size (magnitude, moment), stress drop, and focal mechanisms (moment tensors).
- Relate all of the above to reservoir parameters and processes such as lithology, location and nature of fracturing, steam occurrence, steam withdrawal, liquid injection, and reservoir pressure, temperature and degree of saturation.

### *Expected Outcomes*

- Velocity structure and seismicity patterns to be used to characterize the subsurface in areas not sampled by other means, and to evaluate these areas as possible drilling targets.
- Monitoring changes in velocity structure, seismicity patterns, and source mechanisms through time to be used to devise optimal withdrawal and injection strategies.
- Greater understanding of the nature of seismicity in vapor-dominated geothermal systems, and of the physical effects of steam withdrawal and liquid injection.

## APPROACH

In 1994 and 1995, the MEQ array at the SE Geysers consisted of 13 stations located over a 7 km by 4 km area. Vertical and horizontal ground velocity was continuously monitored at each station by three-component, 4.5 Hz geophones installed on the surface, and digitized at 480 samples/sec. The data were telemetered to a central site where the full-waveform data for triggered events were recorded on tape, and later brought to LBNL for processing. Starting August 1997, data have been collected at 12 stations.

Automatic P-wave picking and locating is applied to all triggered events; P- and S-wave arrival times are then manually picked for all events so located within the SE Geysers study area. The events are then re-located using the hand-picked arrival times and a three-dimensional Vp and Vs model. Source parameters are obtained from the amplitudes and polarities of the P- and S-wave pulses, using a moment tensor inversion procedure. Summaries of these results were sent to representatives of The Geysers operators (Unocal, Calpine, and NCPA) and collaborative work is performed in relating the information to reservoir parameters.

## RESEARCH RESULTS

P- and S-wave arrival-time data were inverted for 3-D seismic velocity structure for two time periods separated by approximately five years: January through June 1994, and October 1998 through March 1999.

The results indicate that Vp increased during this time period over much of the study area, by a factor of up to 4%. Previous investigators (Foulger et al., 1997) found that Vp/Vs ratios decreased by up to -4% over the time period 1991 to 1994 in a portion of the field northwest of our SE Geysers study area. The decrease was due mainly to a decrease in Vp, and was attributed to desaturation of the liquid faction in the reservoir. Although dry steam is produced by The Geysers wells, it is thought that most of the fluid is stored in liquid form in the reservoir pore spaces, and boils after steam is extracted from the fractures and the pressure declines.

Initially, condensate from the power plant cooling towers and seasonal surface runoff was collected and injected into the reservoir in an attempt to recharge part of the produced fluid. In late 1997, the Southeast Geysers Effluent Pipeline Project (SEGEPP) was completed and treated sewage effluent from Lake County began to be piped to the SE Geysers, dramatically increasing the amount of fluid injected into the reservoir. The increase in Vp from 1994 to 1998/99 may be due to resaturation of the reservoir caused by the injection of this fluid.

During the first six months of 1994, 1069 events were located in the SE Geysers using the LBNL seismic array. Of these, 376, with 3081 hand-picked P-arrivals and 1667 S-arrivals, were chosen to be used in the seismic velocity inversion. First, a one-dimensional Vp and Vs model, varying only with depth, was obtained using the progressive inversion method of Thurber (1983). The 1-D model was then used as the starting model for the 3-D Vp and Vs inversion using Thurber’s method as modified by Michelini and McEvilly (1991). A horizontal node spacing of 1 km and a vertical node spacing of 0.5 km was used. The ray-density through the 3-D model was plotted and showed that the layers at depths of -0.5 and -1.0 km msl are the best resolved. Use of the 3-D model results in a 42% reduction in arrival-time variance from the 1-D case, and the final Root mean square (RMS) arrival-time residuals were 0.020 s.

The 3-D inversion was then repeated using data from the last three months of 1998 and the first three months of 1999. Out of 3800 events, 355, with 3056 P-arrivals and 1291 S-arrivals, were chosen to be used in the inversion. The 1994 one-dimensional model was again used as the starting model for the 3-D Vp and Vs inversion. A 60% reduction in arrival-time variance was achieved and the final RMS arrival-time residuals were 0.015 s. The ray density through the 1998/99 three-dimensional model is very similar to that through the 1994 model and lends confidence to a comparison of the two models.

The 1994 one-dimensional model shows low Vp/Vs ratio at all levels, with particularly low Vp/Vs at a depth of -0.5 km. msl. This elevation corresponds to the uppermost part of the steam reservoir and may be the most depleted zone. Low Vp/Vs ratios have also been obtained by other investigators in other areas of The Geysers reservoir (O'Connell and Johnson, 1991; Romero et al, 1995; Julian et al, 1996) and have been attributed to undersaturation of the rock matrix, which would tend to lower the bulk modulus, lowering Vp. In addition, laboratory measurements on Geysers core material have shown that Vp/Vs is lowered as matrix material is desaturated; however, it is not known if the bulk field properties are affected in the same way.

The three-dimensional Vp and Vs models were plotted as deviations from the average velocity of the 1994 model in each layer. There are high-velocity anomalies in Vp and in Vs in the northwestern part of the SE Geysers study area in both the 1994 and 1998/99 models. There is a low-velocity zone slightly northeast of center, which is more pronounced in the 1994 model.

The high-velocity anomaly correlates well with the position of the felsite intrusion in the SE Geysers. To test the assumption that the felsite intrusion was being imaged, a synthetic test was performed with the 1994 data. The felsite is expected to have higher P- and S-wave velocity than the main greywacke and other metamorphic assemblages into which it is intruded because it is less fractured than these units. In addition, a downhole VSP experiment that penetrated the felsite indicated that the Vp of the felsite was approximately 5% greater than that of the overlying rocks.

In the test, a constant background velocity was assigned to each layer, and the felsite body was parameterized by assigning 5% higher Vp and Vs values to the nodes occurring within the felsite. Synthetic arrival times were calculated through this structure for the 1994 hypocenter-station pairs, and were then inverted using the same parameters as the real inversion. The high-velocity synthetic structure was recovered very well. The results were examined as deviations from the average velocity in each layer, so that they could be compared to the real inversion plots.

In the best-resolved layers (at -0.5 and -1.0 km msl) the Vp increased by a maximum of 4% form 1994 to 1998/99. This may be caused by the resaturation of the reservoir rocks due to increased injection resulting from SEGEPP. Injection into the SE Geysers went from an annual level of approximately 20 billion lbs per year before the startup of SEGEPP, to approximately 44 billion lbs per year following the start-up. The operators estimate that only about 50% of the injected water is being recovered as steam.

S-velocity values changed less than Vp, and did not show an overall increase or decrease. Higher damping was applied to the S-model in the inversions because of the lower number of S-arrivals and the higher uncertainty in S-arrival time values. The values are not shown because of low confidence in the results. The geophones were deployed on the surface; borehole installation might improve S-arrival picking accuracy and number and thus Vs-model confidence. However, Vp results and the accompanying changes were similar when only P-arrival times were inverted, as Foulger et al. (1996) have suggested. Therefore, monitoring of pore-fluid properties using periodically collected P-phase data alone may be possible.

## DISCUSSION AND CONCLUSIONS

Spatial correlation with the amounts of water injected into each injection well is not clear. Tracer tests indicate that injectate generally migrates in a north-northeast direction from the injection wells. This may explain why the southwest nodes in the 3-D model showed small increases and decreases, while the northeast nodes presented the greatest increases. Variations in fracture patterns may also control the fate of the injected water. The SE Geysers field is characterized by blocks containing low-angle, discontinuous fractures bounded by high-angle, continuous fractures (Beall, and Box, 1992) and some injectate may be escaping deep into the reservoir along these fractures. The general conclusions of the seismic velocity analysis are:

- Low Vp/Vs ratios are characteristics of the SE Geysers reservoir
- Lowest Vp/Vs ratio corresponds to top portion of steam reservoir.
- Lateral high Vp- and Vs-anomalies is probably caused by the presence of the felsite intrusion.
- Vp increased up to 4% over a five-year period; possibly due to an increased saturation of reservoir associated with an injection rate increase of more than 100% over same time period

## FUTURE PLANS

The MEQ data recording and analysis by LBNL has ended at The Geysers. Calpine would like to upgrade the present field-wide array to have similar capabilities as the present LBNL system. This would allow them to obtain three-component data, gather better event location information, and provide a means for the data to be transferred to the public. Due to concerns over the effects of increased production and injection and to provide complete accessibility to the public, Calpine feels that any upgraded array should be operated independently of their own Geysers activities.

## INDUSTRY AND TECHNOLOGY TRANSFER

The project has been a joint DOE-Industry (Unocal, Calpine, and NCPA) project. The companies provided field support, injection and production data, as well as a list of MEQs recorded by the Unocal (now Calpine) network. Meetings are held periodically to discuss research results, directions, and priorities.

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### CONTACTS

Marshall Reed
Office of Geothermal and Wind Technologies
U.S. Department of Energy EE-12
Washington, D.C. 20585
Phone: (202) 586-8076
Fax: (202) 586-8185
e-mail: marshall.reed@hq.doe.gov

| | | |
|---|---|---|
| Ernie L. Majer | Phone: (510) 486-6709 | e-mail: elmajer@lbl.gov |
| Ann Kirkpatrick | Phone: (510) 486-6985 | e-mail: akirkpatrick@lbl.gov |
| John E. Peterson | Phone: (510) 486-4267 | e-mail: jepeterson@lbl.gov |

Earth Sciences Division
Bldg 90-1116
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
Fax: (510) 486-5686

# MONITORING $H_2S$ AT THE GEYSERS BY CROSS-DISPERSION INFRARED SPECTROMETRY

Charles G. Stevens, James R. Curry, and Carol J. Bruton
Lawrence Livermore National Laboratory

## KEY WORDS

The Geysers, cross-dispersion infrared spectrometry, $H_2S$, geothermal, echelle grating spectrometer

## PROJECT BACKGROUND AND STATUS

To reduce chemical costs at geothermal power plants, we are investigating the use of a new type of infrared (IR) field spectrometer under development at LLNL (Stevens et al., 1995). There is currently no satisfactory way to continuously and accurately monitor the $H_2S$ content in the various streams without manpower requirements for sampling, calibration and maintenance. Contact measurement such as thin film resistance is subject to corrosion and fouling in extended operation. Furthermore, optical monitoring of reflectance changes on lead acetate tapes are subject to drifts that require regular re-calibrations and maintenance. A non-contact optical device, such as the echelle grating spectrometer (EGS), has the potential to meet the requirements for continuous and reliable operation. A key feature of this optical instrument is its capability to simultaneously measure wavelengths where $H_2S$ absorbs light and neighboring wavelengths where it doesn't. This provides a built in calibration source that eliminates one of the major cost factors associated with conventional sensors.

Following power generation, $H_2S$ is present in the Geysers steam at highly variable levels ranging from ~150 to >2000 ppmw (Truesdell et al., 1992). Processes based on oxidizing sulfur to less toxic forms are used to abate the $H_2S$. In one process, an iron chelate (FeHEDTA, where HEDTA = hydroxyethylethylenediaminetriacetic acid) is used to oxidize $H_2S$. Portable analyzers are used to measure $H_2S$ emissions at 36 sample points per cooling-tower cell. The amount of reagent added to the condensed steam is based on the amount of $H_2S$ measured in the incoming steam. Given the wide variability of $H_2S$ content and the noncontinuous nature of the sampling, the power plant operator must use enough iron chelate to oxidize the highest level of $H_2S$ measured. Because iron chelate is an expensive oxidizing agent, the power company could reduce reagent use and thus cost if continuous $H_2S$ monitoring were available to help determine precise iron chelate requirements.

Last year we field tested the spectrometer at a geothermal power plant then operated by Pacific Gas & Electric Company (now operated by Calpine) in The Geysers geothermal field in California. To meet air quality requirements, $H_2S$ emissions from this power plant must be limited to less than 22 kg/h. During this field test, we used the EGS to measure the $H_2S$ concentration in the plant steam condensate. In laboratory experiments we demonstrated that the instrument was sensitive enough to measure $H_2S$ continuously in this stream down to ~ 10 parts per million in a 1 meter pathlength with a 1 minute observation time. In the field, however, it was discovered that the noise floor had increased by a factor of 30 over the laboratory value. Understanding and eliminating this excess noise source is necessary to establish the utility of the instrument for this application.

## PROJECT OBJECTIVES

The overall objective of this project is to develop and test a new type of infrared spectrometer that will be capable of monitoring $H_2S$ emissions at The Geysers accurately, reliably, and continuously in a cost effective manner.

***Technical Objectives***

- Improve the performance of the echelle grating spectrometer to meet the sensitivity requirements of this application

- Design and develop a longer wave instrument that has the potential for directly monitoring $H_2S$ emissions from the cooling towers

- Perform a cost analysis of the infrared spectrometer and compare to alternative commercial $H_2S$ monitors for both capital and operating costs

***Expected Outcomes***

- Reduce chemical costs at geothermal power plants by deploying a new type of IR field spectrometer under development at LLNL

## APPROACH

Our approach is to capitalize on recent developments in infrared instrumentation taking place at LLNL for other programs. The instrument is called the echelle grating spectrometer (EGS), has no moving parts, and is based on cross-dispersive infrared spectrometry. This spectrometer approach allows spectral snapshots of an entire infrared spectral region with sufficient resolution to isolate individual spectral transitions in molecules. This provides a unique spectral signature for each molecule. The EGS uses a very coarse echelle grating operating in high order to yield high spectral resolution in a small package. Because it has no moving parts it is intrinsically robust for field operation and, when coupled with modern infrared (IR) detector arrays, can be more than 100 times more sensitive than existing IR instruments. This increase in sensitivity allows us to accurately, reliably and continuously monitor $H_2S$ emissions. The intrinsic absorption strength of $H_2S$ is weak compared to most molecules and monitoring its concentration at the ppm level represents a significant measurement challenge. We are developing hardware and software implementations that enhance the performance of the instrument for this application.

## RESEARCH RESULTS

Our first task was to address the source of excess noise experienced in our Geyser field study last year. We conducted a series of experiments that demonstrated the noise was due to the interference between different optical modes transmitted by the fiber optic input to the spectrometer. The optical modes of the fiber were not completely filled and this was creating an interference pattern at the focal plane. The intensity of the pattern was such that only when attempting to make measurements at 0.1% precision or better did this problem arise. An optical input lens was designed, fabricated and tested for improved performance. This lens consists of a micro-lens array designed so that it provided individual input injection to each fiber in the fiber array at an angle calculated to most nearly fill the modes. Experiments were conducted that demonstrated a reduction in susceptibility to modal noise by a factor of 45 over the original configuration. A return to the Geysers in early FY00 is scheduled to test this configuration in the field.

In addition to the mode noise issue we also improved our rate of data acquisition to enable good photon statistics (better measurement precision) in a shorter period of time. The detector array data acquisition timing is controlled through a set of timing tables contained in processor memory. New tables were created which implemented pseudo snapshot data collection for only a segment of the spectrum projected on the detector array. This set of tables "skipped" over the columns not of interest on the first clocking cycle of the array, and reset the pixels of interest. On several subsequent clocking cycles the entire array was neither read nor reset. This period is the integration time of the instrument. After the integration passes are complete, a final clocking pass is made reading only the pixel region containing $H_2S$ spectral region. A twenty-fold increase in the data acquisition rate was achieved in this manner.

In conjunction with another program, we designed a new instrument that operates in the long-wave IR spectral region between 8 and 14 microns. The spectrum of $H_2S$ is approximately 10 times stronger in this region than it is in the current wavelength region. In this spectral region the instrument is sensitive to thermal radiation from the molecule and as such it can directly view the $H_2S$ in the plume above the cooling towers from a remote location. This provides a direct monitor of the actual $H_2S$ being released to the environment.

A cost analysis of the two approaches to optical monitoring of the $H_2S$ has been initiated. Also included in this analysis is a comparison with alternative measuring techniques. It is expected that this analysis will be completed in January, 2000.

## FUTURE PLANS

We will test the performance of our fiber filling lens system designed to reduce the fiber ‘modal’ noise problem in a series of field tests scheduled for November, 1999. These tests will be conducted at Northern California Power Agency plant #1 at The Geysers.

We will adapt our long-wave infrared sensor design for performance which is optimized for the detection of $H_2S$ in a cost effective manner. The design effort will consist of two parts. The first part is the adaptation of an existing design toward a dedicated $H_2S$ detector. This would utilize an $H_2S$ ‘mask’ in the focal plane of the cross-dispersion spectrometer that would pass only $H_2S$ lines onto a single detector, thereby eliminating the requirement for costly detector arrays. The second design is based on a high resolution etalon filter that would measure absorption or emission from a single $H_2S$ absorption line. This will be explored as a potential high performance and low cost option. The performance and cost figures of merit for these two approaches will be completed and reported.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Pacific Gas and Electric Company (PG&E) | Tests of the EGS at a PG&E geothermal power plant at The Geysers in 1997 |
| Northern California Power Agency(NCPA) | Tests of the EGS at geothermal plant #1 for potential replacement of $H_2S$ monitoring equipment |

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## CONTACTS

Charles Stevens
Lawrence Livermore National Laboratory
L-183
P.O. Box 808
Livermore, CA 94550
Phone: 925-422-6208
Fax: 925-422-2499
Email: stevens2@llnl.gov

Raymond LaSala
Office of Geothermal and Wind Technologies
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-4198
Fax: (202) 586-8185
Email: Raymond.LaSala@ee.doe.gov

# MAPPING AND CHARACTERIZATION OF HYDROTHERMAL ALTERATION ASSOCIATED WITH THE DIXIE VALLEY GEOTHERMAL SYSTEM, NEVADA

Susan Juch Lutz and Jeffrey B. Hulen
Energy & Geoscience Institute, University of Utah

## KEY WORDS

alteration mineralogy, U-series dating, acid-sulfate, fumaroles, travertine, hot springs, Stillwater Range, rangefront faults, landslides

## PROJECT BACKGROUND AND STATUS

Our studies have focussed on the post-Oligocene alteration of the Jurassic reservoir rocks at Dixie Valley and the relationship and cumulative effect of these alteration events upon the permeability of the current geothermal reservoir. In the well cuttings, much of the secondary mineralization appears to represent older hydrothermal events associated with andesitic dike intrusion and the early stages of Basin and Range extensional faulting, rather than present-day geothermal activity. Our recent efforts have focussed on the mapping of hydrothermal alteration along the Stillwater rangefront immediately adjacent to the geothermal field, where splays of the Dixie Valley fault are exposed in the footwall of the main rangefront fault, and where other surficial manifestations of the current geothermal system (fumaroles and travertine deposits) are present.

## PROJECT OBJECTIVES

The overall objective of this study is to develop better conceptual models for geothermal reservoirs associated with normal faults in extensional terrains.

### *Technical Objectives*

- Describe the occurrence of hydrothermal minerals exposed along the Stillwater rangefront adjacent to the Dixie Valley geothermal field, and the relationship between these minerals in the footwall and hydrothermal alteration in the geothermal reservoir within the hanging wall of the main rangefront fault.

- Characterize the fluids that produced these alteration minerals. Determine their temperatures and salinities, and geochemical and isotopic signatures. Determine the temporal relationships between different fluid regimes using relative (i.e., crosscutting) relationships, or absolute dating techniques.

- Map the distribution of hydrothermal alteration minerals along the Stillwater rangefront. Relate the characteristics of the alteration minerals and altering fluids to major structural features (Miocene dikes, low-angle normal faults, high-angle rangefront faults) in order to understand the history of fluid flow in the area.

### *Expected Outcomes*

- Assist explorationists and developers in targeting geothermal wells along large-scale normal faults common to the Basin and Range province. The fault zone mineralogy can be used as an exploration guide to distinguish older structures and alteration from younger active or reactivated fault zones that are more likely to be permeable in the modern structural setting.

- Develop an improved understanding of the distribution and evolution of permeability through time at Dixie Valley.

## APPROACH

The approach has been to collect and analyze samples from outcrops adjacent to the geothermal field. Once the mineralogy of the samples has been established (using petrographic or X-ray diffraction techniques) and the sample locality has been recorded, distinctive alteration zones can be mapped. Using the geologic map of Plank (1999), the spatial relationships between the alteration zones and lithologic units, mapped faults, and other surficial features along the rangefront can be shown. A variety of materials have been sampled, analyzed, and mapped: green clays and vein minerals along splays of the rangefront fault; fumarole deposits at the north end of the field; travertine and calcite veins from Cottonwood Canyon; acid-altered rocks in an area of fault intersections and large landslides just south of the field; and fossil hot spring sinters and travertine deposits along the rangefront south of the field.

## RESEARCH RESULTS

### *Alteration Mapping*

Alteration mapping was conducted along the eastern escarpment of the Stillwater Range from just north of Senator Fumarole, southwest past the two large landslides south of the Boyer Ranch. Mapping of hydrothermal alteration along the Stillwater rangefront was completed with the aid of topographic and geologic maps, aerial photographs and a GPS. One of the main objectives of this mapping project was to document, using the GPS, the location of various sample localities that have been collected during the past several years. A preliminary map has been prepared that indicates these sample locations and the general hydrothermal alteration zoning along the rangefront.

The types of alteration that were mapped along the rangefront include areas of: prismatic quartz veining, acid-sulfate alteration near active fumaroles, clay alteration along splays of the main rangefront fault, young carbonate veining, travertine fossil spring deposits, fossil hot spring sinters, halite-cemented fault breccias, and acid-sulfate alteration from fossil fumarole deposits.

The characteristics of hydrothermal alteration and zoning from the NE to the SW along the eastern Stillwater rangefront can be summarized by area.

1. North of Senator Fumarole-

   Extensive quartz veining, and argillic alteration (kaolin and smectite) occur in an old mining prospect area north of the Senator Fumarole. A landslide at the mouth of Fumarole Canyon mantles the area with abundant prismatic quartz; hence, the quartz veining likely predates any landslide activity. In contrast, calcite veins are present along the trace of the main rangefront fault within the landslide, and appear to postdate its development.

2. Senator Fumarole and other active fumaroles-

   Low-temperature acid-sulfate assemblages consisting of native sulfur, kaolin, quartz, alunite and gypsum around the active fumaroles, with veins of laumontite, calcite, dolomite, and hematite in surrounding areas.

3. Rangefront fault and associated fault splays near Little Cottonwood Canyon-

   There is a distinctive green clay in the cores of the faults that is composed of corrensite, a mixed-layer chlorite-smectite. Orange-colored bands along the faults are composed of veins of ferroan dolomite that cut the green clayey gouge. Much of the dolomite in the veins is porous and exhibits dissolution textures, suggesting some acidic alteration or fumarolic activity after deposition of the dolomite veins.

4. Landslide deposits at the mouth of Black Canyon-

   Landslides overlie the older rangefront faults with their green clayey gouge and apparently formed after these faults. The headwall scarps for the landslides are located along zones of green clay alteration associated with fault splays RF2 through RF4 (terminology of Plank, 1999). The smectitic clay along the high-angle faults likely provided planes of weakness for the landslides, which may have formed during subsequent seismic events.

5. From Black Canyon to the mouth of Cottonwood Canyon-

   There is a conspicuous absence of hydrothermal alteration or landslides along the rangefront. This area of the footwall is adjacent to the center of the geothermal reservoir within the hangingwall of the Dixie Valley fault.

6. From the mouth of Cottonwood Canyon southwest to a large landslide south of the Boyer Ranch -

   Isolated calcite veins are present in the footwall rocks along the main rangefront fault.

7. Between the two large landslides-

   South of the geothermal field is an area of intensely altered rocks (the so-called “Altered Area”) that occurs at the intersection of a north-trending fault, a low-angle normal fault (the Boyer fault) and the northeast-trending rangefront fault (the Dixie Valley fault). Several episodes of fossil acid-sulfate alteration and spring activity are apparent. The complex alteration in this area was mapped in detail, and is discussed in the following section. Weak, active fumarole activity was also noted in this area.

8. Southwest of the southernmost landslide-

   Several small spring deposits are present; one consists of siliceous sinter, and the other of travertine with some sinter. Both are located parallel to, but upsection of, the trace of the main rangefront fault. The sinter deposit has terraces that dip 10 to 15° S-SE into the valley.

***Alteration Mineralogy of the “Altered Area”***

Triassic siltstone at the area of fault intersections appears bleached and is altered to a yellow-green color. Acid-sulfate alteration is recorded by the presence of chalcedonic quartz and traces of alunite, jarosite, barite, anhydrite, goethite, hematite and kaolin in these rocks. The alteration is interpreted to be associated with a fossil fumarole system.

Finely laminated (perhaps algal?) fossil spring deposits occur as a veneer on the siltstone exposure along the north side of the Altered Area. These fossil hot (or warm?) spring deposits cement clasts of Tertiary "dirty" sand and iron oxide sinter material. The springs appear to have emanated from one of the younger rangefront fault splays and deposits from the spring have cemented fluvial and alluvial material along a surface that dips about 15° towards the valley. The laminations consist of black bands of iron-manganese oxides and light brown carbonate bands. XRD analysis indicates that the laminations are composed of calcite (64 wt %) and dolomite (1 wt %), hematite (21 wt %) and barite (14 wt %).

These laminated spring deposits probably: 1) postdate most of the acid alteration that is assumed to have formed in association with fumarolic activity, and 2) predate a landslide deposit that partially covers the spring deposit. Younger travertine (consisting of just calcite) cements the landslide material.

Dark-colored knobs along the rangefront fault are composed of quartz, halite, sylvite, and poorly crystalline iron and manganese oxides. These halite-cemented deposits appear to cement fault zone breccias and may be younger than the laminated calcite-hematite-barite spring deposits, the landslide, or the travertine spring deposits.

The details of the timing of secondary mineralization and faulting in this area still need to be worked out. Weak fumarolic activity is still ongoing along the present rangefront fault and it is difficult to determine whether formation of springs versus fumaroles is a result of climatic changes or tectonic activity. It is possible that as rangefront faults step basinward through time, previous spring deposits uplift and become exhumed as parts of the footwall. If this happens, the ground water table effectively drops relative to its original position and boiling may occur at a deeper level, creating a steaming fumarole and causing acid alteration of the rocks between the older and younger splays of the rangefront fault system. Renewed spring activity may indicate either: increased precipitation and water table elevation (forming cool springs with travertine); changes in the subsurface hydrology, such as the formation of a carbonate or clay aquitard (possibly by mixing of upwelling geothermal fluids with shallow meteoric fluids); or, changes in the stress regime along local faults (causing hot springs and the formation of sinter terraces).

### *Fluid-inclusion gas studies*

About twenty vein samples from the Dixie Valley geothermal field were submitted to Dave Norman of New Mexico Tech for fluid-inclusion gas chemistry. The sample set includes both outcrop vein samples and vein fragments collected from the geothermal wells. The fluid-inclusion gas chemistry of the alteration assemblages will be used to characterize the types of fluids (meteoric, crustal, magmatic) that were active during the evolution of the geothermal/fault system. Combined with the apparent salinities and homogenization temperature data from our fluid inclusion studies of these veins, the fluid-inclusion gas analyses will augment our geochemical modeling study of the paleofluids within Dixie Valley (see Future Plans).

### *U-series dating*

Nine calcite vein and travertine samples from the Dixie Valley area have been sent to Dr. Troy Rasbury of SUNY-Stonybrook for U-series radiometric dating. She has a student working on pushing U-Pb dating into the Pleistocene and will try these techniques on these samples. Of special interest are the finely-laminated fossil hot spring deposits from the Altered Area that are composed of calcite, hematite and barite. The hope is that there is enough uranium in the barite for this sample to be dated by high-precision U-Th methods.

## FUTURE PLANS

The next step in the mapping of the alteration mineralogy at Dixie Valley is to place the geochemical, mineralogical, and spatial data into a GIS system. The data will include the sample number/date of collection, location (UTM coordinates), mineralogy (XRD analyses), vein/lithology/alteration type, structural setting, petrographic description, and the results (homogenization temperatures, apparent salinities, gas compositions) of any available fluid-inclusion analyses.

Now that we have a good understanding of the hydrothermal alteration mineralogy and the general chemical and thermal conditions under which the minerals formed, we can begin to use geochemical modeling programs (i.e., Chiller) to characterize the kinds of paleofluids that were present in the Dixie Valley geothermal system. We want to compare the different types of alteration minerals observed in cuttings from the geothermal wells and in outcrop (Parry et al., 1991; Lutz et al., 1996; 1997; 1998), with the known compositions of various well and spring waters in the Dixie Valley area (Bruton et al., 1997; Hulen et al., 1999; Nimz et al., 1999). We can model the kinds of fluids that were present during the evolution of the fault/geothermal system, and how they were mixed, heated, or boiled to precipitate the observed alteration minerals. This geochemical modeling will also provide estimates of fluid flow rates and the amount or masses of minerals produced during the history of the geothermal system.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| | |
|---|---|
| Oxbow Power Services | Fluid geochemistry and scaling in geothermal and injection wells |
| Caithness Corporation | History of permeability and fluid flow in the reservoir rocks |
| | Exploration in the Basin and Range province or other extensional terrains |

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## CONTACTS

Susan Juch Lutz
Energy and Geoscience Institute
University of Utah
423 Wakara Way
Salt Lake City, UT 84108
Phone: (801) 585-9688
Fax: (801) 585-3540
e-mail: sjlutz@egi.utah.edu

Jeffrey B. Hulen
Energy and Geoscience Institute
University of Utah
423 Wakara Way
Salt Lake City, UT 84108
Phone: (801) 585-8497
Fax: (801) 585-3540
e-mail: jhulen@egi.utah.edu

# REGIONAL HYDROLOGY SURROUNDING THE DIXIE VALLEY GEOTHERMAL FIELD: RELATION TO GEOTHERMAL FLUIDS

Gregory Nimz
Lawrence Livermore National Laboratory

## KEY WORDS

reservoir hydrology, fluid recharge, fluid transport, water ages, solute chemistry, chemical evolution, $^{36}Cl$, $^{14}C$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$

## PROJECT BACKGROUND AND STATUS

As a collaborative effort among Lawrence Livermore National Laboratory, Los Alamos National Laboratory (lead: Fraser Goff), and the U.S. Geological Survey (lead: Cathy Janik), we have used water chemistry and solute isotopic compositions to characterize the regional hydrology of the area surrounding the Dixie Valley geothermal field, and determine the relation between regional hydrology and the geothermal system. This project is part of the ongoing work conducted by several agencies and researchers concerning the geology, geophysics, and hydrology of the Dixie Valley geothermal system. The project began in late 1996 and most major aspects of this work were completed in 1999. This project is conducted in conjunction with Oxbow Power Services, Inc., operators of the Dixie Valley geothermal plant.

## PROJECT OBJECTIVES

The objective is to better understand fluid circulation within the production zones, recharge to the system, and the interfacing of the thermal water with regional cooler groundwaters. The purpose is to provide information that will: 1) permit better siting of exploration, production, reinjection, and monitoring wells, 2) provide a basis for interpreting observed changes in the system and for predicting future behavior of the system, and 3) allow assessment of the effects of the geothermal operations, if any, on the regional groundwater system used for agriculture and ranching in the area.

### *Technical Objectives*

- Determine the solute chemistry of Dixie Valley thermal fluids/groundwaters
- Determine the isotopic compositions of these solutes
- Use the chemical/isotopic data to characterize the hydrology of the geothermal reservoir, fluid origins (recharge) and transport, and the chemical evolution of the regional waters and geothermal fluids
- Provide a data set that can be used to model fluid/rock interactions, including those detrimental to the system such as scaling, and those experienced by reinjected waters
- Provide a baseline data set by which future changes in the system can be interpreted

### *Expected Outcomes*

- Better long-term management of the Dixie Valley geothermal resource, increasing production capacity, and lengthening the lifetime of the field. Information from this project can also be used to reduce the cost of locating future wells for production, reinjection, and monitoring.

- Provide information useful to the development of other geothermal resources because the Dixie Valley geothermal system is similar in many respects to other geothermal systems in the United States. In particular, cost-savings during exploration would be anticipated.

- Permit improvements in the employed techniques, allowing wider application to geothermal fields in other geologic/hydrologic settings

## APPROACH

The chemical and isotopic compositions of thermal fluids and groundwaters indicate their origins, interactions, and clues to their ultimate fates; for example, the ages and locations of recharge and the relation between different waters within and adjacent to geothermal systems can be determined. This approach was chosen for use at Dixie Valley so that we could better understand the role of local geologic structure and tectonics in determining fluid flow within the geothermal system. It addresses the following specific questions:

- Where do the geothermal fluids originate and what flowpath(s) do they use?

- Does the Stillwater fault impede or enhance fluid flow?

- Are regional hot springs hydrologically connected to the economic production zone? Are regional groundwaters?

- Will future use and development of the geothermal field impact valley groundwaters?

- How rapidly can the cone of depression caused by production pumping be expected to recover at reduced production rates?

- Why are reinjection tracers recovered in some parts of the geothermal field but not others?

- What is the best strategy for making sure that reinjected fluids recharge the reservoir?

We used an integrated multi-chemical, multi-isotope approach to address different aspects of the hydrology of the system, and utilized capabilities from the Los Alamos National Laboratory (major and trace elements, tritium, petrology), the U.S. Geological Survey ($\delta^{13}C$, $\delta^{18}O$, $\delta D$), and Lawrence Livermore National Laboratory ($^{14}C$, $^{36}Cl/Cl$, $^{87}Sr/^{86}Sr$).

## RESEARCH RESULTS

Chemical and isotopic data indicate the following:

- Waters issuing to the surface in the Clan Alpine and Augusta ranges to the east of Dixie Valley are dominantly young (<50 yrs old) and bicarbonate in character. Waters issuing to the surface in the Stillwater range to the west are dominantly older (up to ~9ka) and chloride in character.

- All waters within the valley, including geothermal fluids, are late-Pleistocene in age (~12-14 ka). Therefore transport times are short and all recharge must be local as opposed to long-distance underflow into the basin.

- The young ages for the geothermal fluids imply unusually fast cycling of water to depths sufficient to reach the observed geothermal temperatures (~7 km) and then rising to the depth of the production reservoir (~3 km).

- $^{36}Cl/Cl$ modeling indicates that the reservoir fluids evolved directly from the most dilute waters within Dixie Valley, incorporating Cl through rock dissolution, and did not evolve from water types observed today in either the Stillwater or Clan Alpine ranges. Fluid movement to reservoir depths has therefore been nearly vertical, as opposed to curvilinear and originating in the mountains east and west of the valley, as suggested in previous studies (Bohm et al., 1980).

- Thermal springs are not closely similar in chemical or isotopic signature to the reservoir fluids. Their maximum depth of origin may be much shallower.

- Mixing between thermal waters and non-thermal waters appears to occur only in limited cases. Large-scale mixing does not seem to occur. Therefore the production reservoir may be shielded or enclosed from the rest of the hydrologic system. These “barriers” are likely the controls of tracer movement at depth. Geothermal production zones outside of the enclosed zone may be unlikely within Dixie Valley. Reinjection outside this zone may be ineffective; monitoring outside of this zone might prove misleading.

- $^{14}C$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$, and $^{36}Cl$ data indicate that reservoir fluids do not react significantly with lopolithic rocks that occur abundantly at reservoir depths. Rather, interaction is primarily with Triassic marine sequences underlying the lopolithic rocks. This suggests that the fluids circulate widely through the Triassic rocks but then rise directly along the Stillwater Fault to the production zone. Absence of lopolith-affected water implies poor hydrologic conductivity in this unit. Reinjection into these rocks may not actually recharge the system or may lead only to cooling.

This research is the first study to integrate a wide range of chemical and isotopic techniques for geothermal characterization. As a general result, it indicates that isotopic and chemical data can be diagnostic of the hydrologic structure of geothermal systems. Preliminary results from this work were published in the Geothermal Resources Council Transactions, Volume 23 (1999), pp. 333-338.

## FUTURE PLANS

We are concluding our work of verifying water isotopic measurements by comparison to rock isotopic measurements, and are currently preparing a paper presenting our findings for publication in a peer-review hydrology journal.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Oxbow Power Services, Inc. (operators of the Dixie Valley geothermal plant) | Technical guidance and logistic support |

## CONTACTS

Gregory Nimz
Lawrence Livermore National Laboratory
L-219
P.O. Box 808
Livermore, CA 94550
Phone: 925-423-2766
Fax: 925-422-0208
Email: nimz1@llnl.gov

Marshall Reed
Office of Geothermal and Wind Technologies
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-8076
Fax: (202) 586-8185
Email: Marshall.Reed@ee.doe.gov

# MAPPING VEGETATION ANOMALIES FOR FRACTURE DETECTION: DIXIE VALLEY, NEVADA

Gregory D. Nash and Glenn Johnson
Energy and Geoscience Institute
University of Utah

## KEY WORDS

hyperspectral, AVIRIS, geobotany, vegetation anomaly, Dixie Valley, Nevada, fracture

## PROJECT BACKGROUND AND STATUS

Hyperspectral data, such as those produced by NASA's AVIRIS instrument, can be used map a variety of features on the earth's surface, including stressed vegetation. The area near the Oxbow Power Services geothermal power plant in Dixie Valley, Nevada, was flown to collect hyperspectral data using NASA's AVIRIS instrument in May, 1995. This data set was acquired by the Energy & Geoscience Institute in 1996 for analysis to detect vegetation anomalies that may be related to fractures penetrating the hydrothermal convection system. Work by Hinkle and Erdman (1995), and Hinkle et al. (1995) has shown that soil-geochemical anomalies exist in the area (Figure 1). This gave reason to believe that vegetation anomalies may exist as well. The experiment was to determine if these anomalies did indeed exist, using spectral analysis, and if they were spatially related to faults. This report summarizes the final results.

## PROJECT OBJECTIVES

- Determine if geobotanical anomalies exist;
- Determine if geobotanical anomalies can be detected spectrally;
- Determine if geobotanical anomalies correlate spatially with known geologic structures.

### *Technical Objectives*

- Collect and analyze field vegetation spectra;
- Test analytic methods for airborne hyperspectral data;
- Determine if vegetation anomalies can be detected with AVIRIS data;
- Determine if the above techniques are be appropriate for use in future geothermal applications.

### *Expected Outcomes*

Past work by Nash and Wright (1996) has shown that soil-geochemical, biogeochemical, and related vegetal-spectral anomalies can often be found over hydrothermal convection systems. This conclusion was drawn from data collected in the field, including spectra obtained with a potable spectrometer. The challenge for this project would be detecting anomalous vegetation using airborne data with a spatial resolution of 20 m. Each 20 m pixel over the study area is a mix of soil, rock, and vegetation or man-made materials. Therefore, although we expected vegetation anomalies to be present, we questioned the feasibility of using airborne hyperspectral data to meet our goals. The challenge was made even more formidable as the vegetation cover in Dixie Valley was relatively sparse. However, Oxbow Power

Services geochemist, Stuart Johnson, noticed some changes in vegetation on the aluvial fan above the production bore-field, and just below Senator Fumarole, a few months after the AVIRIS imagery was acquired. This vegetation anomaly was accompanied by new fumarole development which has been attributed to reservoir boiling as a result of pressure reduction. By the following summer (1996) noticeable changes we occurring in the Bailey's greasewood. This made the project intriguing. A serendipitous and relatively large vegetation anomaly was manifesting after the acquisition of the AVIRIS data, thus giving us the rare opportunity to determine if this phenomena could be detected before it became visibly noticeable to the human eye. We anticipated that we could.

## APPROACH

The approach was to (1) collect data in the field, (2) analyze the field data, (3) analyze the AVIRIS data, and (4) determine spatial relationships between the analysis results and geologic features. The first field data collection excursion was made early in July, 1996. Two transects were plotted and data were collected along their length at 0.1 mile intervals. At each sample station, spectra were taken from either big or Bailey's greasewood. These spectra were then examined to determine if spectral features representing stress were present. One such feature, the spectral blue-shift along the red edge, is relatively easy to check (Baret et al., 1990; Lourim and Buxton, 1988; Collins et al., 1983). Each of the spectra were examined to determine if a blue-shift along the red edge could be detected. This was done by determining the position, along the x-axix, of the point-of-inflection of the curve between 690 and 760 nm. On a second field excursion, during late May - early June 1997, sampling was repeated and followed by blue-shift analysis. The results can be seen in Figure 2, which shows multitemporal spatial correlation of blue shifting with the Buckbrush Fault. Seasonal effects (Nash, 1998) are believed to have caused some temporal variation in the results. However many samples remained consistent through time, with good temporal and spatial correlation occurring between vegetation spectra and said fault. Soil-geochemical anomalies also correlate on and near Buckbrush Fault (Figure 1 for an example). NOTE: No field spectra were acquired from the anomaly below Senator Fumarole during the 1996 field work as the Bailey's greasewood were going into senescence. By the summer of 1997 most of the greasewood in the anomalous were dying or had died. With evidence of vegetation anomalies from spectral data, and from visual inspection in the case of the anomaly below Senator Fumarole, it was time to begin AVIRIS data analysis.

Hyperspectral data have a sampling interval and spectral resolution such that spectral features, such as diagnostic absorption features of minerals, can readily be identified. AVIRIS data have a sampling interval of 10 nm across the 400 nm - 2500 nm spectral region. To facilitate detection of subtle diagnostic features, atmospheric interference must first be removed. For this study the AVIRIS data were preprocessed with ATREM to remove atmospheric effects and convert the data to apparent reflectance (Gao, B-C et al., 1993).

Atmospheric correction was followed by the testing of several analytical techniques to determine their effectiveness in detecting vegetation anomalies. The first was polytopic vector analysis (PVA) (Johnson and Nash, 1998). PVA is an unsupervised statistical unmixing technique that has been used successfully in the identification of soil and water contaminant end-members. When applied to the AVIRIS data four end-members were identified. One of the end-members was clearly a vegetation spectrum. However, as anticipated, the paucity of vegetation and the spatial resolution of the data precluded the extraction of specific vegetation species or anomalous end-members. The resultant PVA image did, however, successfully identify the vegetation anomaly below Senator Fumarole. Subsequently, principal components analysis (PCA) and application of the maximum noise fraction technique (MNF) (Green et al., 1988) were tested. Both of these methods also clearly defined the vegetation anomaly below Senator Fumarole (Figures 3 and 4 ). The ATREM processed AVIRIS image can be seen in Figure 5 for comparison with Figures 3 and 4.

In conclusion, vegetal-spectral anomalies were found in Dixie Valley, with the most prominent being directly related to the hydrothermal convection system. Spectral data collected in the field show good correlation between vegetal-spectral blue shifting and Buckbrush Fault. Ground-based spectral surveys such as this may be useful for locating faults and fractures associated with hydrothermal convection systems where vegetation cover exists. Modern field spectrometers with fiber-optics can be used to collect hundreds of spectra daily, allowing the coverage of a relatively large area in a short time. The AVIRIS data, due to the mixing of surface features within pixels as a function of spatial resolution, could not be used to define an anomalous vegetation spectral end-member. However, it was determined that AVIRIS, or similar hyperspectral data sets, can be used to map relatively large vegetation anomalies in semiarid areas with relatively sparse, low-lying, vegetation cover. This type of data will likely be useful in regional geothermal reconnaissance exploration. In areas of dense vegetation, it may be possible to extract an anomalous vegetation end-member using PVA.

## FUTURE PLANS

Future Plans include: (1) testing the MNF method to enhance structural features; and (2) mineralogic mapping using the AVIRIS data. This study summarized here will be detailed in a paper soon to be submitted to *Geothermics.*

## INDUSTRY INTEREST

| Organization | Type and Extent of Interest |
|---|---|
| Oxbow Power Services | Exploration and field management |

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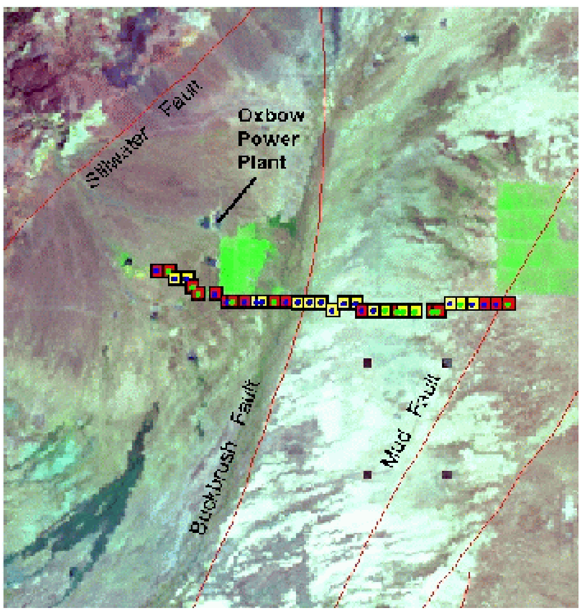


**Figure 1.** Arsenic concentrations represented by the size of the orange dots.

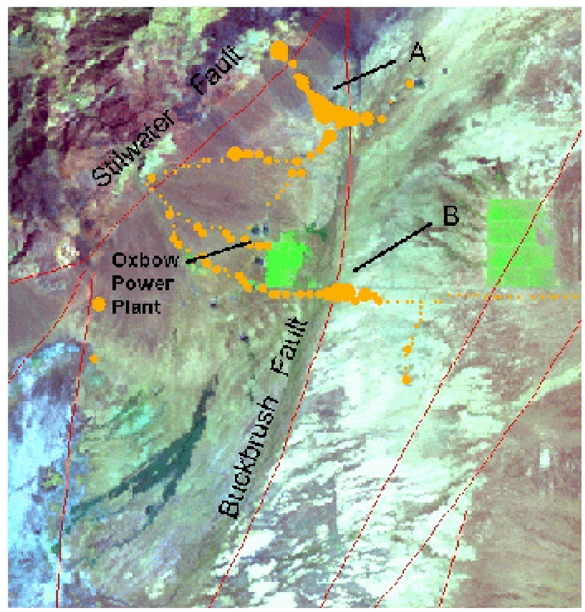


**Figure 2.** Spectral blue shift. Small blue dots represent July 1996 big greasewood with spectral blue shift. Small green dots represent 1996 big greasewood with no blue shift. Yellow boxes represent Early June 1997 big greasewood with blue shift. Red boxes represent June 1997 big greasewood with no blue shift.

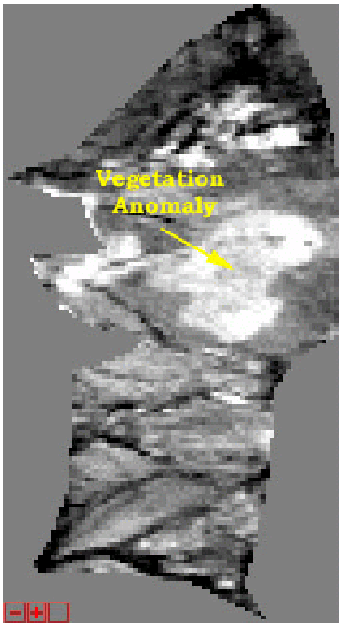


**Figure 3.** PCA processed AVIRIS image.

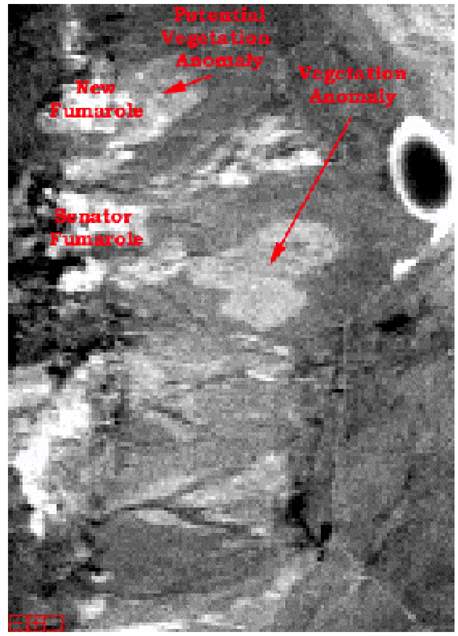


**Figure 4.** MNF processed AVIRIS image.

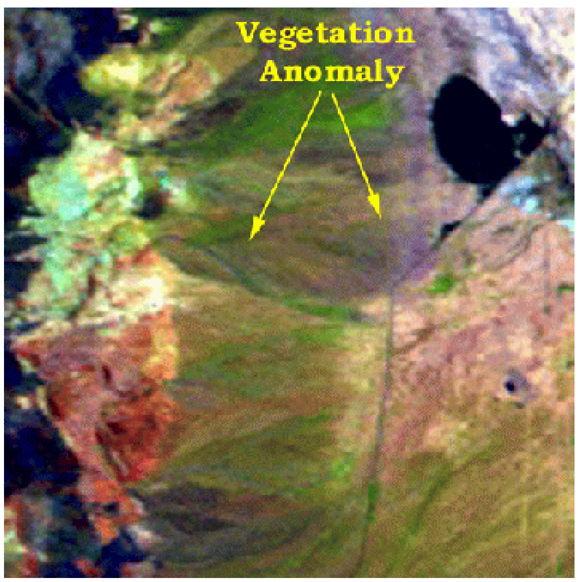


**Figure 5.** ATREM processed AVIRIS image.

## CONTACTS

Marshall Reed
Geothermal Division, EE-122
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D. C. 20585

Gregory D. Nash
423 Wakara Way, Suite 300
Salt Lake City, Utah 84108
Phone: (801) 585-3889
FAX: (801) 585-3540
gnash@egi.utah.edu

Robert J. Creed, Jr.
U. S. Department of Energy
Idaho Operations Office, MS 1220
850 Energy Drive
Idaho Falls, ID 83401-1563785
Tel:(208) 526-9063
Fax:(208) 526-6249

# STRESS AND PERMEABILITY HETEROGENEITY WITHIN THE DIXIE VALLEY RESERVOIR: RECENT RESULTS FROM WELL 82-5

Stephen Hickman, Colin Williams
U.S. Geological Survey

Mark Zoback
Stanford University

Colleen Barton
GeoMechanics International

Dick Benoit
Oxbow Geothermal Corporation

## KEY WORDS

permeability, fractures, stress, faulting, geothermal reservoir, fluid flow

## PROJECT BACKGROUND AND STATUS

Beginning in 1995, we have been conducting an integrated study of stress and fracture permeability in wells penetrating the Stillwater fault zone (SFZ) at depths of 2 to 3 km (Figure 1). This fault is a major, active, range-bounding normal fault that comprises the main reservoir for a ~62 MW geothermal electric power plant at Dixie Valley, Nevada. The long-term goal of this study is to determine the nature, distribution and hydraulic properties of fractures associated with the SFZ, and to characterize the manner in which these fractures, and hence the overall reservoir hydrology, are related to the local stress field. This has involved conducting borehole televiewer (BHTV) and temperature/pressure/spinner (TPS) logging and hydraulic fracturing stress measurements in wells within the primary zone of geothermal production (transmissivities ~1 $m^2$/min) and in wells outside the boundaries of the geothermal reservoir that were relatively impermeable (transmissivities ~$10^{-4}$ $m^2$/min). These previous results indicate that fault zone permeability is high only when individual fractures as well as the overall SFZ are favorably oriented and critically stressed for frictional failure (see Hickman et al., 1998; Barton et al., 1998).

## PROJECT OBJECTIVES

A number of "dry" legs have been drilled within the known boundaries of the Dixie Valley Geothermal Field (DVGF), where permeability is expected to be high but, in reality, is low to nearly nonexistent. In this report, we present results from BHTV logging and stress measurements recently conducted in a well (82-5) located within the DVGF but which failed to encounter sufficient permeability to be economically viable (Figure 1). Well 82-5 was drilled and then redrilled three times in 1985 and 1986 in an attempt to encounter reservoir permeabilities. The most recent (open-hole) leg penetrated abundant sealed fractures starting at a depth of about 2740 m – which we infer to be the top of the SFZ – before passing through the main range-front fault at 2833 m. Importantly, this well is located only about 600 m southwest of some of the most permeable production wells in the DVGF.

### *Technical Objectives*

- Obtain BHTV and TPS logs from well 82-5. Use these data to determine the orientation and relative permeability of natural fractures encountered and the distribution and orientation of stress induced borehole wall failure (breakouts and tensile cracks). TPS logs collected in well 82-5 are still undergoing analysis under a separate DOE contract and will not be discussed in detail here.

- Conduct a hydraulic fracturing stress test in well 82-5 to determine the magnitude of the least horizontal principal stress, $S_{hmin}$. Use these data along with observations of borehole wall failure to place bounds on the magnitude of the greatest horizontal principal stress, $S_{Hmax}$.

- Interpret these results to characterize the in-situ stress field at 82-5 and integrate them into our regional understanding of tectonic and geochemical controls on reservoir permeability and stress heterogeneity at Dixie Valley.

***Expected Outcomes***

- Better understanding of factors responsible for low permeability encountered in non-productive wells (like 82-5) drilled within the margins of the otherwise productive DVGF.

- A conceptual model to explain the origin of localized perturbations in stress orientations and magnitudes observed previously in nearby wells 27-33 and 37-33 (see Figure 1).

- Determine if and in what manner massive hydraulic fracturing or other reservoir stimulation techniques might be used to turn well 82-5 into a viable production or injection well.

## APPROACH

Three basic efforts comprise the overall approach to the Dixie Valley study:

(1) Obtain BHTV and TPS logs (under static and flowing conditions) from producing and non-producing wells to provide information on stress orientations, fracture geometry and fluid flow.

(2) Conduct hydraulic fracturing stress measurements in producing and non-producing wells to determine the magnitude of the least horizontal principal stress.

(3) Relate stress orientations and magnitudes and fluid flow indicators to the orientations of fractures and faults to see if changes in stress regime (i.e., proximity to failure), fracture orientations or other parameters might be responsible for variations in reservoir productivity.

## RESEARCH RESULTS

The results from this investigation are discussed in more detail in Hickman et al. (2000). During what should have been a routine work-over to clear a blockage and condition well 82-5 for testing, the drill pipe became inextricably stuck and had to be severed at a depth of 2724 m, preventing further access to the SFZ. Therefore, we of necessity restrict our attention to observations made above the SFZ and their implications for the nature of heterogeneities in stress and fault zone permeability within the DVGF and the potential for reservoir stimulation in well 82-5.

***Stress Orientations and Magnitudes***

Excellent quality BHTV logs were obtained over the entire open-hole interval in well 82-5. They revealed extensive stress-induced borehole breakouts and, to a lesser extent, drilling-induced tensile (cooling) fractures. Borehole breakouts were observed from 2280 m to the top of the stuck drill pipe at 2724 m, undergoing a sudden ~90° shift in orientation at about 2660 m. Tensile cracks were observed only between 2420 and 2620 m. The azimuth of the least horizontal principal stress, $S_{hmin}$, indicated by these tensile cracks and breakouts above 2660 m is N23°E ± 12° whereas below 2660 m it is S66°E ± 13°. The azimuth of $S_{hmin}$ above 2660 m is anomalous in that it is roughly parallel to the strike of the SFZ, while the orientation of $S_{hmin}$ below 2660 m (i.e., directly above the fault zone) is nearly perpendicular to the strike of the fault (Figure 1). This deeper $S_{hmin}$ direction is thus in good agreement with stress directions obtained previously in well 73B-7, in the producing interval of well 74-7 and in the nearby injection well 25-5. If this $S_{hmin}$ direction observed just above the SFZ persists to greater depths, then the Stillwater fault where penetrated by well 82-5 would be nearly at the optimal orientation for normal faulting.

The well 82-5 hydraulic fracturing test shows that the magnitude of $S_{hmin}$ is 31.1 ± 0.6 MPa at a depth of 2448 m (Figure 2). As borehole breakouts were observed in the BHTV log from this well, a lower bound to the magnitude of $S_{Hmax}$ was obtained using the $S_{hmin}$ magnitude from the hydraulic fracturing test together with theoretical models for breakout formation (see Hickman et al., 2000). This analysis indicates that $S_{Hmax}$ is greater than or equal to 49 MPa at a depth of 2.5 km (Figure 2). In contrast, no breakouts were observed in nearby production well 73B-7, even though it exhibited comparable $S_{hmin}$ magnitudes and penetrated the same rock types as 82-5 (Hickman et al., 1998). This suggests that the magnitude of $S_{Hmax}$ in 82-5 is significantly higher than in 73B-7. Using the Coulomb failure criterion with laboratory-derived coefficients of friction of 0.6 to 1.0 indicates that the $S_{hmin}$ magnitude at 2.5 km in well 82-5 is low enough to result in incipient frictional failure on optimally oriented normal faults (Figure 2). However, as no hydraulic fracturing data are available below 2660 m in this well, it is not known if and to what extent this condition of incipient frictional failure persists into the SFZ.

A conceptual model for permutation (or exchange) of the horizontal principal stresses due to a normal faulting earthquake in the hanging wall of the SFZ can explain the current stress state in well 82-5. In this model (Figure 3), the state of stress before the hypothesized earthquake was similar to that observed today in well 73B-7 (Hickman et al., 1998): with $S_{hmin}$ perpendicular to the strike of the SFZ and at the critical magnitude for frictional failure. We further propose, consistent with the upper bound to $S_{Hmax}$ obtained for 73B-7, that $S_{Hmax}$ prior to this earthquake was nearly equal in magnitude to $S_{hmin}$. Under these initial stress conditions, a normal faulting earthquake on either the SFZ or a subparallel fault would result in a significant reduction in shear stress on that fault (i.e., a coseismic stress drop). Since $S_V$ is fixed by the weight of the overburden, this stress drop causes an increase in the magnitude of $S_{hmin}$. Aside from the small elastic (Poisson) coupling of changes in $S_{Hmax}$ to $S_{hmin}$, the magnitude of $S_{Hmax}$ remains relatively unchanged since it lies in the plane of the fault and contributes nothing to the shear stress driving the earthquake. Given the nearly equal magnitudes of the horizontal principal stresses prior to the earthquake, the effect of the large coseismic increase in $S_{hmin}$ relative to that for $S_{Hmax}$ is for $S_{hmin}$ to transform into $S_{Hmax}$ and $S_{Hmax}$ to transform into $S_{hmin}$. As can be seen by comparison of Figure 3 with Figures 1 and 2, this model can explain both the anomalous $S_{hmin}$ orientation and the current magnitudes of $S_{hmin}$ and $S_{Hmax}$ above 2660 m in 82-5.

### *Fracture Orientations*

As observed in other nearby wells (Barton et al., 1998), BHTV logs from 82-5 show pervasive natural fractures with a wide range of orientations throughout the logged interval. To facilitate comparison of these fractures with the in-situ stress data, we have grouped them according to whether they are above or below the stress rotation at 2660 m (Figure 4). Above 2660 m these fractures fall into two distinct populations: one striking between west and northwest with moderate to steep dips (40° to 85°) to the south, the other is more diffuse and strikes between north and east with moderate dips (45° to 75°) to the northwest. Although the west to northwest fracture set strikes nearly perpendicular to the SFZ, it is near-optimally oriented for normal faulting given the local azimuth of $S_{hmin}$ (Figure 4a). Thus, fractures above 2660 m appear to be dominated by normal faulting antithetic to the Stillwater fault (i.e., at high angles to the SFZ).

The orientations of natural fractures below 2660 m in well 82-5 (i.e., directly above the SFZ) are markedly different from those observed above 2660 m. In particular, the west to northwest fracture set above 2660 m is notably absent in the deeper fracture population (Figure 4b). Instead, these deeper fractures tend to strike in a northeasterly direction and dip 40° to 75° either to the southeast or the northwest, with the dominant southeast-dipping set being subparallel to the SFZ. As the azimuth of $S_{hmin}$ below 2660 m is S66°E, this conjugate fracture set is optimally oriented for normal faulting. The geometry of this conjugate fracture set is remarkably similar to that observed for permeable fractures in production wells to the northeast and southwest of well 82-5 (Figure 1).

Coulomb failure analysis (see Barton et al., 1998) using the $S_{hmin}$ magnitude and orientation determined in 82-5 above 2660 m shows that many of the natural fractures in this interval are critically stressed for frictional failure. However, as the magnitude of $S_{hmin}$ below 2660 m is unknown, a corresponding analysis could not be performed for the fractures shown in Figure 4b. Thus, it is not known if and to what extent the natural fracture population located immediately above the SFZ is critically stressed for frictional failure.

The observation that well 82-5 is orders of magnitude less permeable than the nearby production wells suggests that there may be fundamental changes in the fracture population or the stress regime in proximity to the SFZ over distances of less than 600 m that are exerting a profound influence on well productivity. As stuck drill pipe is covering the SFZ in well 82-5, we cannot rule out anomalous fracture or stress orientations within the damage zone of the Stillwater fault as the cause of low fault zone permeability at this location based on our observations. However, we consider this to be an unlikely explanation for this low permeability because both the azimuth of $S_{hmin}$ and the orientation of natural fractures directly above the SFZ are nearly identical to those seen in nearby, highly productive wells (c.f., Figures 1 and 4b).

Rather, we consider it more likely that the low productivity of well 82-5 is due to localized increases in the magnitude of $S_{hmin}$ (i.e., a reduction in shear stress) due to the presence of weak talc within the main shear zone of the Stillwater fault at depth. In contrast to other (productive) wells drilled within the DVGF, approximately 10 m of talc-rich fault gouge was encountered at the base of the SFZ during drilling of 82-5. Laboratory strength measurements show that talc is extremely weak, with a coefficient of friction ranging from 0.2 to 0.25 (Morrow et al., 2000). Thus, the presence of weak talc in the core of the SFZ at reservoir depths could reduce the differential stress ($S_V$ - $S_{hmin}$) in the immediately adjacent country rock, effectively shielding the potentially permeable (and now sealed) fractures within the overlying damage zone from high tectonic shear stresses. If this "stress shadow" hypothesis is correct, it suggests that the spatial extent of impermeable patches within the SFZ like that encountered by well 82-5 may be directly determined by the distribution of talc (or other weak minerals) within the main range-front fault.

### *Potential for Reservoir Stimulation*

Several factors suggest that well 82-5 may be a good candidate for reservoir stimulation through massive hydraulic fracturing. First of all, as noted above, it is close to highly productive wells (e.g., 37-33) located ~0.6-0.9 km to the northeast. Secondly, it is in weak pressure communication with the reservoir. Third, the bottomhole temperatures measured in the various legs of 82-5 are similar to those measured in nearby production wells at comparable depths. Thus, one of the goals of this investigation was to evaluate the feasibility of conducting a massive hydraulic fracture in 82-5 to convert it into a viable production or injection well.

Since hydraulic fractures propagate in a plane perpendicular to the least principal stress, it is essential that the azimuth of $S_{hmin}$ and the orientation and spatial distribution of permeable (or potentially permeable) fractures within the SFZ be accurately known in evaluating the feasibility of reservoir stimulation through massive hydraulic fracturing. If the $S_{hmin}$ azimuth observed directly above the fault zone persists to greater depths, then a massive hydraulic fracture within the SFZ would propagate toward the highly permeable wells to the northeast (Figure 1). Thus, well 82-5 may still be a good candidate for massive hydraulic fracturing, although it would probably require that the well be redrilled around the stuck drill pipe so that a massive hydrofrac could be targeted directly within the SFZ. In this regard, it is encouraging that the water level in 82-5 following our hydraulic fracturing test has declined below pre-test levels and is approaching that recorded in nearby production well 45-33 (Hickman et al., 2000). This suggests that our small-scale hydraulic fracturing test enhanced the hydraulic connectivity of well 82-5 to the overall geothermal reservoir.

## FUTURE PLANS

In the coming year we will: 1) complete our analysis of TPS and BHTV logs from wells 27-33 and 25-5, 2) conduct Coulomb failure analyses on fractures in well 27-33 using stress measurements conducted in nearby well 37-33, and 3) produce a comprehensive digital data base and archive for all of the televiewer, TPS and hydrofrac data collected to date at Dixie Valley.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Oxbow Geothermal Corporation<br>Caithness Energy LLC<br>California Energy Company | Improved understanding of relationship between in-situ stress, fault slip and reservoir productivity. |
| Sandia National Labs<br>Geothermal Energy Association | New or improved techniques for geothermal energy exploration and/or reservoir enhancement. |

The main conduit for technology transfer is through publication and presentation of results to the geothermal industry at the Annual GRC Meeting and the Stanford Geothermal Workshop.

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## CONTACTS

Colleen Barton
GeoMechanics Int.
250 Cambridge Ave.
Palo Alto, CA 94306
Phone 650 322-6506
Fax 650 322-6508

Dick Benoit
Oxbow Geothermal Corp.
5250 S. Virgina St.
Reno, Nevada 89502
Phone 775 851-1199
Fax 775 850-2211

Peggy Brookshier
U.S. Dept. of Energy
DOE Place, MS 1220
Idaho Falls, ID 83401
Phone 208 526-1403
Fax 208 526-5964

Stephen Hickman
U.S. Geological Survey
345 Middlefield Rd.
Menlo Park, CA 94025
Phone 650 329-4807
Fax 650 329-5163

Marshall J. Reed, CE-122
U.S. Dept. of Energy
Washington, D.C. 20585
Phone 202 586-8076
Fax 202 586-8185

Colin Williams
U.S. Geological Survey
345 Middlefield Rd.
Menlo Park, CA 94025
Phone 650 329-4881
Fax 650 329-5163

Mark Zoback
Dept. of Geophysics
Stanford University
Stanford, CA 94305
Phone 650-725-9295
Fax 650-725-7344

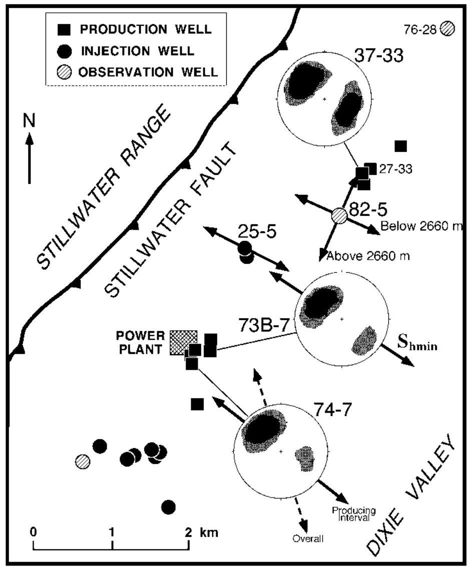


**Figure 1**. Map of the Dixie Valley Geothermal Field. The orientation of the least horizontal principal stress, $S_{hmin}$, is shown along with Kamb-contoured lower hemisphere stereographic projections of poles to permeable fractures in selected production wells (from Barton et al., 1998).

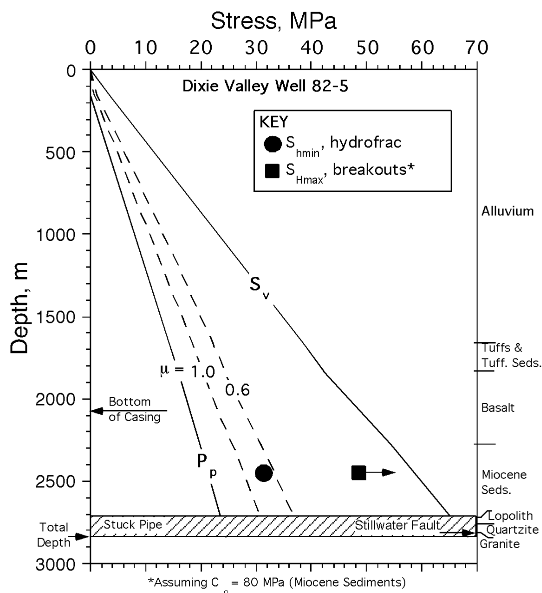


**Figure 2.** Magnitude of $S_{hmin}$ from the hydraulic fracturing test in well 82-5. Also shown is a lower bound on the magnitude of the greatest horizontal principal stress, $S_{Hmax}$. The vertical stress, $S_V$, and the formation fluid pressure, $P_p$, were calculated for the appropriate densities. The dashed lines indicate the range of $S_{hmin}$ at which incipient normal faulting would be expected on optimally oriented faults for coefficients of friction of 0.6 - 1.0.

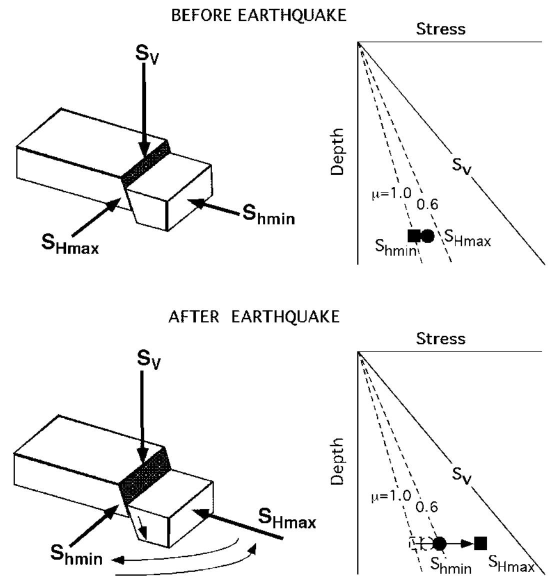


**Figure 3.** Illustration of the manner in which a normal-faulting earthquake accompanied by a large decrease in shear stress (stress drop) on the causative fault could lead to a 90° flip in the orientation of the two horizontal principal stresses.

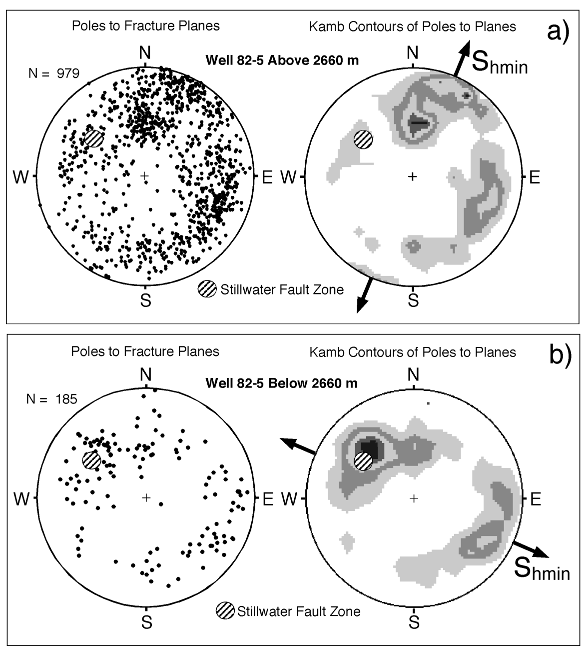


**Figure 4.** Kamb-contoured lower hemisphere stereographic projections of poles to natural fractures observed in the BHTV log from well 82-5: (a) above 2660 m and (b) below 2660 m. Also shown are the azimuth of $S_{hmin}$, over the corresponding depth interval and the pole representing the local orientation of the Stillwater fault zone. The total number of fractures is N.

# DRILLING TECHNOLOGY

# UNSHIELDED ELECTRONICS FOR DOWNHOLE APPLICATIONS

Joseph Henfling and Randy Normann
Sandia National Laboratories

## KEYWORDS

silicon-on-insulator, SOI, logging tools, data logger, Field-Programmable-Gate-Array, FPGA, Application Specific Integrated Circuit, ASIC, Dewarless, geothermal

## PROJECT BACKGROUND AND STATUS

Unshielded logging tools that operate indefinitely at temperatures up to 300°C are becoming possible. The benefits of unshielded logging tools are reduced cost, increase reliability, small diameters, and increased operating time inside of the well.

The Dewar is the single highest cost item in most geothermal logging tools. In 1996, the cost of a seven-foot Dewar was approximately $10,000.00. Eliminating the Dewar reduces costs while increasing reliability. Conventional logging tools are designed with low-temperature components. These devices are not rated for temperatures above 125°C and have limited operating time within the wellbore. Tools not returned to the surface in time are destroyed and must be replaced. Increased downhole operating time also allows the well operator to place sensors downhole for continuous measurement while altering production strategies. This can lead to a better understanding of the geothermal reservoir dynamics.

This project was initiated in FY97. At that time, a very limited number of SOI devices were available for testing. They included operational amplifiers, and digital switches, (HT83c51) microprocessor and accompanying 32-kbyte of memory. In order to test the microprocessor with memory, a number of non-SOI devices had to be identified and oven tested. Also, non-conventional assembly techniques had to be developed.

In FY98, sufficient devices existed to design and test a simple memory-based temperature tool. A microprocessor-controlled circuit operating at 300°C while measuring the external room temperature was demonstrated at the 1998 HiTEC (High-Temperature Electronics Conference, sponsored in part by Sandia and the Air Force). Also in FY98, a high-temperature electronics workshop was held. The workshop was well attended by companies including Honeywell, Halliburton, Endevco, Maurer Engineering, and KD Components.

In this fiscal year, many more components were available for testing. They included a clock oscillator, 5 volt regulator, 10 volt regulator, field-effect transistors (FET), 5 volt reference, and a strain-gage based pressure transducer. The testing revealed that all components functioned well to 250° C but many suffered above this temperature. Utilizing these components, a complete pressure/temperature downhole tool that was capable of sustained operation at 250°C was designed and field-tested. This tool was also demonstrated in an oven operating at 225° C at the SPE (Society of Petroleum Engineers) conference.

During this fiscal year, Sandia also formed an industry advisory panel to evaluate and guide the direction of the high-temperature electronics technology. The newly formed panel is called HiTED, High-Temperature Electronics Downhole. There are presently five members from industry and two university professors.

This ongoing project is evolving with the developing high-temperature industry.

## PROJECT OBJECTIVES

The objective of this program is twofold: identify and assist the high-temperature-component industry in creating electronics for geothermal applications, and assist geothermal companies in the development of NEW high-temperature instruments. These new high-temperature instruments will operate at a lower cost and higher reliability without the need for heat-shielding.

These objectives are possible with Silicon-On-Insulator (SOI) technology. This technology was developed, in part, at Sandia National Labs for radiation hardened electronics used in weapon applications. SOI is now being commercially produced by Honeywell's Solid State Electronics Center (SSEC) and Allied Signal for operation at 225°C. Many of these devices continue to operate well above 225°C, as high as 315°C, with reduced performance and shortened operational life. They have great potential for greatly altering geothermal drilling and logging.

### *Technical Objectives*

- Test and evaluate SOI devices and high-temperature sensors as they become available.
- Design, lab and field-test a pressure/temperature Dewarless downhole tool complete with uphole and downhole software.
- Form an industry advisory panel to evaluate and guide the direction of the high-temperature electronics technology program.

### *Expected Outcomes*

- Although the geothermal industry views high-temperature instrumentation as critical, it is difficult to show direct cost savings. Specialize tools can provide a substantial drilling cost savings. An example of such a tool is the core-tube data logger (CTDL). This tool enables the driller to obtain valuable information about bottom hole temperatures, pressures and hole inclination without loss of rig time. It is virtually free information that will help guide the drilling process. Utilizing this information will lead to better decisions concerning the well being drilled and the need for an additional well. It has been estimated that this type of tool could eliminate the need of one well in ten. The Sandia developed CTDL has been a high-demand extremely reliable tool and converting it to a Dewarless tool utilizing high temperature electronics is within reach.
- Stimulate the growth of the high-temperature industry by releasing test data on new high-temperature components, new high-temperature logging tool circuits and new high-temperature packaging.
- Demonstrate that a useful Dewarless downhole tool can be designed for sustained operation at 240°C.

## APPROACH

The Sandia approach is simple: “Adapt and expand high-temperature electronics technology to downhole applications”. The aircraft industry was providing the driving force for the commercial production of SOI circuits. The aircraft industry needs high-temperature electronic engine controllers. The components needed for electronic engine controllers are nearly identical to the components needed of a simple logging tool.

Geothermal applications will require features and components not necessary for aircraft. For example, special batteries and narrow tubular packaging must be developed for unshielded geothermal logging tools. Once new high-temperature designs are demonstrated for geothermal wellbore applications, the geothermal industry will gain never-before-realized instrumentation capabilities that will lead to new approaches to well logging reservoir.

Sandia has tested a number of components to 300°C and built a complete pressure/temperature logging tool that was oven tested to 250°C and successfully wellbore tested to 240°C. As the high-temperature electronic industry matures, so will performance at higher temperatures toward the target temperature for geothermal applications of 300°C.

## RESEARCH RESULTS

Several newly available components were evaluated up to 300°C. They included the SOI 5 volt regulator, SOI 10 volt regulator, SOI 5 volt reference, SOI FET, clock oscillator, and a strain-gage pressure transducer. Also, a more detailed analysis was performed on the SOI operational amplifier.

The voltage regulators continued to function at 300°C. The performance suffered significantly above 275°C but it is quite usable to this temperature. The voltage reference's maximum operating temperature is 250°C. Above this temperature the device's output rolls off sharply. The FET was tested with satisfactory results to 300°C.

The crystal oscillator results are presently inconclusive due to the limited number of oscillators that were available for testing. To date, Sandia has evaluated four batches of crystals manufactured for operation to 300°C and have received mixed results. The first two batches failed due to lead attachments separating internal to the oscillator. The last two batches have worked up to 250°C for several days. Exposures of 300°C appear to significantly limit the life of the oscillator. Also, the oscillators are load sensitive. A minimum of a 200 ohm/50pf load must by maintained to ensure the oscillator will continue to oscillate at the elevated temperatures. The oscillator also exhibits a sharp frequency shift of greater than 10% between 20 and 90°C (depending on the oscillator tested). The manufacturers are aware of the shortcomings and will continue to improve their oscillator design based on the feedback from Sandia hem.

The strain-gage pressure transducer worked well up to 300°C. The offset voltage varies considerably over the temperature range. This is an undesirable attribute, and will increase the complications of calibrating the unit, but is quite adequate to demonstrate the pressure/temperature tool concept.

The SOI operational amplifier was further evaluated to determine the bandwidth at various gains and to determine the offset voltage error at temperatures up to 300°C. It was determined the bandwidth is suitable for most geothermal applications. The offset voltage was quite large and will need to be kept in mind when designing circuits with this operational amplifier. Second generation devices will improve analog performance.

Two memory-based data loggers were designed and built. The first design was a data logger capable of storing and transmitting temperature information. The second design was a data logger capable of storing and transmitted three temperature channels and a pressure channel.

The first data logger design used a machinable ceramic substrate as the board material and mechanical lead attachment with laser spot-welded connections to ensure reliable performance. This design incorporated a field-programmable-gate-array (FPGA) with SOI components. The FPGA limited the maximum continuous operating temperature to 200°C with short excursions to 225°C.

The goal is to ultimately design a geothermal logging tool that will operate continuously at 300°C which will require the use of non-conventional board assembles such as the ceramic board concept. The board design with the FPGA paves the way for working with Honeywell in FY00. The FPGA circuit design is the same one needed in a high-temperature Honeywell Application Specific Integrated Circuit (ASIC) capable of operating continuously to 300°C. This needed component would replace the mil-spec devices that are currently required and would make a data logger designed using qualified high-temperature components exclusively, a reality. The data logger was tested in a geothermal well in August. It performed satisfactory up to 200°C, but experienced intermittent difficulties above this temperature. The temperature data did correlate with the previous temperature well profile and the ceramic board assembly performed well in the downhole field test.

The second data logger design used more conventional board material and high-temperature solder for the connections. A photo of this board is shown in Figure 2. This design incorporated tested mil-spec and SOI components that would allow continued operation up to 250°C. A block diagram of this design is shown in Figure 3. Utilizing more conventional board assembly techniques eased the integration of additional data channels and allowed Sandia to demonstrate a prototype pressure/temperature tool. This tool successfully logged a 240°C/12000 foot geothermal well. It successfully operated within the well for more than 56 hours at temperatures greater than 225°Celsius (up to 240°C) and pressures up to 5000 psi. While the prototype high-temperature PT Tool was designed more for functionality than absolute accuracy, it did provide a favorable well profile. As indicated in Figure 1, the temperature data correlates with the Dewared tool. As expected from oven tests, the pressure data contained false pressure gradients. Several reasons contribute to the cause including the limited component choices for the pressure transducer interface circuit and temperature gradients that existed between the pressure transducer and the temperature compensation circuit. The next generation tool will include a high-temperature analog-to-digital converter that just recently became available. This device will enable the accuracy of the temperature and pressure measurements to increase significantly.

After approximately 56 hours of exposure, the wireline cablehead experienced a small leak, shorting the cablehead conductors and leaking into the tool. The tool was evaluated after the test and it was determined two components had failed due to the leak. After their replacement, the tool was again functional. The development of HT SOI electronics will push the evolution of improved downhole hardware for long-term deployment.

The test results were conveyed to the high-temperature industry through the High-Temperature Electronics Downhole (HiTED) panel.

## FUTURE PLANS

Sandia's objectives in FY00 will be to evaluate and report on commercial activities to produce new high-temperature components and to develop Dewarless tool designs deployable within the geothermal wellbore and transfer this technology to the geothermal industry. Sandia will also support DOE's Small Business Innovated Research program to help small businesses develop new devices such as high-value capacitors, voltage references, pressure and inclination sensors and new high-temperature logging tools such as a pressure/temperature tool.

The FY00 objectives include working with Honeywell to develop an Application Specific Integrated Circuit (ASIC) that will be packaged and programmed for geothermal applications. This component is needed to overcome the shortcomings (and lack of availability) of mil-spec components. With this ASIC, a tool can be designed using only qualified high-temperature components. The ASIC also will greatly enhance the capabilities of the developed tool by providing several new capabilities such as precision counters (for use in sensor applications such as pressure, spinner and caliper), fm transmission, and increase memory for 64K to 8M bytes among other improvements. The developed ASIC will be made available to the geothermal industry.

Support for converting existing tool designs to high temperature is also planned. Many tools lend themselves for such a conversion. Examples include 1) pressure/temperature tool; 2) fluid/steam sampling tool; 3) core-tube data logger; and 4) casing inspection tool. Geothermal companies have requested assistance for this type of support.

## INDUSTRY INTEREST

| Organization | Type and Extent of Interest |
|---|---|
| Pruett Industries | Commercial Dewarless logging tools |
| Welaco | Commercial Dewarless logging tools |
| Engineering Spectrum | Commercial Dewarless logging tools |
| Southern Methodist University | Using Dewarless well logging tools |
| Thermochem, Inc. | Commercial Fluid/Gas Sampler |
| Material Integrity solutions, Inc. | High temperature instruments |

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## CONTACTS

Joseph Henfling
Sandia National Laboratories
P.O. Box 5800 M.S. 1033
505/844-6720; Fax 505/844-3952
e-mail: jahenfl@sandia.gov

Randy Normann
Sandia National Laboratories
P.O. Box 5800 M.S. 1033
505/845-9675; Fax 505/844-3952
e-mail: ranorma@sandia.gov

Michael R. Prairie
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823, Fax (505) 844-3952
e-mail: mrprair@sandia.gov

Raymond J. LaSala
Office of Geothermal and Wind
Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
e-mail: Raymond.LaSala@ee.doe.gov

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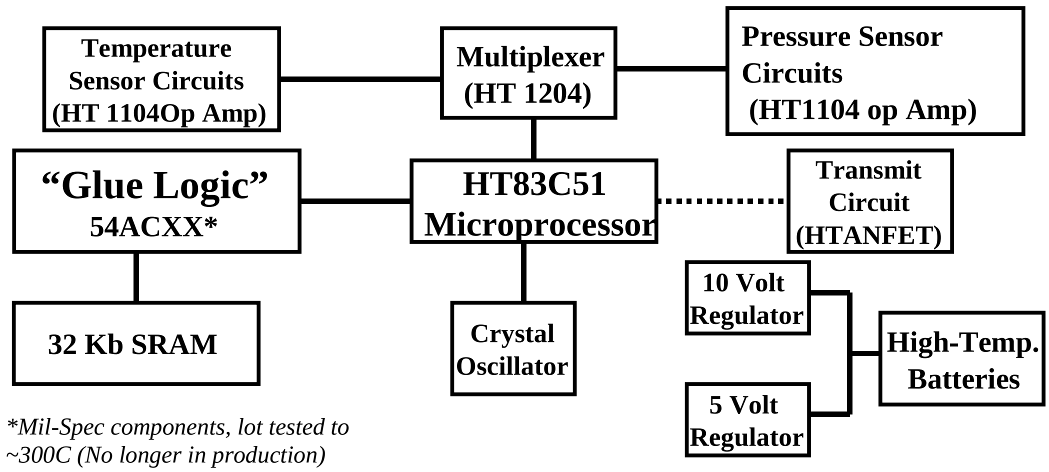


**Figure 1.** Block Diagram of the prototype pressure/temperature data logger.

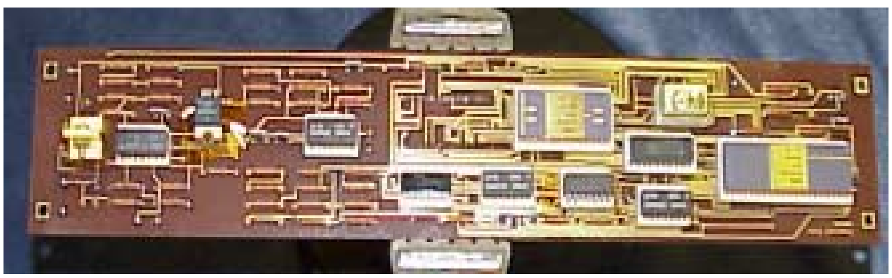

**Figure 2.** Present Pressure/Temperature Data Logger board.

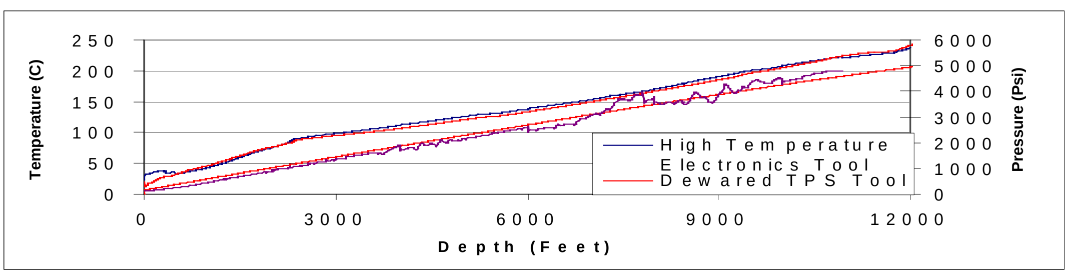


**Figure 3.** Temperature/Pressure plot comparing a conventional Dewared logging tool with the prototype Dewarless logging tool.

# HIGH-TEMPERATURE BATTERY DEVELOPMENT

Randy A. Normann and Ronald A. Guidotti
Sandia National Laboratories

## KEY WORDS

thermal-battery, low-temperature electrolytes, high-temperature electronics, logging tools, halide electrolyte, nitrate electrolyte

## PROJECT BACKGROUND AND STATUS

Commercial batteries only operate up to 180°C (356°F). New SOI (Silicon-On-Insulator) electronics are capable of operation up to 300°C (~600°F). To fully exploit SOI electronics for geothermal applications, a new power source is needed.

Thermal battery technology was chosen as the leading technology solution. To date, battery electrolytes have been evaluated and several have been found promising. Prototypes test cells have been demonstrated for temperatures up to 250 and 300°C.

These electrolytes led to a press release seeking commercialization partners. The press release meets Sandia/DOE requirements for fairness of opportunity objectives. At least two companies have responded favorably offering private funding and marketing capabilities. At present, a review of commercial interest is on going.

## PROJECT OBJECTIVES

- To develop suitable, cost competitive electric power sources for operating electronics up to 300°C (~600°F).

### *Technical Objectives*

- Battery to operate between 180-300°C
- 1.5in cell diameter
- Multiple cell capability for a nominal 15volts/ 100mA load for 8hrs

### *Expected Outcomes*

- Establish a viable downhole measurements (logging) industry in support of the geothermal industry
- When coupled with SOI electronics, provide downhole data for drilling, reservoir evaluation, and remediation
- Expand the resources of the geothermal industry for problem solving and risk reduction

## APPROACH

Thermal batteries use eutectic salts to form battery electrolytes. These salts melt at elevated temperatures activating the battery. Currently, these batteries power weapon systems where extremely high reliability and extremely long shelf life are required. This technology is cost competitive with commercial high-temperature batteries. However, thermal batteries designed for weapons systems do not activate until 315°C.

Our first direction was computer modeling a logging tool using a 315°C thermal battery. Here the battery would be electrically heated on the surface to activate it. Once running, the battery would self-heat using electric heaters wrapped around the battery under a layer of insulation. Clearly, this system will work for logging a 300°C production well where well temperature is uniform top to bottom. The question was, could the thermal battery afford to self-heat in an exploration well where the up-hole temperature is 25°C and the downhole temperature is 300°C? Most logging tools only log at 20ft per minute requiring many hours of operation in a well. The answer: Power loss, giving the size restrictions for insulation, is too great for self-heating batteries at 315°C.

Our second direction was to explore eutectic salts with lower melting points. There are eutectic salts that melt at or near room temperature. These salts would be perfect, however, their operation at the elevated temperatures expected in boreholes has not been demonstrated. Recent work has indicated that some of these salts may be stable at over 300$^{o}$C for limited periods of time. More work is needed with regard to long-term chemical compatibility with candidate anodes and cathodes A battery chemically active at room temperature when heated to 300°C could suffer chemical breakdown, resulting in either a dead battery or an explosion.

The desired melting range of 150-180°C was chosen as a goal. This range is low enough to insure automatic battery activation in virtually all geothermal production wells. It’s also low enough to cover the existing battery gap between 180-300°C left from commercial batteries and the upper operating limit of SOI electronics and greatly improves thermal management requirement for exploration wells using self-heating thermal batteries.

## RESEARCH RESULTS

Approximately 200 chemical combinations have been tested for temperature stability. From these tests, a few were chosen for trials in fabrication of a test battery cell. Of these, one was made into a stack of 5 cells for a full up testing. The results from that test are shown in figure 1. The batteries supplied 125mA at 250°C for more than 20hrs. The test was prematurely terminated when power was accidentally turned off within the room.

The bulk of the research effort so far has focused on halide-based electrolytes. Recently, however, work was initiated using a mixed-nitrate electrolyte that melts at 125$^{o}$C. Initial results are very promising in terms of current and voltage that could be delivered at 150-250$^{o}$C. More work is warranted with this system, to fully exploit its capabilities and assess any liabilities.

Last year, several thermal battery chemistries were demonstrated. These chemistries had melting temperatures between 150 and 250°C. Most continued to operate up to and above 300°C. Given these encouraging results, a CBD (Commerce Business Daily) ad was placed seeking commercialization partners to further advance high-temperature batteries. The press release meets Sandia/DOE for fairness of opportunity objectives. At least two companies have responded favorably offering private funding and marketing capabilities.

## FUTURE PLANS

For now, there is a wait and see approach. The CBD ad listed a closing date of January 12. Once the closing date has been reached, favorable respondents will be contacted. From those discussions, a plan for commercialization will be developed.

Sandia will work with the appropriate company(ies) to insure that a final product becomes realized and is made available to the geothermal industry.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Velaco | Geothermal service company needing HT batteries |
| Pruett Ind. | Geothermal service company needing HT batteries |
| Spectrum Engineering | Oil and Gas Instr. developers needing HT batteries |
| Aerospatiale Batteries | Battery Co. wanting technology transfer |
| Battery Engineering | Battery Co. wanting technology transfer |
| Wilson Greatbatch | Battery Co. wanting technology transfer |

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## CONTACTS

Randy Normann
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-6359; FAX (505) 844-3952
e-mail: ranorma@sandia.gov

Michael R. Prairie, Manager
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823; FAX (505) 844-3952
e-mail: mrprair@sandia.gov

Ronald .Guidotti
Geothermal Research Department
Sandia National Laboratories, MS 0614
P.O. Box 5800
Albuquerque, NM 87185-0614
(505) 844-1660; FAX (505) 844-6972
e-mail: :raguido@sandia.gov

Raymond J. LaSala
Office of Geothermal &
Wind Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
e-mail: Raymond.LaSala@ee.doe.gov

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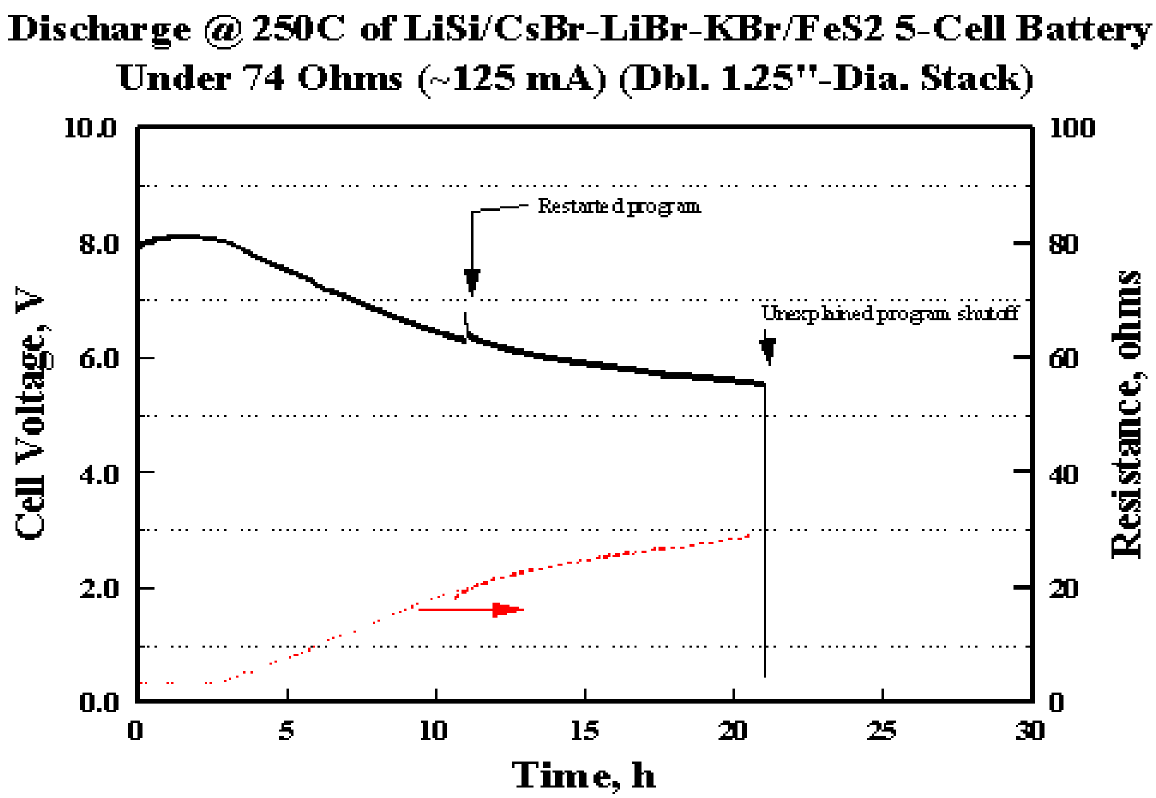


**Figure 1.** Stacked battery test data.

# PLUGGING LOST-CIRCULATION ZONES WITH POLYURETHANE

A.J. Mansure and J.J. Westmoreland
Sandia National Laboratories

## KEY WORDS

lost circulation, polyurethane, borehole stabilization, and drilling.

## PROJECT BACKGROUND AND STATUS

Lost circulation, when drilling mud flows into the formation rather than back to the surface, is one of the most persistent problems associated with geothermal drilling accounting for 10-20% of total drilling costs. It can result in numerous other drilling problems including stuck drill pipe, damaged bits, slow penetration rates, and collapsed boreholes. Plugging lost circulation zones is a very difficult and costly part of drilling geothermal wells.

Sandia National Laboratories is developing polyurethane grouting to plug lost circulation zones. In past work, more than 10 years ago, polyurethane foam was tried with limited success in laboratory tests and Geothermal Drilling Organization (GDO) sponsored field tests (Glowka et al.). Goals were that "the foam expanded significantly and harden to a drillable firmness quickly." In that work, expansion proved erratic. Aqueous polyurethane formulations have improved since the earlier work and the probable causes of the failures of previous tests have been identified. Furthermore, the goals of polyurethane grouting have changed (Mansure and Westmoreland). Recent successes (Ng and Bruce et al.) in solution grouting (proper classification chemical grouting using polyurethane – Naudts) of boreholes encourages reevaluating its use to control lost circulation.

An advantage of polyurethane is that the chemist can control its properties, in particular, viscosity and setting time. The material can be engineered to have a low viscosity while being pumped and then gain strength in a short period, minimizing “waiting-on-cement” and the potential for the plug to be washed out.

Best polyurethane plugging practices have been developed. A delivery mechanism is yet to be developed for geothermal drilling. The current project began in FY98; the project is expected to continue on into FY02 in order to accomplish field demonstrations.

## PROJECT OBJECTIVES

*The target application has changed.* Many of the most troublesome loss zones are in the upper part of geothermal boreholes; thus, there is a need for cost-effective techniques that can be used near the surface. At the Long Valley Exploratory Well for example, more than $400k was spent on cement plugs in the first 700 ft all above the water table. It is estimated that polyurethane grouting of the entire section could have been accomplished for $150k. Initially, lost circulation zones should be targeted that can be serviced from the back of a “pick-up truck” using the infrastructure that supports construction and civil engineering projects; the goal: simple & cheap. The depth should be less than 1000 ft and the temperature less than 250°F. The deployment of the chemicals must be as simple as possible—a challenge that has been addressed for the mining industry.

### *Technical Objectives*

- Establish best practices for successfully plugging lost circulation zones with polyurethane.

- Identify/develop high-temperature, high-pressure polyurethane formulations.
- Develop and demonstrate deployment/emplacement techniques.

***Expected Outcomes***

- Development of faster cheaper methods of plugging lost-circulation zones (12 times faster & 50% cheaper).
- Field demonstrations in geothermal wells of polyurethane grouting of lost-circulation zones (more than 3 wells).
- Commercially available approaches for plugging lost circulation zones in geothermal wells using polyurethane (material & emplacement specifications).

## APPROACH

A major problem with past work (Tschoepe, Polk et al., and Glowka et al.) is understanding why some of the tests were successful and others failed. Thus, the reinvestigation of plugging lost circulation zones with polyurethane has been done on a scale and in a manner that allows comparison of success and failure (when the scale is too large, the temptation is to only allow successful tests).

It is believed that past failures were effected by both process control practices and the chemical formulations used. To isolate causes of failure, the current approach began with commercially available chemical formulations (minimizes QA issues) at ambient temperature and low pressure (<100 psi.). These conditions allowed a large number of tests (>25) on a scale and in a manner from which best practices for deployment/process control were determined.

An important aspect of the current approach is to learn from other industries where polyurethane grouting is being applied. In particular, polyurethane is becoming the material of choice in dam remediation for sealing boreholes with large voids and high inflows, conditions associated with the worst lost circulation problems. An unexpected benefit of this learning process has been the identification of new two-part, high-temperature polyurethane foam used to insulate 400°F underground steam lines. Since lost circulation is an issue where casing is set (above the reservoir), 400°F should cover more than 90% of all lost circulation zones.

Having established best practices for process control in FY99, the project focus is shifting to developing deployment mechanisms. Previous field tests were done using a reusable two-chamber canister that was lowered down the well on the end of the drill pipe. Such a canister can deliver only a limited supply of chemical (makes expansion critical) and creates a cleanup waste disposal problem. What is needed is a disposable, drillable canister and/or a means of pumping the material down the well into the loss zone.

New chemical formulations will be developed in outyears only as needed, e.g., if emplacement of polyurethane would be greatly facilitated by high temperature one-part chemical formulations. Commercially available one-part formulations are only useable below 180°F, inadequate to reach 90% of geothermal applications.

Merely demonstrating how to successfully plug lost circulation zones with polyurethane in the lab is not enough. Geothermal field tests must be conducted in conjunction with industry to demonstrate and gain acceptance for the technology.

## RESEARCH RESULTS

While polyurethane expansion can be beneficial, tests have shown that expansion is not required to form a good plug. Advantages of expansion are that it decreases the cost of a plug and helps squeeze material into the loss zone. A plug that is not squeezed into the loss zone, is merely on the surface of the borehole, will not last. It can be broken off by subsequent drilling and drill pipe motion. Dumping polyurethane into the well did not result in penetration into the loss zone. Penetration into the loss zone was only reliably achieved by applied hydraulic pressure, not by expansion. Too much expansion produced open-celled, weak, leaky plugs.

The cost of sealing a lost circulation zone with a polyurethane plug depends upon a number of factors including expansion of the material, raw material cost, borehole diameter, depth of penetration into the loss zone, and loss zone void fraction. Polyurethane density can vary from ~2 lb./ft$^3$ for foam formed at atmospheric pressure to ~70 lb./ft$^3$ for solid polyurethane. Figure 1 shows the material cost per foot for a polyurethane plug penetrating 2” into a 30% void fraction loss zone as a function of foam density for various borehole diameters assuming $2.65/lb. raw material cost.

A successful polyurethane lost-circulation plug should be able to withstand 1000 psi. across the plug while leaking at an acceptably low level (<< 1 BBL/day per 100 psi for 10' long zone in 12-$^1/_4$" diameter hole was assumed for this project). 1000 psi. is needed to withstand the pressures of tripping and cementing. Rigid polyurethane foams with a density of about 4 lb/ft$^3$ were demonstrated to be capable of forming a plug meeting these requirements (Mansure and Westmoreland).

Plug formation best practices include:

- the loss zone must be packed off and the polyurethane squeezed into the loss zone,
- sufficient polyurethane must be injected to sweep out the mud and become the continuous phase,
- injection time should be longer than the gel time so that the material starts to set (becomes viscous) during injection.

Initially, before the raw materials react to form polyurethane foams, their density may be heavier than the drilling mud. However, lab tests show that this density difference is not sufficient to overcome the gel strength of the mud allowing the raw material to sink. Thus, one cannot rely on raw material flowing out into the loss zone due to gravity. The only way to insure raw material goes out into the loss zone is to push it there. This requires some means of packing the hole off and forcing the raw material to flow into the loss zone.

Both the quantity and rate of injection must be sufficient for the polyurethane to sweep out the mud and/or formation water so that the polyurethane becomes the continuous phase (Figure 2). Granules of polyurethane dispersed in the mud were formed when insufficient polyurethane was used. While the granules were sufficient to turn the mud white, when pressure was applied, the granules were swept away in a matter of seconds. Injecting more, but still inadequate, polyurethane resulted in a porous material much like that used for thermal insulation in the construction industry. Such material, while very open celled, allowed the formation of a mud cake; however, the mud cake did not resist pressure above 20 psi. When adequate polyurethane was injected, a hard, dense, almost-closed-cell plug was formed. If polyurethane is injected at too slow a rate, it can be washed away by cross flow before it sets.

It is important that the injection time and gel time be in the right relationship. If the polyurethane sets too fast, material in the wellbore sets before an adequate volume is injected and all the fractures are plugged.

In the extreme case, tests where the gel time was much too fast, the polyurethane set before any of it entered the loss zone. In tests where the gel time was too slow, injection ended before any of the material set resulting in a poor plug that was porous, permeable, and contained mud channels.

Figure 3 explains the critical relationship between injection time and gel time. The initial flow path for squeezing polyurethane into the loss zones is into the wider, more permeable, channel (top channel). If the polyurethane in the top channel does not gel during injection, there may be no flow into the lower channel. If the polyurethane gels during injection, the more permeable flow channels close off. Subsequent polyurethane entering permeable channels is compacted forming a hard impermeable plug. Also, subsequent polyurethane injected is forced into new, less permeable channels (lower channel). Thus, by timing the gel to occur during injection and by injecting an adequate quantity of polyurethane, all the loss zone channels are filled. Subsequent polyurethane injected is packed into a hard impermeable plug, one that does not leak and can withstand high pressures.

## FUTURE PLANS

Emplacement techniques to deliver polyurethane to lost circulation zones will be developed. This involves a number of choices: should one-part or two-part polyurethane be used, should the material be tripped in a canister or be pumped in, should canisters be reusable or disposable/drillable, etc? Industry input is being sought to guide such choices. Testing of some components, inflatable packers etc., has begun as the first step in developing emplacement schemes. Once experience is gained with emplacement techniques in the lab, field demonstrations will be conducted.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

In this project, Sandia is building upon existing polyurethane grouting infrastructures, in particular that which exists in civil engineering for dam remediation and mine water control. Elements of that infrastructure include consulting companies, chemical formulators, chemical distributors, hardware manufactures, grouting companies, and drilling companies. Over 20 such companies have been contacted. Several of these companies are interested in expanding their business to support geothermal drilling and have provided support to the project in terms of materials, consulting, access to in-house test data, and permission to observe field work.

Recognizing that the most likely companies to apply polyurethane grouting to geothermal drilling are those companies already in the geothermal infrastructure, Sandia is in close contact with Baroid and Boart Longyear. Baroid was a partner on the original testing of polyurethane grouting and remains interested as a service provider. The one-part polyurethane being used by Boart Longyear is only good to ~180°F, limiting its application to geothermal lost circulation.

Sandia is seeking opportunities to test the application of polyurethane grouting to geothermal lost circulation zones. Prime targets would be close to or above the water table, near the surface (<1000 ft.).

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### CONTACTS

George E. Staller
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-9328, Fax (505) 844-3952
e-mail: gestall@sandia.gov

Michael R. Prairie
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823, Fax (505) 844-3952
e-mail: mrprair@sandia.gov

Arthur J. Mansure
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-9315, Fax (505) 844-3952
e-mail: ajmansu@sandia.gov

Raymond J. LaSala
Office of Geothermal & Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
e-mail: Raymond.LaSala@ee.doe.gov

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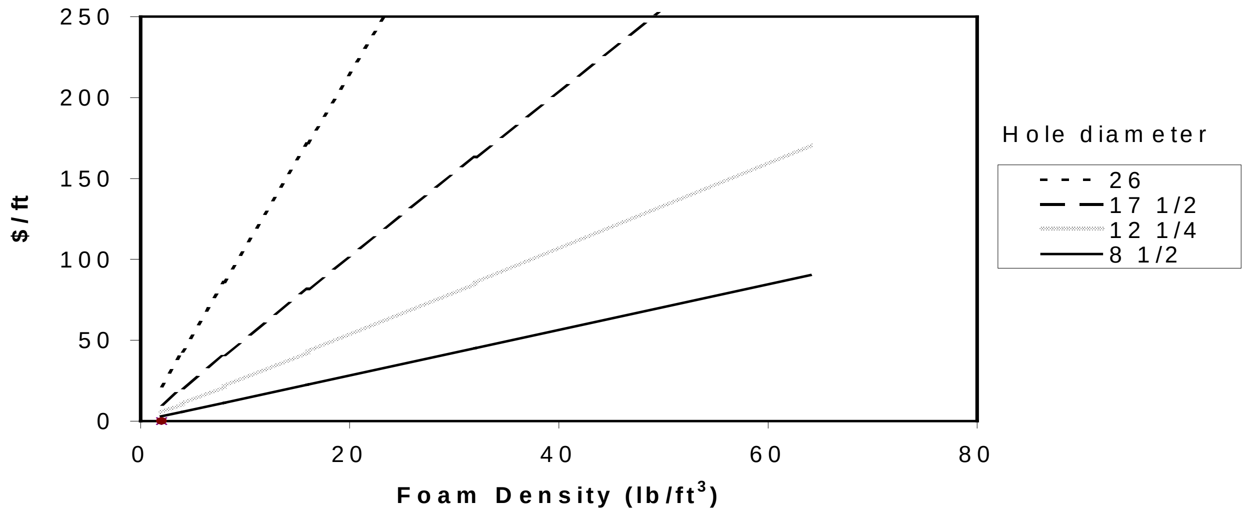


**Figure 1.** Material cost per foot for a polyurethane plug penetrating 2” into a 30% void fraction loss zone as a function of foam density for various borehole diameters assuming $2.65/lb. raw material costs.

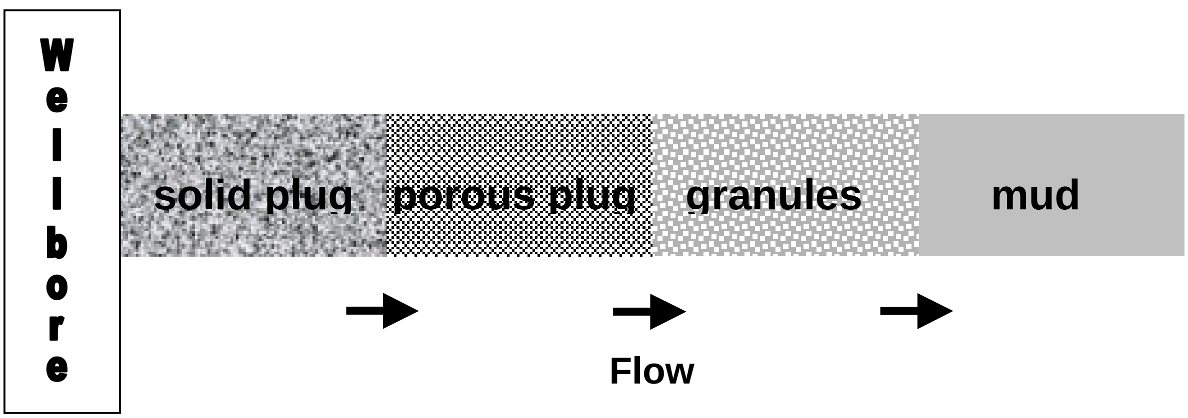


**Figure 2.** As the polyurethane sweeps out the mud in the loss zone there is a transition from polyurethane granules dispersed in the mud, to porous polyurethane, and finally a hard solid plug of polyurethane.

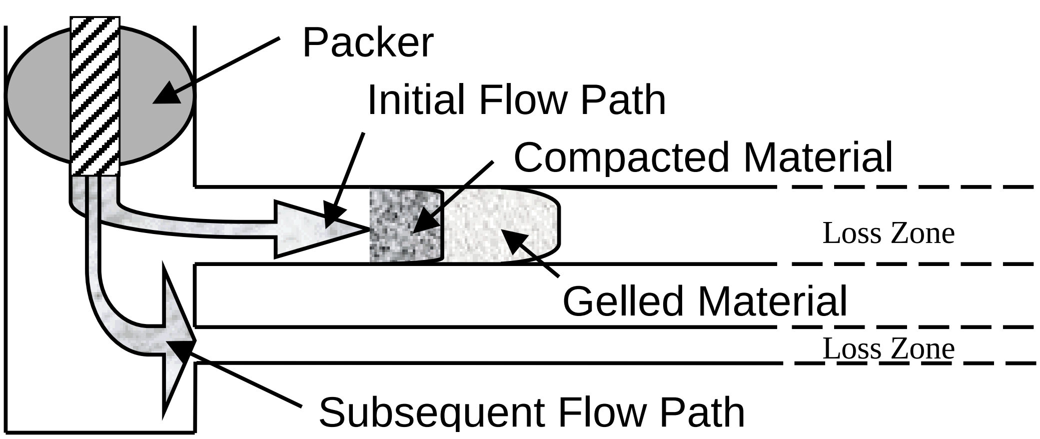


**Figure 3.** Effect of polyurethane gelling on injection process.

# EXPERT SYSTEM AND THE ROLLING FLOAT METER FOR LOST CIRCULATION CONTROL

George E. Staller and Gary L. Whitlow
Sandia National Laboratories

## KEY WORDS

expert system, circulation monitoring system, rolling float meter, lost circulation, wellbore hydraulics

## PROJECT BACKGROUND AND STATUS

Lost circulation is one of the most persistent problems associated with geothermal drilling, accounting for roughly 10-20% of the total cost of drilling a typical geothermal well. When the drilling fluid is lost to the formation, it cannot perform some of its vital functions, namely, removing rock chips, stabilizing the borehole walls, and lubricating the drill pipe in the hole. Rapid detection and treatment of lost circulation is critical to cost effective geothermal drilling. Sandia has been conducting an ongoing research program since the early 1980's to reduce the costs associated with lost circulation[1].

The Sandia lost circulation technology program has been focused in two areas: detection and treatment. The first objective is to develop hardware, software, and procedures for identifying and quantifying lost circulation zones to more quickly and accurately detect the problem and identify treatment options. The second objective is to develop new materials, hardware, and procedures to cost-effectively treat various types of lost circulation. Success in these areas will translate to a reduction in lost circulation costs when drilling geothermal wells.

This program update report will address the Expert System and Rolling Float Meter projects dealing with lost circulation detection. These two projects have been combined since they are used together for monitoring wellbore hydraulics while drilling. The Expert System or Circulation Monitoring System (CMS) project began in FY96; the final phase of initial development will be completed in FY00. The Rolling Float Meter (RFM) work began in 1991 and through continuous improvement, as a result of laboratory and field testing, an accurate, robust outflow meter has been developed[2]. Successful transfer of the RFM technology to the drilling industry should be completed in FY00.

## PROJECT OBJECTIVES

The Expert System or CMS, currently under development at Sandia, is a computer-based software system for analyzing drill rig data in real time, reference Figure 1[3]. It will be useful for detecting, characterizing, and quantifying impending and occurring rig and wellbore problems such as lost circulation, gas/steam kicks, mud pump degradation, drill pipe and nozzle washouts and stuck drill pipe. The heart of this expert CMS is a Bayesian network that analyzes incoming rig data and identifies temporal changes in conditions. The most likely causes of these changes are identified, and their implications are assessed. The driller is then notified of significant changes through the rig floor monitor. The CMS also provides the potential to offer the driller access to on line advice on how to deal with drilling problems.

The RFM was developed to accurately measure the outflow rate of geothermal well return line drilling fluids in a partially filled pipe. The quantitative RFM responds quicker and is more sensitive to changes in return fluid flow rates than the current industry-standard qualitative paddle meter outflow measurement instrument. Comparing real time inflow and outflow rates, while drilling, provides the fast response to delta flow (outflow minus inflow) needed to promptly detect and treat lost circulation.

*Technical Objectives*

- Reduce geothermal drilling costs by making more informed and timely decisions on lost circulation control.
- Develop state-of-the-art drill rig information management systems that integrate data acquisition hardware and analyses software such that advanced information sciences developed for other applications can be applied to drill rig functions (e.g. local area networks).
- Develop an expert CMS, operating procedures, and data acquisition algorithms for monitoring, recording, and analyzing drilling fluid inflow and outflow rates while drilling, for the purpose of identifying, characterizing, and accurately treating lost circulation zones.
- Demonstrate to industry how accurate inflow/outflow measurements and analysis can be used to reduce rig time and make drilling decisions that are more informed. Advise geothermal service and operating companies interested in using this technology on their drill rigs.
- Develop and document the RFM and demonstrate its usefulness in measuring drilling fluid outflow rates in both geothermal and oil and gas drilling. Develop procedures for the proper use of the RFM during drilling operations.

*Expected Outcomes*

- Reduced down time and costs associated with lost circulation are the expected outcomes of this work.
- With a rig rate of $300-500/hr and a single cement treatment (including rig time) costing over $10,000, small improvements in the efficiency of dealing with loss zones can have a significant effect on total well costs. For example, circulating to confirm a drilling fluid loss by monitoring mud pit levels, the standard industry practice, may require more than one hour of time for each loss zone. The CMS and RFM technology under development can detect fluid loss as soon as it occurs.
- The CMS, when carried through to its ultimate configuration, will provide drillers with real time assistance in detecting and analyzing fluid anomalies throughout the drilling process. This could substantially reduce the down time associated with the non-drilling parts of the process, thereby improving overall efficiencies and reducing well costs[4].

## APPROACH

Our research approach for this work has been to provide concept development, hardware design, procurement, and laboratory testing at Sandia, along with extensive field testing in cooperation with industry. This approach allows first-hand field-operation feedback from industry to be directly incorporated into hardware design. For example, by loaning RFMs to industry participants willing to test them, data about their performance under a wide variety of conditions have been obtained. This resulted in several of the suggestions from potential industry users being incorporated into the RFM design. In addition, other RFM modifications resulting from Sandia's direct experience during cooperative field-testing resulted in a robust user-friendly tool. It was recognized that a cost-effective approach to developing the CMS software would be to build on the Well Site Advisor (WSA) expert system, developed by Tracor Applied Sciences, Inc. The WSA is used to train drillers in gas kick control when drilling oil and gas wells. Development and evaluation testing of the CMS, which must use data from a large number of sensors to accurately diagnose drilling problems, focused on our cooperative field testing experience.

## RESEARCH RESULTS

A contract for Phase III of the CMS work was initiated with MARCONI (formally Tracor Applied Sciences, Inc.). The use of Bayesian networks to evaluate the circulation data was demonstrated. Laboratory testing of CMS operation at the Louisiana State University, in cooperation with GRI, was completed. Software changes to expedite interfacing the CMS with software from several industry mud logging companies was completed. Laboratory testing of the CMS using data from a geothermal drill rig was completed. Field testing of a prototype CMS began on an oil and gas well drilling operation.

In early FY99, Epoch Wellsite Services made an urgent request to use our RFM on a natural gas relief well they were mud logging near Bakersfield, CA. This well was being drilled in response to an earlier blowout and fire on a nearby wildcat well. Epoch was concerned about the rapid detection of gas kicks while drilling this relief well. Based on their prior experience with the RFM, Epoch believed that it was the only instrument capable of providing the level of accuracy and response to mud flow needed to quickly detect kicks and minimize the risk of a blowout on this critical second well. A conventional paddle meter was located downstream of the RFM to provide redundancy and the opportunity to compare the two meters during the drilling operations. Several small kicks, not obvious on the paddle meter data, were detected with the RFM. These kicks were successfully circulated out of the well. This rapid detection of small kicks also indicated when the mud density needed to be adjusted in order to maintain control of the well. Data from this operation will also be used during evaluation tests of the CMS.

Although the RFM was designed to detect lost circulation while drilling geothermal wells, it also performed as expected in detecting gas kicks during this drilling operation. Consequently, its use has been requested on two additional oil and gas wells being drilled in this same field. Ongoing efforts to transfer the RFM technology to industry have resulted in several contacts being initiated between potential industry suppliers and RFM users. We worked with industry to develop a "smart" RFM that will eliminate the need for external software used to convert the non-linear RFM output signal to a linear flow rate. This modified RFM will not only provide a linear output signal for flow but can respond to changes in flow calibration as a result of changes in return line pipe angle. The "smart" RFM will then be evaluated during CMS field tests on offshore oil and gas drill rigs in cooperation with MARCONI and Petron Industries, Inc.

## FUTURE PLANS

Our plans are to continue to investigate, develop, and through cooperative field testing evaluate this technology to improve lost circulation detection. We will continue to develop the CMS as a tool for use with future Advanced Drilling Technology applications. We will work with industry to transfer the RFM technology to reduce costs and improve the safety of geothermal and oil and gas well drilling. Initial work on this combined project should be completed in FY00.

A spin-off of the CMS is the available database to document loss zones as they occur during drilling. This data base could be modified to include real time data entry of lost circulation treatment techniques used and the results of the treatment. Our CMS development contract with MARCONI, will expire in FY00, and continuing work in this area will be competitively bid. This unknown contract situation and the loss of funds in FY99 have resulted in a reduction in work requirements for this project. However, we are planning on making the CMS software available to the geothermal industry at the end of FY00 on an as is basis.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Epoch Wellsite Services, Inc. | CMS and "smart" RFM evaluation and RFM technology application/use |
| MARCONI | CMS and "smart" RFM development, testing, fabrication and marketing |
| Petron Industries, Inc. | CMS and "smart" RFM testing and evaluation |
| Tecton Geologic, Inc. | RFM procurement and technology application/use |
| International Logging Overseas, Ltd. | RFM procurement and technology application/use |
| Drill Cool Systems, Inc. | RFM fabrication and marketing |
| Engineering Spectrum, Inc. | RFM fabrication and marketing |

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## CONTACTS

George E. Staller
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-9328, Fax (505) 844-3952
e-mail: gestall@sandia.gov

Arthur J. Mansure,
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-9315, Fax (505) 844-3952
e-mail: ajmansu@sandia.gov

Gary L. Whitlow
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-5755, Fax (505) 844-3952
e-mail: glwhitl@sandia.gov

Michael R. Prairie
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823, Fax (505) 844-3952
e-mail: mrprair@sandia.gov

Raymond J. LaSala
Office of Geothermal & Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
e-mail: Raymond.LaSala@ee.doe.gov

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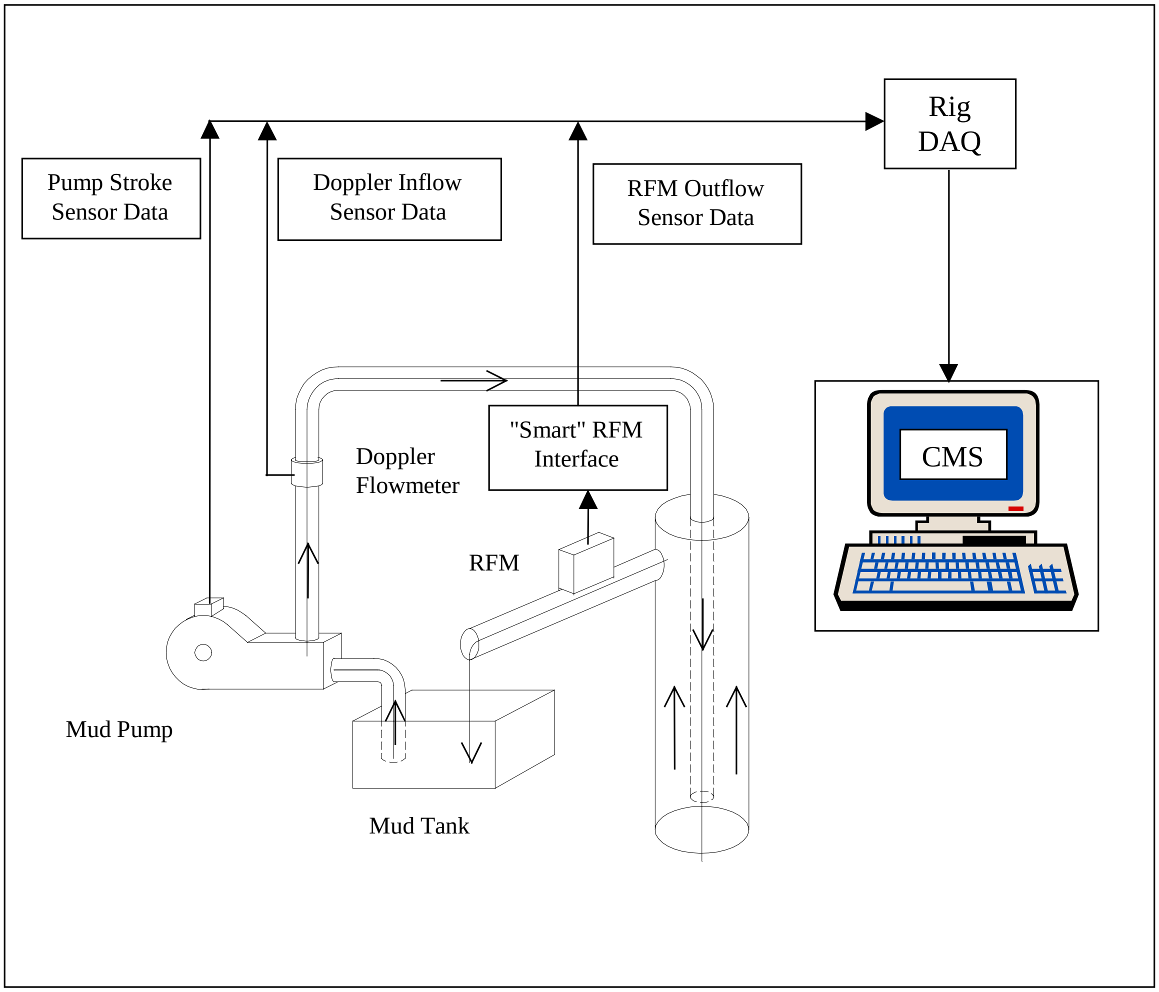


**Figure 1.** CMS Diagram.

# ACOUSTIC MEASUREMENT-WHILE-DRILLING SYSTEM

Douglas S. Drumheller and Steven D. Knudsen
Sandia National Laboratories

## KEY WORDS

measurement-while-drilling, MWD, acoustic telemetry

## PROJECT BACKGROUND AND STATUS

Collection of navigation data at the drill bit and transmission to the surface is done in real time on virtually every offshore drilling rig in the world. A very limited amount of logging data is sometimes included in this transmission. This technology is called "Measurement-While-Drilling" or simply MWD. The communication of this information from the drill bit to the surface is achieved primarily by generating a coded sequence of pressure pulses in the mudflow. This method yields exceedingly slow data rates---about 3 bits of data per second. As an example of just how slow this is, it would take 2 days to transmit a one-second portion of a CD recording---such as the simple voice message “Hello world.” Moreover, even this slow rate is often not achievable. During under-balanced drilling when nitrogen is injected into the well and during drilling with oil based mud, the communication link is usually lost.

Our initial goal is to improve this data rate and provide a more robust communications technology capable of working in a wider range of applications. We have concentrated on wireless telemetry by means of stress waves that propagate within the steel tubular components themselves. Our estimate of data rates versus range for the various tools we are developing is shown in Figure 1.

Retrieving data from and sending control signals to downhole instruments is necessary if major advancements in geothermal drilling and well technology are to be achieved. Improving the downhole data link will reduce geothermal drilling and other well costs by improving the efficiency and effectiveness of wellbore operations. The potential impact of this technology also extends beyond drilling applications to the area of production. A significant portion of geothermal energy is produced with line-shaft pumps. Our technology offers a potential improvement to the design of these pumps.

Earlier, we developed a downhole tool to acquire, store, and transmit temperature and pressure data to the surface via acoustic signals traveling through oil-well production tubing. It is a battery-powered device designed to eliminate the troublesome wiring used in conventional downhole production data transmission. In FY97, in cooperation with Baker Oil Tools, we tested this prototype downhole tool in a 2500-ft well (Figure 2). Our measurements of signal strength at the surface indicated that the device was capable of transmitting data from at least the bottom of 10,000-ft well. A second test in FY98 confirmed the success of the tool, where it also survived a short interval of drilling for which it was not originally designed. These successful field tests convinced Baker to license the technology from Sandia.

Although the Baker tool was designed for use in oil wells, the project has demonstrated significant applicability to geothermal wells. This is particularly true with the advent of unshielded high-temperature electronics capable of surviving the geothermal environment for an indefinite period of time. While Sandia completed its mission of assisting Baker Oil Tools with commercialization of this technology in FY 99, the progress we made has obvious and direct applicability to geothermal MWD.

Based on the success of the wireless production monitoring field test, we are developing another communication tool for use in geothermal drilling operations. This new tool has been designed to meet Unocal’s stated need to measure annular fluid levels when drilling without returns in permeable, underbalanced geothermal production zones. Knowledge of changes in this fluid level during the penetration of the formation will provide the data necessary to quantify the permeability of the formation and thereby locate the production zones.

## PROJECT OBJECTIVES

The objective of this project is to produce a telemetry system capable of transmitting data from drill bit to surface via sound waves through the drill pipe. The system will be used for geothermal drilling and must therefore withstand the harsh conditions encountered within the geothermal reservoir.

### *Technical Objectives*

- Develop a prototype telemetry system for geothermal drilling
- Data Rate: 30 baud with data compression
- Range: 8,000 - 10,000 ft
- Temperature: Use at 200°C, survives at 300°C

### *Expected Outcomes*

- Our goal is a 5% reduction of well costs as a result of application of acoustic telemetry technology.
- A commercially available measurement-while-drilling system for geothermal drilling.
- The system will be used initially for pressure-while-drilling measurements to help the geothermal driller characterize formation permeability and locate the production zone. This information will be useful for better determination of the optimum time to complete drilling.
- Acoustic MWD will enable the development and use of new downhole bits, tools and sensors. The complete system will have greater potential to reduce the cost of geothermal drilling and logging. Logging alone can account for up to 18% of drilling time.

## APPROACH

Critical components of the system have been designed and competitive manufacturing contracts have been initiated with industry. The components will be laboratory tested and then prepared for field verification in FY00 at Sandia's ORPHEUS test range.

## RESEARCH RESULTS

We have calculated the power requirements necessary for a successful downhole acoustic device, which is capable of generating a signal that can overcome the anticipated signal attenuation through drill pipe. We have also finished the design of the mechanical packaging and have begun assembly of the system. The acoustic transducers are completed (Figure 3). They represent the basic embodiments of two new patents. The Phase I version of the downhole power amplifier is completed. We have also identified all of the system components necessary to the operation of the prototype in a 200°C environment and to survive 300°C.

## FUTURE PLANS

The design of the logic systems and power amplifier will be completed in FY00. These components as well as the mechanical packaging will be assembled and tested at our surface facility. The surface data acquisition system will also be developed. The completed prototype system will be ready for fielding with a geothermal operator in FY 01.

## INDUSTRY INTEREST

| Organization | Type and Extent of Interest |
|---|---|
| Baker Oil Tools | Wireless Production Monitor |
| ABB | Acoustic Drilling Telemetry System |
| Ryan Energy | Acoustic Drilling Telemetry System |
| Unocal | Pressure-while-Drilling System |
| EDO Corporation | Manufactures piezoelectric transmitters |
| North Star Research | Manufactures the power amplifiers |

## RECENT PATENTS RESULTING FROM THIS WORK

In addition to 7 existing patents:

US Patent Accepted, D.S. Drumheller, An Improved Acoustic Transducer
US Patent Accepted, D.S. Drumheller, Extension Method of Drillstring Component Assembly

## CONTACTS

Douglas S. Drumheller
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-8920, Fax (505) 844-3952
dsdrumh@sandia.gov

Michael R. Prairie
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823, Fax (505) 844-3952
mrprair@sandia.gov

Raymond J. LaSala
Office of Geothermal & Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
Raymond.LaSala@ee.doe.gov

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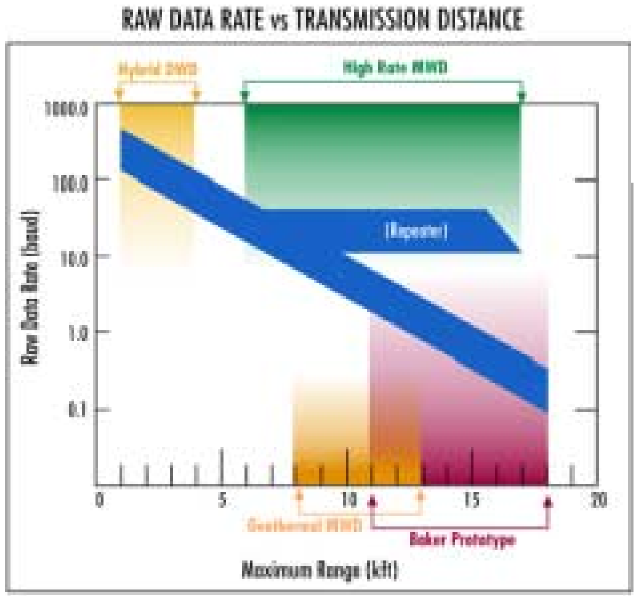


**Figure 1.** Raw data rate as a function of telemetry range for acoustic, and acoustic/hybrid drillstring telemetry systems.

**Figure 2.** The Baker prototype with its cover removed showing batteries, microprocessor, coil and ceramic transducer.

**Figure 3.** A piezoelectric transmitter for acoustic MWD.

# DIAGNOSTICS-WHILE-DRILLING

John T. Finger
Sandia National Laboratories

## KEWORDS

drilling data telemetry, high-speed telemetry, diagnostics-while-drilling, logging-while-drilling, rate of penetration, drilling cost

## PROJECT BACKGROUND AND STATUS

Drilling is an essential, ubiquitous, and expensive part of the oil, gas, geothermal, minerals, water-well, and mining industries. Research targets to make the drilling process cheaper and more effective are not obvious, because its technology is very mature. This project is devoted to a new technology that will improve drilling in two ways: 1) It will reduce the cost of conventional drilling, where “conventional” includes even high-risk, high-cost operations such as off-shore horizontal drilling; and/or 2) It will provide beneficial new capabilities that did not exist before, regardless of cost.

Because the industry’s breadth of activity is so large, reducing drilling expenditure by even a small fraction pays off with many dollars saved. Cost reduction can take many forms – faster drilling rates, increased bit or tool life, less trouble (twist-offs, stuck pipe, etc.), increased production per well through multi-lateral completions, and others – but the key to each of these improvements is better knowledge at the surface, in real time, of what is happening downhole. A new way to gain that knowledge – called Diagnostics-While-Drilling (DWD) – is the focus of this project.

As shown in Figure 1, the central concept of DWD is a closed information loop, carrying data uphole and control signals downhole, between the driller and the tools at the bottom of the hole. Up-coming data will give a real-time report on drilling conditions, bit and tool performance, and imminent problems. The driller can use this information either to change surface parameters (e.g., weight-on-bit, rotary speed, mud flow rate) with immediate knowledge of their effect, or to return control signals to active downhole components.

The principal technical challenge in the DWD system is the high-speed data link. To minimize downhole signal processing, the data link should have a minimum transmission rate of 100 kbits/sec, which is four orders of magnitude above the data rate of mud-pulse telemetry used in conventional MWD systems.

DWD is a new initiative that was kicked off in FY99.

## PROJECT OBJECTIVES

DWD has a potential for ***reducing geothermal well costs*** by at least 25% through the following effects:

- Improved penetration rates, resulting in more footage per day, or less cost per foot;
- Increased bit life, resulting in fewer trips and bit purchases; doubling penetration rates and bit life would reduce geothermal well costs by about 15%;
- Reduced tool failures through the ability to closely monitor downhole tools and detect incipient problems before they occur; this would reduce the number of trips and service/repair costs, saving at least 5% of the costs of an average geothermal well;

- Reduced hole problems through the ability to closely monitor hole conditions and diagnose events such as lost circulation and gas or steam kicks; this could eliminate problems such as stuck pipe and easily reduce average well costs by 10%; and

- Reduced completion costs, resulting from an improved ability to construct multi-leg completions in geothermal wells; this would reduce casing and cement costs, thereby reducing overall well costs in a given geothermal field by another 5-10%.

*Reducing the number of dry wells drilled* by 25% would result from the following developments due to DWD:

- Improved resource detection and real-time drilling course correction to re-drill sections of dry holes and turn them into producers; and

- Fewer hole problems such as stuck pipe and permeability damage that can cause abandonment of a well.

*Increasing average well productivity* by at least 25% would result from the following capabilities made possible by DWD:

- Multi-leg completions, which could increase well productivity two- or three-fold; made possible by improved directional drilling capability and increased use of surface-controllable downhole tools;

- Improved resource detection and real-time drilling course correction to intercept the maximum resource possible; well productivity should roughly increase in proportion to the length of hole drilled through the productive reservoir rock; and

- Improved underbalanced drilling operations that prevent well permeability damage due to drilling mud and rock chips; made possible by real-time measurement and diagnosis of downhole flow conditions; several-fold improvements in well productivity are possible with properly controlled underbalanced drilling.

***Expected Outcomes***

Reaching the technical objectives goals set for DWD would reduce the cost of geothermal-produced electricity by 2-31%. The predicted cost reductions could provide geothermal power a significant competitive advantage in locations where it is currently marginal.

## APPROACH

Most of the effort in FY99 was devoted to preparing a detailed plan for the DWD program and establishing contacts with industry. A cost model that predicts the cost of electricity (COE) was developed and exercised over the range of conditions found for geothermal plants in flashed-steam, binary, and enhanced-reservoir (e.g., Hot Dry Rock) applications. The model was used to explore the potential of DWD to influence geothermal COE. The model includes two major cost components:

- Debt servicing of capital costs, including well costs, plant costs, and other non-well costs, over 30 years at 13% interest rate; and

- Operating and maintenance (O&M) costs.

The model was run for flashed-steam, binary, and enhanced-reservoir geothermal fields. Well depths ranging from “shallow” at 2,000 ft to “ultra-deep” at 15,000 ft were considered. Well productivity ranging from 3 to 10 MW/well was assumed. A 25% dry well rate was also assumed, which means that for every four productive wells, one dry well was drilled. The calculations were then repeated for a case in which DWD technology has been used to reduce well costs by 25%, reduce the dry well rate by 25%, and increase the average well productivity by 25%.

## RESEARCH RESULTS

The results shown in Figure 2 indicate that reaching the goals set for the DWD system would reduce the cost of geothermal-produced electricity by 2-31%, depending on the depth, productivity, and type of geothermal field. In general, the deeper and less productive a given geothermal resource, the greater the potential benefit of DWD. For instance, if a high-temperature geothermal reservoir exists at 6,000 ft below the surface and is relatively “tight” so that well productivity is limited to only 3 MW/well, the model predicts the COE to be about 4.9 cents/kwh. This may not be economically competitive if power can be generated in that location for 4.5 cents/kwh with natural gas. With the cost savings promised by DWD, however, the geothermal COE could be reduced by nearly 20%, to 4.0 cents/kwh. Thus DWD could make the difference in getting geothermal selected as the energy source of choice. This is particularly true for deeper, less productive geothermal reservoirs.

Such a reduction in the cost of electricity would give geothermal power a competitive edge over other types of power at many locations across the U.S. and around the world. It is thus believed that DWD technology could significantly expand the role of geothermal energy in providing efficient, environment-friendly electric generating capacity.

Fourteen companies (operators and service companies), DOE Geothermal, DOE Fossil Energy, the Drilling Engineering Association, and the University of Oklahoma received one-on-one briefings about the program and have provided feedback to guide our efforts. Industry is very supportive and has volunteered approximately 300 person-hrs of support in FY00 to help guide and focus the program

## FUTURE PLANS

During FY00, Sandia in cooperation with industry will assemble a prototype closed-loop DWD system. This prototype will be used to demonstrate the value of DWD and study the issues of how to make DWD practical.

The capability for installing a hardwire high-speed data link that would provide the data transmission rate of interest exists today and can be installed on any rig for a price. This price has generally been too high for routine drilling because the benefits of such a system have not been demonstrated. Thus, the first step of developing a DWD system must be a convincing demonstration of the need and utility of such a system.

A technical advisory committee (TAC) from the oil & gas, drilling service, and geothermal industries will be assembled to advise Sandia on technical aspects of the DWD program. The TAC is needed to 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 and assure that technology developed by the DOE-Geothermal program will be adopted by industry.

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

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The geothermal and hydrocarbon industries are inextricably linked in their quest to reduce drilling cost. Historically, drilling cost per foot tracks the price of oil very closely because high oil prices encourage more drilling, and market forces drive up drill rig rates. Paradoxically, then, when oil prices go up, geothermal energy becomes more competitive, but drilling for it becomes more expensive because drill rigs cost more. We have tried to accommodate this linkage by involving both industries – and both the Fossil Energy and Renewable Energy Technology offices in DOE – in planning and implementing DWD development.

Even though geothermal energy is already a substantial contributor to domestic supply (the U. S. geothermal industry is the world's largest), it is a niche market and will remain so even if the goals in DOE's Strategic Plan are met. As such, the geothermal industry alone cannot support a development program of this size, and without this aggressive approach to lower costs, especially for deeper drilling, geothermal energy will not increase its penetration of the world's growing electricity market.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Arco E&P Technology | Member of TAC |
| Chevron Petroleum Tech | Member of TAC |
| Conoco, Inc | Member of TAC |
| Diamond Offshore Drilling | Member of TAC |
| Exxon Upstream Development Co | Member of TAC |
| GeoThermex | Member of TAC |
| Marathon Oil Co | Member of TAC |
| Maurer Engineering | Member of TAC |
| Mobil E&P | Member of TAC |
| Schlumberger | Member of TAC |
| Scientific Drilling | Member of TAC |
| Technology International | Member of TAC |
| ThermalSource, Inc | Member of TAC |
| Texaco Upstream Technology | Member of TAC |
| University of Oklahoma | Member of TAC |
| Unocal Corporation | Member of TAC |

## PUBLICATIONS

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

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## CONTACTS

John T. Finger
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-8089, Fax (505) 844-3952
jtfinge@sandia.gov

Michael R. Prairie
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823, Fax (505) 844-3952
mrprair@sandia.gov

Arthur J. Mansure
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-9315, Fax (505) 844-3952
ajmansu@sandia.gov

Raymond J. LaSala
Office of Geothermal & Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
Raymond.LaSala@ee.doe.gov

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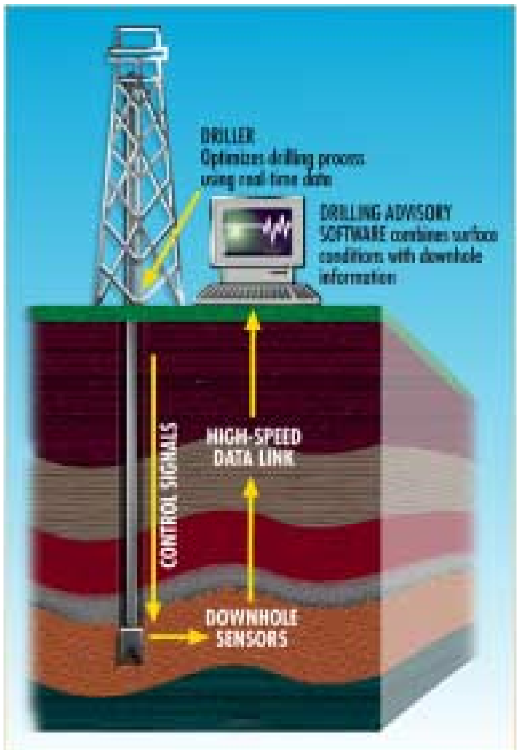


**Figure 1.** Schematic representation of the Diagnostics-While-Drilling System.

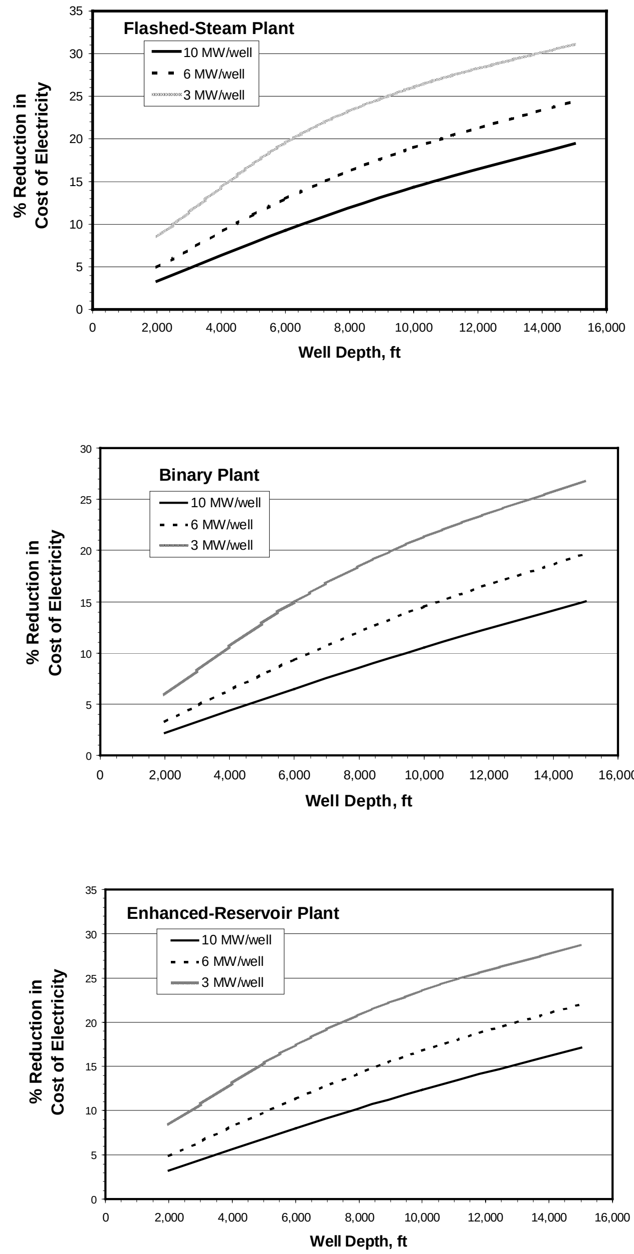


**Figure 2**. % Reduction in the Cost of Electricity for 50-MW flashed-steam, binary, and enhanced-reservoir geothermal power plants, assuming a 25% reduction in Well Costs, a 25% reduction in the Dry Well Rate, and a 25% increase in Average Well Productivity.

# SELF-INDUCED PDC BIT VIBRATIONS

David W. Raymond and Jack L. Wise
Sandia National Laboratories

## KEY WORDS

bit dynamics, chatter, drilling, drillstring vibrations, hard-rock drilling, polycrystalline diamond compact (PDC) cutters, PDC bits, self-induced vibrations

## PROJECT BACKGROUND AND STATUS

Polycrystalline diamond compact (PDC) bits have performed well in the petroleum industry where soft to medium-hard rock types are encountered. However, these bits often fail in the presence of hard-rock stringers. Contrary to this field experience, PDC bits have exhibited reasonable life in laboratory-based wear testing in hard rock. Further, polycrystalline diamond has been used reliably for cutting operations in the consumer rock-processing industry. Nevertheless, PDC bits have yet to be routinely applied to drilling the hard-rock formations characteristic of geothermal reservoirs. The prevailing mode of failure encountered by PDC bits returning from hard-rock formations in the field is catastrophic. Failures range from chipping and delamination of the diamond table to catastrophic failure of the carbide support. These types of failures are generally attributed to impact or cyclic loading mechanisms and usually occur in advance of any appreciable wear that might dictate cutter replacement. Self-induced bit vibration, or "chatter", is one of the mechanisms that may be responsible for impact-type damage to PDC cutters during hard-rock drilling.

Chatter is a phenomenon whereby the drillstring becomes dynamically unstable and excessive sustained vibrations occur. Chatter is more severe in hard-rock formations because they induce greater dynamic loading on the cutter elements. Excessive chatter may cause cutter damage leading to premature bit failure. The vibration environment can also damage components in the bottom hole assembly and the tool joints throughout the drillstring. If chatter can be effectively mitigated, PDCs could be employed in drilling hard rock.

PDC bits have a more aggressive cutting structure than the roller cone bits currently used in most geothermal drilling. The capacity for increased penetration rates could result in significant cost savings. Increased bit life would result in further cost-saving benefits, which could also be extended to the petroleum industry. If PDC bits could be used to double penetration rates and bit life, geothermal well-drilling costs could be reduced by 15 percent or more.

Many of the chatter principles derived in the machine tool industry are applicable to drilling. However, it is a simple matter to make changes to a machine tool to study chatter effects. This is not the case with rotary drilling. Hence, laboratory simulation is necessary to research the mechanisms contributing to chatter.

This project started in FY97 and is currently on schedule with all annual milestones satisfied since initiation. The project has work scoped for the next five years, with incremental improvements to be realized and expanded upon each year to deliver chatter mitigation technology to the field.

## PROJECT OBJECTIVES

The fundamental objective of this project is to research the mechanisms that contribute to self-induced PDC bit vibrations. This involves characterizing the relationships between rock properties, PDC bit design features, and drillstring stiffness and mass properties and their influence on bit vibrations. Additional relationships must be established between the steering parameters in the drilling process (e.g., weight on bit, rotary speed) and the degree of chatter in the system.

***Technical Objectives***

- Demonstrate chatter is a cause of impact-type failures in PDC bits.
- Investigate influence of chatter on penetration rate and bit life.
- Investigate effect of bit vibration and shock loading on cutter integrity.
- Demonstrate chatter can be suppressed through engineering controls and methods.
- Develop means to reduce undesirable effects of chatter via hardware and software development.

***Expected Outcomes***

- Extend PDC bits to geothermal drilling.
- Predictive models for chatter as a function of rock type, bit design, drillstring configuration and steering parameters.
- Improved understanding of methods to reduce effects of chatter.
- Increased PDC bit life.
- Improved penetration rates.
- Downhole hardware development to suppress chatter.
- Algorithm to control drilling process to mitigate chatter.

## APPROACH

To directly observe the effects of chatter, the Hard-Rock Drilling Facility (HRDF) at Sandia was modified with the addition of springs, as shown in Figure 1, to allow the axial compliance of field drillstrings to be simulated. Torsional compliance, also inherent in field drillstrings and of particular concern considering that PDC bits "plow" the formation, was eliminated in this first phase for simplicity. Torsional compliance will be addressed in FY2000.

To be representative of field-drilling conditions, the range of parameters used in the experimental setup must reflect conditions that a drillstring equipped with a PDC bit might typically experience. Weight on bit (WOB), rotary speed, and the fundamental vibration modes of the drillstring are important parameters in the experimental design. The penetrating forces and surface speeds for the cutters on the test bit should be characteristic of what cutters experience in the field in comparable formations. The experimental setup is designed to make the fundamental frequencies of the test fixture as low as possible to simulate field drilling. Using this approach, chatter effects observed at the natural frequency of the test setup are representative of the system characteristics at frequencies which may be encountered in the field.

Testing was conducted in Berea Sandstone, a soft formation, and Sierra White Granite, a hard rock representative of geothermal formations, to determine the conditions under which chatter originates. The tests involved drilling a series of holes at constant WOB and constant rotary speed while recording drilling parameters for post-test analysis. The peak-to-peak vibration of the drillstring was monitored by a displacement transducer. Drilling tests were conducted over a range of WOB values and rotary speeds to simulate a variety of conditions.

Sandia has contracted with the University of Louisiana at Lafayette on this project. Professor Mike Elsayed has participated in chatter test design and data acquisition each summer at Sandia since 1997.

## RESEARCH RESULTS

Modal testing of the modified HRDF was conducted to characterize the frequency response of the drillstring and its compliant support. As planned in our experimental design, the fundamental mode corresponds to axial translation of the drillstring at approximately 6 Hz. However, subsequent higher frequency modes at approximately 10, 12 and 16 Hz are associated with several "rocking" modes in the stiffened beam supporting the drillstring. These rocking modes can also result in axial translation of the drillstring as the center of rotation often occurs at either end of the stiffened beam. This multi-mode system allowed observation of the effects of closely-spaced modal frequencies that are also characteristic of field drillstrings. The center position displacement transducer (CPDT) on the drillstring centerline provides a response that is a direct measure of vibration amplitude at the bit. This was used in the analysis to discern the position of the bit in relationship to the rock.

Figure 2 shows vibration of the bit about its average position as the bit advances into the rock. This figure represents one WOB and rotary speed condition that was evaluated. One measure of chatter severity is the difference between the bit's peak-to-peak vibration and its depth-of-cut per revolution. This parameter, the "out-of-cut distance," is shown in Figure 3 for sandstone. This plot shows the relative amplitude of vibration at various WOB and rotary speed combinations. When the parameter is negative, the bit remains in the cut. Conversely, when the parameter is positive, the bit bounces above the free-rock surface. The power spectral density for the data presented has the same general character suggesting that the out-of-cut parameter is indicative of the vibration energy resident in each of the operating conditions across the measurement range.

The data show that severe chatter occurs in sandstone. This implies that chatter can play a significant role in oil and gas drilling. However, no damage to the PDC cutters was observed throughout the sandstone testing. In accordance with the theory of chatter applied in the machine tool industry, the tests show that there are pockets of stability (i.e., WOB and RPM pairs) for which the vibration level is reduced. Figure 3 shows that a given WOB has preferential rotary speeds for the drilling configuration represented. However, since stability is dependent upon the dynamic characteristics of the drillstring, the stability for a drillstring in the field would change as drilling progresses. Further, although not apparent from the data displayed here, the rate of penetration decreases in the presence of significant chatter. This is intuitive as the bit penetrates the rock less when rising out of the cut during part of its rotation. As expected, increasing the WOB at a given rotary speed acts to decrease the chatter. However, even at higher WOB some rotary speeds are better than others. The zigzag nature of the higher WOB data shown in Figure 3 is due to the excitation of higher-frequency vibration modes at increased WOB.

Important to geothermal drilling, Sandia's testing in Sierra White Granite produced chatter with much higher impact loading that lead to PDC cutter damage and failure. In fact, the quantity of PDC cutter failures limited the progress of the testing. Figure 4a is a photo of a PDC cutter that drilled 96 ft at 30 ft/hr under stable, non-chatter operating conditions that resulted in initial stages of wear. Figure 4b shows a cutter that drilled one ft at 10 ft/hr in Sierra White Granite under chatter conditions, resulting in bulk failure of the diamond table and carbide support. These results validate chatter as a cause of impact-type cutter failures for drilling in hard-rock formations and underscore the potential of PDCs in geothermal drilling if they can be effectively employed. Controlling the level of chatter in the drillstring is crucial to using PDCs in geothermal drilling.

These results are significant to the drilling community. In a parallel project at Sandia, a high-speed telemetry link is under development to allow diagnostic drilling conditions to be monitored at the bit. The level of vibration measured at the surface is attenuated from the vibration actually occurring at depth. If accurate dynamic conditions are known downhole, drilling parameters could be modified at the rig using feedback control to reduce the chatter level at the bit and improve the drilling process.

Yet another approach is to reduce chatter using a downhole-controllable damper. Such a device would monitor the response of the bit and apply appropriate damping to reduce chatter, thereby reducing the impact loading of PDC cutters in hard-rock formations. Sandia will use results from the chatter research to develop design requirements for such a damper. The approach will be tested in the HRDF. A prototype damper will eventually be transferred to industry and available to mitigate chatter.

Results from the chatter testing are of additional interest to the diamond products development industry. The HRDF can be used to characterize the shock and vibration environment that PDC cutters must endure under typical drilling conditions. This information may be used to develop advanced cutters that are capable of surviving chatter in the hard-rock formations characteristic of geothermal drilling.

## FUTURE PLANS

In FY2000, torsional compliance will be added to HRDF and the chatter testing will be repeated. This will allow coupling interdependencies between axial and torsional vibration to be investigated. It will allow the more common type of PDC cutter failures to be observed that occur due to backward rotation of the drillstring. Controllable dampers will also be added to the HRDF in FY2000, along the axial direction, to demonstrate that chatter can be reduced with damping. Torsional dampers will be added in FY2001. Eventually, the cutter layout on the HRDF test bit will be modified to observe the influence of bit design on chatter.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Technology International, Inc. | Fracture-resistant cutter development |
| US Synthetic | " " |

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## CONTACTS

David W. Raymond, P.E.
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-8026 FAX (505) 844-3952
e-mail: dwraymo@sandia.gov

Mike Elsayed, Ph.D., P.E.
University of Louisiana at Lafayette
Mechanical Engineering Department
P.O. Box 44170
Lafayette, LA 70504-4170
(318) 482-5363, FAX (318) 262-5472
email: melsayed@usl.edu

Jack L. Wise, Ph.D.
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-6359, FAX (505) 844-3952
e-mail: jlwise@sandia.gov

Raymond J. LaSala
Office of Geothermal & Wind Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, FAX (202) 586-8185
e-mail: Raymond.LaSala@ee.doe.gov

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

**Figure 1.** Sandia's Hard-Rock Drilling Facility Modified to Include Axial Compliance.

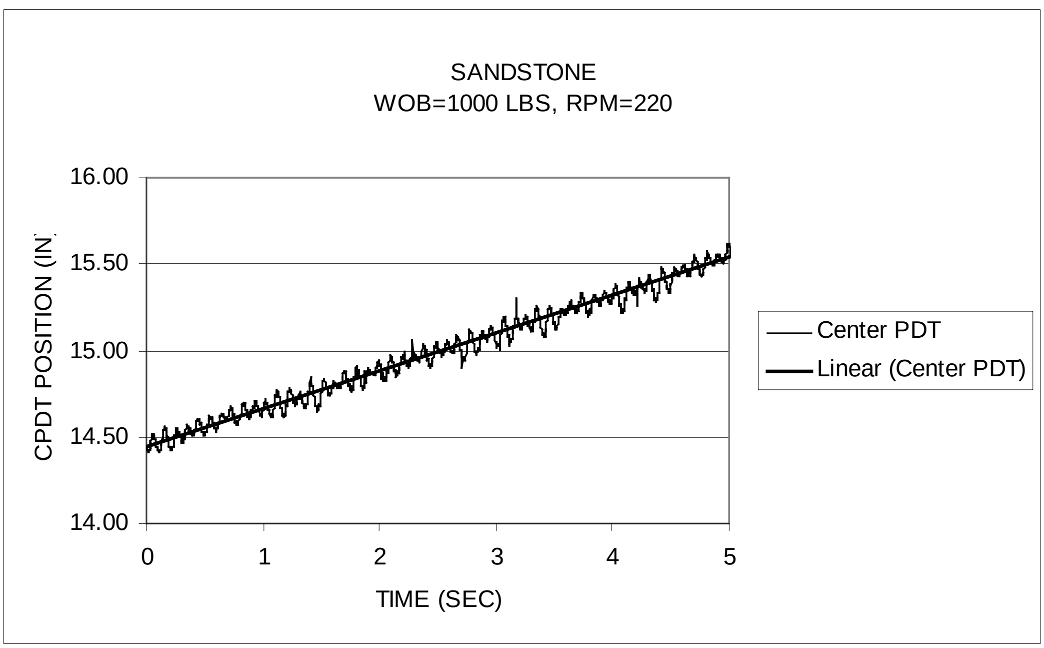


**Figure 2.** Bit Response for Drilling in Sandstone, 1000 lb. WOB, 220 RPM.

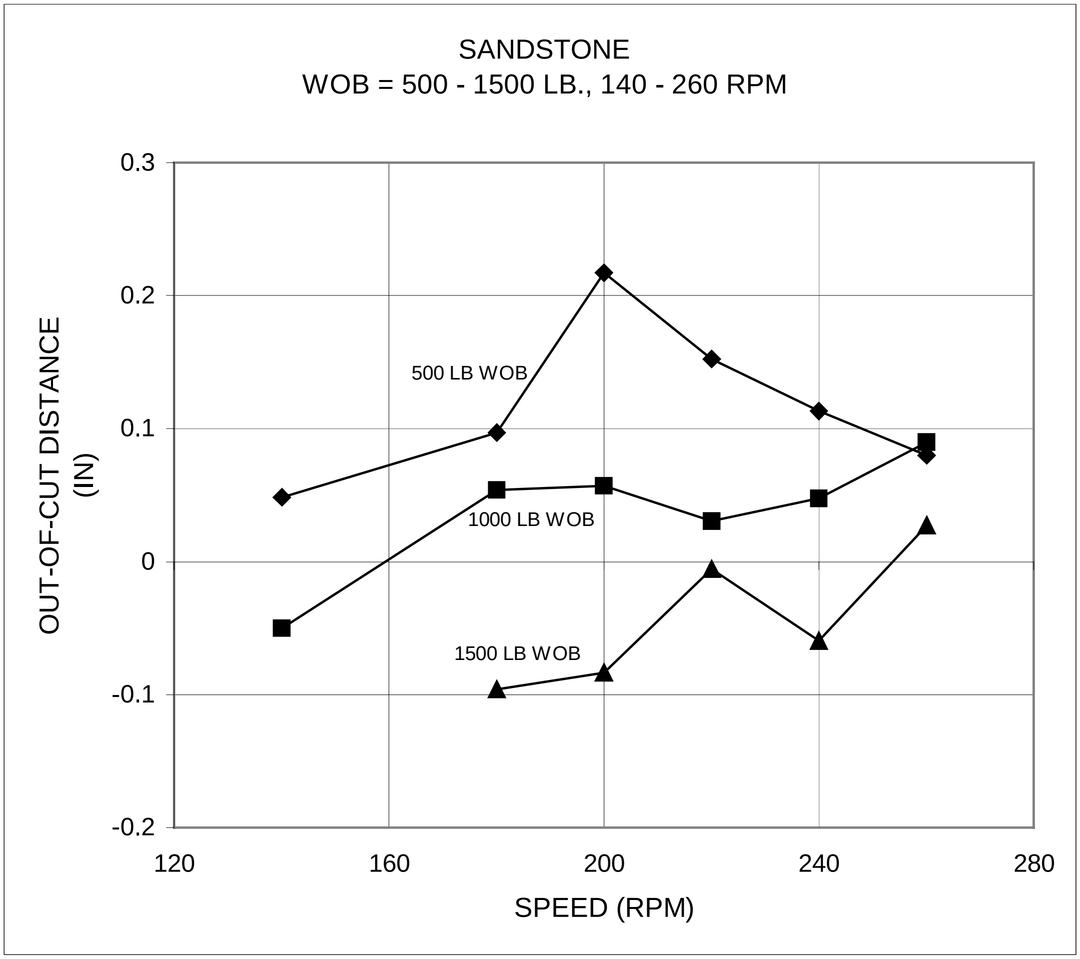


**Figure 3.** Bit Vibration Measurements from Drilling Tests in Berea Sandstone.

Figure 4a. Lightly-worn PDC at Stable Drilling Condition (96 ft of Sierra White Granite at 30 ft/hr, 2000 lb. WOB and 100 RPM).

Figure 4b. Failed PDC cutter in chatter conditions (1 ft of Sierra White Granite at 10 ft/hr, 1500 lb. WOB and 140 RPM).

# DRILL-BIT TECHNOLOGY ASSESSMENT

Jack L. Wise and David W. Raymond
Sandia National Laboratories

## KEY WORDS

synthetic-diamond bits, polycrystalline diamond compact (PDC) cutters, thermally stable polycrystalline (TSP) diamond cutters, hard-rock drilling, geothermal drilling, single-cutter testing, cutter wear testing, drillable straddle packer, bit stabilizers

## PROJECT BACKGROUND AND STATUS

Drilling operations provide access to geothermal energy reserves. If the life and penetration rate of bits used in geothermal drilling could both be doubled, a 15% reduction in geothermal well costs would result. Advances in synthetic-diamond bit technology can potentially yield such improvements. Sandia played a key role in the initial development of polycrystalline diamond compact (PDC) drag bits during the 1970s and early 1980s, with landmark work documented in more than thirty reports and articles. This work, including Sandia-sponsored bit demonstrations, first showed the utility of drag bits in formations of *medium* hardness. Millions of dollars in drillings costs are now saved annually through the use of PDC bits, which presently account for about one-third of worldwide bit sales. The savings in drilling costs for a single PDC bit run often exceed $100,000 in boreholes with appropriate lithology.

Sandia renewed its bit-development program in 1992[1,2] to address the persistent, unfulfilled need for drag bits suitable for a *hard*-rock environment. A large number of companies were contacted and a comprehensive program proposal for synthetic-diamond drill bit technology development was written. This proposal was presented to the Drilling Engineering Association (DEA) for evaluation in February 1993. After favorable review, the DOE Office of Fossil Energy approved funding for the program under the Natural Gas and Oil Technology Partnership (NGOTP). This funding was received in August 1993. Joint-work, cost-shared contracts were placed with multiple companies, and the program began at the end of October 1993. Additional funding came from the DOE Office of Geothermal Technologies in FY94. Overall funding for the program was shared equally by industry, DOE Fossil Energy, and DOE Geothermal in FY95. The NGOTP funding was depleted in FY95, but support by DOE Geothermal has continued because of the importance of Sandia's bit-development program to realizing DOE's vision of making geothermal energy the preferred worldwide alternative to polluting energy sources by the year 2010.

Sandia's *Hard-Rock Drill Bit Technology Program* features an ongoing project that focuses on drill-bit technology assessment. This project, which is summarized in the present update, involves multiple development and testing activities to appraise various innovative drilling hardware designs and materials. Funding for this project has been allocated through FY00, with scheduled milestone completion dates in the FY00 to FY01 time frame and beyond.

## PROJECT OBJECTIVES

The overriding goal of Sandia's bit-technology work is to dramatically expand the range of applications for drag bits by developing capabilities to effectively penetrate the hot, hard, abrasive, and fractured formations that are predominant at geothermal energy production sites and in difficult oil and gas drilling environments. Such conditions exceed the performance limits of existing synthetic-diamond drag bit technology. However, the inherent cutting efficiency and lack of moving parts of drag bits make them a very promising prospect for future increases in penetration rate and bit life in hard formations. Not surprisingly, PDC bits already hold the all-time records for single-run footage, cumulative footage by a single bit, and penetration rate.

Sandia's drill-bit technology assessment project aims to generate and qualify improved drilling hardware via cooperative national-laboratory/industry efforts. The specific objectives of this project change from year to year, evolving in response to the needs and interests expressed by industry and/or university partners. The most current objectives and expected results are summarized below.

***Technical Objectives***

- Design, fabricate, and demonstrate an instrumented PDC bit for laboratory testing of drag cutters in Sandia's Hard-Rock Drilling Facility (HRDF). Demonstrate the real-time acquisition of dynamic data characterizing the drag and penetration force components acting on a test cutter during hard-rock drilling in the laboratory. Use this data to relate wearflat growth to cutter forces, ultimately allowing development of improved models for bit performance.

- Design, fabricate, and test an instrumented coupling spool for HRDF bits. Demonstrate the real-time acquisition of dynamic data characterizing the weight on bit (WOB) and torque acting on a bit during hard-rock drilling in the laboratory. Deconvolute this data in conjunction with measurements from the instrumented bit to estimate the contributions of the gage cutters to the net force and torque on the bit.

- Conduct a series of HRDF tests in conjunction with Technology International, Inc., to determine the influence on cutter wearflat growth of one or more holes that are premachined through the diamond table (*i.e*., cutter face) to, or through, the cutter substrate near the cutting edge.

- Drill a series of boreholes in hard rock to demonstrate the performance of the PDC cutter (GE 1308WB) currently used as a standard for HRDF testing.

- Support Sandia's DOE-funded development of a drillable straddle packer for lost-circulation control by using a rollercone bit in the HRDF to drill through packer assemblies that have been cemented into boreholes in rock.

- Work cooperatively with RA-TECH to evaluate a bit stabilization system (*i.e*., STA-BIT).

***Expected Outcomes***

- Cut well costs 15% by fostering new drag-bit technology that yields *twice* the life expectancy and rate of penetration (ROP) provided by existing bits used for hard-rock drilling in geothermal and other applications.

- Achieve significant improvements in drilling performance (*e.g.*, ROP), particularly in harder formations, by successfully demonstrating and commercializing a bit-stabilization system for drillstrings.

- Develop new cutter geometries that offer increased resistance to wear and impact damage, thereby prolonging bit life and reducing drilling costs.

- Validate new drilling hardware concepts, such as the drillable straddle packer, in preparation for full-scale field demonstrations and eventual commercial production of cost-saving devices.

## APPROACH

Various drill-bit companies, cutter manufacturers, and universities have teamed with Sandia National Laboratories on projects to advance the state of the art in drag-bit performance. These joint projects explore different approaches to cutter and bit design and build on the capabilities and current interests of the research partners. Sandia integrates the individual projects into a coherent program that benefits from synergy among the separate projects[3].

For the bit-technology assessment project, Sandia has developed and maintained analytical tools (*e.g.*, the PDCWEAR code[4]) and unique in-house experimental capabilities (*e.g.*, the Hard-Rock Drilling Facility, HRDF). Using these tools and capabilities, Sandia's experienced staff provides general consulting, analysis, and laboratory test services. When warranted, field tests are arranged in conjunction with an industry partner (*e.g.*, RA-TECH) for full-scale demonstration and appraisal of new drilling hardware and/or techniques.

Sandia personnel conduct cutter wear tests on the HRDF, which was referred to as the Cutter Wear Test Facility (CWTF) in earlier reports. This Sandia-developed facility comprises a laboratory-based drilling rig that is used to evaluate the performance of polycrystalline diamond cutter blanks under controlled, reproducible drilling conditions.

Research on PDC wear is accomplished in the HRDF by using a replaceable-cutter coring bit to drill multiple boreholes through a large (3-foot cube) rock sample to simulate deep penetrations in an actual hard-rock environment. By drilling a series of holes with a three-cutter bit equipped with “standard” cutters in the inner-gage, test, and outer-gage locations, the “baseline” cutter performance for the HRDF is established. Performance comparisons can then be accomplished by replacing the test cutter with the nonstandard product under study (*e.g.*, a prototype cutter supplied by Technology International), installing new gage cutters identical to those used for the baseline, and repeating the testing with the same operating conditions. This procedure allows newly developed cutter specimens to be evaluated with respect to the baseline and relative to each other.

The cutter wearflat and damage patterns are documented between boreholes using a high-resolution videomicroscope system, and image-processing software provides a quick, accurate measurement of the wearflat area. To complement the cutter wear data, an instrumented coring bit has recently been developed for the HRDF that dynamically monitors the drag and penetration forces on the test cutter during the drilling process.

Baseline cutter wear on the HRDF has been established using GE 2741-DTC (diamond table chamfer) PDC cutters manufactured by General Electric. To establish the baseline, the HRDF was operated at a constant rate of penetration of 30 feet per hour in Sierra White Granite (SWG) with a constant rotary speed of 100 rpm and water as a drilling fluid. Cutter wear was measured periodically during each series of boreholes.

## RESEARCH RESULTS

Continuing work on the bit-technology assessment project effectively supports product innovation efforts by industry. As noted in the previous section, this work includes the development of new laboratory test capabilities, the application of new and existing laboratory capabilities to prototype testing, and the implementation of full-scale field tests.

In FY99, a novel instrumented bit, which was designed and fabricated at Sandia, was demonstrated during HRDF testing. This 3-cutter coring bit, shown in Figure 1, has a split body that supports the center, or test, cutter on its own separate pedestal. The shaft of this pedestal is instrumented with strain gages whose signals are processed to determine the dynamic axial (*i.e*., penetration) load and drag load acting on the test cutter. This data can be correlated with measurements of wearflat area acquired during the same test to examine the interrelationship between cutter forces and wearflat growth. The instrumented bit has a cutter configuration that is identical to that of the standard solid-body bit typically used for most wear testing; consequently, force data from the instrumented bit can also be directly correlated with wearflat data from the solid-body bit when operating conditions are matched.

In order to dynamically monitor the net WOB and torque experienced by HRDF bits, an instrumented coupling spool for these bits was designed, and assembly of the spool and associated signal-processing equipment started during FY99. This spool, which will be demonstrated in FY00, will yield data that can be interpreted in conjunction with test-cutter force measurements from the instrumented bit to estimate the contributions of the individual gage and test cutters to the net force (WOB) and torque on the bit.

Sandia personnel used the HRDF during FY99 to conduct wear tests on specially modified PDC cutters that were supplied by Technology International, Inc. These tests examined the influence on cutter wearflat growth of one or more premachined holes (circular or triangular) in the vicinity of the cutting edge; the holes penetrated the diamond table and, in some cases, the cutter substrate. This set of experiments was prompted by earlier results at Sandia for which D.A. Glowka noted that a small hole through a cutter near the cutting edge (*e.g*., for thermocouple installation) seemed to correlate with a lower wearflat growth rate than that obtained for a cutter with no hole. This effect was confirmed in the present tests only for the case where a single small-diameter hole went through the diamond table and partially penetrated the tungsten-carbide substrate. In this case, the modified cutter exhibited a wearflat area after the first 3-foot borehole that was 33% smaller than the wearflat obtained for a cutter with no hole. Such improved performance relative to the unmodified cutter persisted as the cumulative number of boreholes for each cutter increased to twelve and beyond. However, consistent with intuition, the wearflat area for the remaining modified cutters after a given number of boreholes was higher than that for an unmodified cutter in approximate proportion to the amount of material removed from the vicinity of the cutting edge by the introduction of the premachined hole(s).

In other HRDF testing during FY99, the performance of a set of Sandia's current standard cutters (GE 1308WB) was examined by drilling an extended series of boreholes in hard rock (*i.e*., Sierra White Granite). These cutters were mounted in the standard laboratory coring bit, which was run at 100 rpm with a 30 ft/hr rate of penetration. Although all drilling was accomplished without the benefit of cutter rotation or maintenance, the test cutter and two gage cutters exhibited no significant damage and only moderate wear after generating about 100 feet of new hole. This achievement underscores the benefits derived from continuing developments in drag-bit and cutter technology.

The HRDF is not restricted to operations with the standard 3-cutter coring bits used for wear studies. To support the DOE-funded development by Sandia of a drillable straddle packer for lost-circulation control, the HRDF was equipped with a rollercone bit for several tests during FY99. In these tests, the rollercone bit was first used to produce boreholes in a sandstone block. Next, scaled packer assemblies were cemented into the boreholes, and were then successfully drilled out by the rollercone bit (see Figure 2). This result marks the fulfillment of an important milestone for Sandia's lost-circulation program and justifies planning for a full-scale field demonstration of a drillable straddle packer.

A mutual nondisclosure agreement was established between Sandia and RA-TECH during FY99 that will facilitate Sandia's evaluation of innovative drilling technology developments by RA-TECH. The proprietary 'STA-BIT' stabilization system is of primary interest. This design reportedly prevents bit whirl and chatter so as to maintain stable rotation and cutting under a wide range of speeds and weight-on-bit conditions, thereby increasing penetration rates in virtually all formations. RA-TECH is teaming with a drag-bit manufacturer, DOWDCO (Diamond Oil Well Drilling Company), for the purpose of a joint demonstration of stabilizer and bit performance. DOWDCO has prepared a proposal and cost estimate for conducting such a demonstration with Sandia's support and participation.

## FUTURE PLANS

Working in conjunction with its multiple industry and university partners, Sandia plans to continue a variety of research activities contributing to the advancement of synthetic-diamond bit technology for application to hard-rock drilling. Dynamic measurements of cutter force will be acquired with the instrumented bit, and complementary measurements of WOB and bit torque will be obtained simultaneously with a new instrumented spool that couples the bit to the drillstring. Data from the instrumented bit and spool will be analyzed to determine forces on the individual cutters. Correlations will be made between cutter wear and cutter forces. Additional work with Technology International, Inc., and its partners, including the Colorado School of Mines and the Jet Propulsion Laboratory, will examine novel techniques for enhancing the impact resistance of PDC and TSP cutters. The viability of these techniques will be assessed via bit chatter tests on the HRDF. A field demonstration of PDC bits used in conjunction with a stabilization system is being planned with RA-TECH and DOWDCO. As in the past, other project tasks will be added as appropriate to assess new developments in bit and cutter technology.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Technology International, Inc. | PDC and TSP cutter development and testing |
| Colorado School of Mines<br>Jet Propulsion Laboratory | |
| RA-TECH<br>DOWDCO | Stabilizer and PDC bit demonstration |

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## CONTACTS

Jack L. Wise, Ph.D.
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-6359; FAX (505) 844-3952
e-mail: jlwise@sandia.gov

Michael R. Prairie, Manager
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823; FAX (505) 844-3952
e-mail: mrprair@sandia.gov

David W. Raymond, P.E.
Geothermal Research Department
Sandia National Laboratories, MS 1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-8026, FAX (505) 844-3952
e-mail: dwraymo@sandia.gov

Raymond J. LaSala
Office of Geothermal and Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Avenue
Washington, DC 20585-0121
(202) 586-4198, FAX (202) 586-8185
e-mail: Raymond.LaSala@ee.doe.gov

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

**Figure 1.** Breakdown view of the HRDF instrumented bit. Note that the test cutter is mounted in the section of the bit body shown at the left side of the image.

**Figure 2.** Rollercone bit used in HRDF to remove drillable straddle packer from cemented borehole.

# GEOTHERMAL DRILLING ORGANIZATION

Allan R. Sattler
Sandia National Laboratories

## KEY WORDS

Geothermal Drilling Organization (GDO), drilling technology, cost sharing, joint DOE/industry ventures, industry partners

## PROJECT BACKGROUND AND STATUS

The Geothermal Drilling Organization (GDO), founded in 1982 as a joint DOE-industry organization, develops technology for near-term applications to geothermal drilling and well maintenance. Sandia National Laboratories administers DOE funds to assist industry critical cost-shared projects and provides development support for each project. GDO assistance to industry is vital for developing products and procedures to lower drilling and well maintenance costs because the Geothermal Industry is small and has limited resources for technology improvement.

The types of projects usually considered by this organization 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. These projects often stem from R&D by private industry, but occasionally build upon Sandia's work.

The GDO consists of the following organizations:

APS Technology
Baker Hughes INTEQ
Ballew Tool Systems
Boart Longyear Company
CalEnergy
Calpine Corporation
Drill Cool Systems
Epoch Well Logging Company
EVI Oil Tools McAllister
EVI Weatherford
Geo Hills Associates
Halliburton Services
Layne Christensen Corp.
Livesay Consultants, Inc.
Los Alamos National Labs
M-I Drilling Fluids Co.
Maxwell Technologies
Nabors Drilling USA, Inc.
Novatek
Pajarito Enterprises
Resource Group
Sandia National Laboratories
Smith Drilling & Completion
ThermaSource, Inc.
Tonto Drilling Services, Inc.
Trans Pacific Geothermal
Unocal Geothermal

## PROJECT OBJECTIVES

### *Technical Objectives*

The goal of the GDO is to reduce geothermal drilling and well maintenance costs by developing and commercializing new tools, materials, and techniques in cost-shared projects with industry.

### *Expected Outcomes*

The GDO makes technology commercially available to the geothermal industry. These technologies reduce the cost of drilling and well maintenance.

## APPROACH

The GDO is composed primarily of geothermal operators and service companies. The objective of the GDO is to reduce geothermal drilling and well maintenance costs by developing and commercializing new tools, materials, and techniques by means of cost-shared projects with industry**.** GDO projects require a 50% cost share from the industry partner. The contribution from industry is usually much greater than 50% when labor, use of their facilities, and all aspects of their contribution are considered. Most of the development work is accomplished by industry. The GDO meets on a quarterly basis.

A new process for selecting projects is in place. A solicitation for proposals is sent to the GDO members annually. Sandia reviews and score all proposals. High-ranking proposals are matched to available funds and contracts are issued to accomplish the work. Sandia provides technical support when needed, often by providing expertise and equipment for field verification activities.

## RESEARCH RESULTS

### *INSULATED DRILL PIPE*

To demonstrate the value of insulated drill pipe for reducing bottom hole mud temperatures and extending the usefulness of drilling tools and instruments to the hottest sections of a reservoir, Drill Cool manufactured 5500 ft of 5" insulated drill pipe (IDP). Conventional and insulated drill pipes were tested side by side, Figure 1. Insulated drill pipe successfully suppressed bottom hole temperatures and is now commercially available.

Welding-related fabrication problems encountered during the course of the project were solved with the assistance of experts from the national labs.

### ALTERNATIVE CEMENTS (NITROGENFOAM) TO CONTROL LOST CIRCULATION

Field testing of alternative lost-circulation cements has been underway as a GDO project for several years. CalEnergy, Halliburton, and Sandia initiated a field test at the Coso Geothermal Field and, using foam cement, sealed a very troublesome, extremely persistent loss zone where four “normal” cement plugs failed to stem the loss. However, during the pumping operation, the fracture gradient of the formation was exceeded. The packer had to be fished out. CalEnergy expressed a desire for GDO assistance in designing a drillable cement retainer/packer for pressurized foam cement squeezes that would make the operation consistently successful in future foam cement operations.

As part of a GDO project, EVI McAllister manufactured a prototype packer for geothermal foam cement applications. The first test of the packer in the EVI yard failed. A second test is being prepared. The packer will probably be tested at Coso under Caithness who has taken this GDO project from CalEnergy. This type of packer is also being evaluated for use in the Imperial Valley in casing and for The Geysers.

### *EVALUATION AND INTERPRETATION OF FOAM INTEGRITY LOGS*

Evaluation of the integrity of nitrogen foam cement continues to present a serious problem for geothermal operators. This is due to large geothermal casing sizes, lack of experience on the part of the service companies and operators with foam cement logs, and a lack of consistent procedures to run the logs. The GDO approved a project in late FY98 to demonstrate procedures for verifying the integrity of foam cement applications. A contract was issued to CalEnergy in late FY99. Work is expected to begin in FY00.

### *PERCUSIVE MUD HAMMER FOR GEOTHERMAL DRILLING*

Novatek is under contract with Sandia on a GDO project to develop a mud-actuated percussive hammer for geothermal drilling applications. This project hinges on the successful development of a similar, smaller mud hammer for hydrocarbon drilling, funded by DOE/FE. Progress has been slow on the 7 ¾ inch oil and gas hammer due to technical problems associated with valves. Basic impact optimization studies were completed recently and improved performance was observed. Parts for the new 8 ½-inch tool that would be used for geothermal drilling are on order.

In FY00, Novatek is going to deliver an 8 ½-inch hammer for field testing and provide a road map for a scaling up to 12 ¼-inches.

### *HIGH-PRESSURE, HIGH TEMPERATURE VALVE-CHANGING TOOL ASSEMBLY*

The project to develop a high-pressure valve-changing tool was initiated in early FY97 and was substantially completed in its first year. The new tool was designed, fabricated, and lab tested by Smith International, Inc. The tool was then shipped to Hawaii for testing on a geothermal well operated by Puna Geothermal Ventures. It was successfully run through a lubricator into the well and set while the wellhead assembly was replaced. The tool is now commercially available and is in the Smith catalogue.

In FY99, capability was to be added for use in milling out stuck gate valves in older wells. The modified tool will probably be field-tested at The Geysers. Parts have been ordered to add a milling capability to the tool. The long delay in adding the milling capability is due to repeated changes of personnel and changes in priorities on the part of oilfield service companies.

### *GEYSERS CASING REMEDIATION*

Unocal approached the GDO for assistance with well problems in the Geysers; 50 or 60 wells were experiencing casing deformation. Causes are largely formation slip, subsidence, and tectonic effects. A GDO project was developed to verify a universal approach for milling out and patching deformed casing sections.

Sandia worked with Halliburton to successfully develop a through-tubing bridge plug, TTBP, to set below the deformed section (the portion of the casing with a dogleg) so that the wellbore could be filled with water for milling without having to kill the well. Unocal explored and utilized dogleg-reaming technology offered by Baker Oil Tools.

The first remediation operation was performed at The Geysers. The TTBP was set successfully according to all indications but was compromised by operational problems. Because of the compromise of the TTBP, milling out the deformed section of the casing had to be accomplished with air rather than water. The dogleg reaming itself with air was very successful. However, the casing parted during the latter stages of the milling operation, presumably due to residual stresses. Reentry was impossible and the well had to be abandoned.

Future remediation activities should be carried out with the benefit of the lessons learned from the initial attempt at casing remediation. These include: (1) milling as little as possible, (2) making the casing patch as simple and small as possible consistent with production and plug-and-abandon requirements (3) setting the TTBP successfully and without compromise, (4) milling with water rather than air, and (5) and using the successful dogleg-reaming technology. The TTBP is now available commercially.

### *LOW-EMISSIONS, ATMOSPHERIC METERING SEPARATOR (LEAMS)*

In late FY98, Two Phase Engineering was funded to develop a Low-Emission Atmospheric Metering Separator as a replacement for the inefficient blooie muffler. Two Phase Engineering devised a new approach to separate rock chips and drilling mud from steam. This should reduce and possibly eliminate site cleanup costs associated with blowing solids and liquids out the blooie line. As environmental concerns heighten, the need for such a unit is becoming recognized by operators and also by those in the regulatory arena. The prototype has been manufactured (Figure 2) and is awaiting a field test scheduled for February 2000 at Coso.

### *HIGH TEMPERATURE DOWNHOLE MOTOR STATOR*

A GDO project was started in mid FY98 to develop a high-temperature downhole motor stator. APS Technologies has invented a metal wire-impregnated motor stator that should have a higher temperature operating range than other downhole motor stators. Modeling has been completed. Problems that occurred in final fabrication of the small-scale stator have been resolved as a result of successful molding of small samples. Molding of a small-scale stator section should be completed in the next fiscal year.

## FUTURE PLANS

The industry is taking an extremely active role in identifying future projects for funding. Several new projects have been proposed for FY00. A solicitation was sent to the GDO membership and approximately 35 other “interested parties”. These solicitations will be screened by the GDO members and the GDO board and forwarded to Sandia for evaluation. Available funding will be matched to the highest ranked proposals. The following proposals are being considered:

- Geysers Deformed Casing Remediation - *Calpine*
- Proposal to Develop and Test in Laboratory Slimhole Dual-Body Bits for Geothermal Drilling Application - *University of Oklahoma*
- LEAMS II - Low Emissions Atmospheric Monitoring Separator Plus Noise Attenuation for Drilling and Well-Testing - Two-Phase Engineering
- Slim Hole Drilling, Logging, and Testing at the Salton Sea Geothermal Field, California - *CalEnergy Operating Corporation*
- Circulation Monitoring System (CMS), Testing and Enhancement - *Marconi Aerospace Defense Systems, Inc.*
- Continued Development of Protected PDC bits for Hard Rock Drilling - *Foster-Miller*
- Proposal to Develop a “Toolkit” for Predicting the Production Characteristics of Large-Diameter Wells Based on Measurements in Slim Holes - *Maxwell Technologies, Inc.*

## INDUSTRY INTEREST

Following are the names of collaborators on GDO/DOE projects along with their particular interests. There are many other parties interested in these projects, but only GDO members and project-specific contractors are listed below. There is also an interested parties (non-members) list of nearly 35 industry entities that follows GDO activities. The entire membership of the Geothermal Drilling Organization is interested in improving the overall geothermal drilling operation while cutting costs.

| Organization | Type and Extent of Interest |
|---|---|
| Smith International, Puna Geothermal Ventures, Geyser Field Operators | High-temperature, pressure valve-changing tool. |
| **Caithness** | Alternative (foam) cements, Low Emissions Atmospheric Metering Separator (LEAMS) |
| Novatek, Unocal, CalEnergy | Construction and testing of improved mud hammer for geothermal use. |
| Cal Energy | Insulated drill pipe |
| Drill Cool | Insulated drill pipe, LEAMS |
| Unocal | Deformed Casing Remediation. |
| EVI McAllister | Foam Cements. |
| APS Technology | High Temperature Stator. |
| Two Phase Engineering, Drill Cool | LEAMS |
| CalEnergy, GWB Consultants | Interpretation of cement foam integrity logs. |

## CONTACTS

Allan R. Sattler
Secretary-Treasurer, GDO
Sandia National Laboratories
P O Box 5800, MS-1033
Albuquerque, NM 87185-1033
(505) 844-1019, Fax: (505) 844-3952
arsattl@sandia.gov

Michael R. Prairie
Sandia National Laboratories MS-1033
P.O. Box 5800
Albuquerque, NM 87185-1033
(505) 844-7823, Fax (505) 844-3952
mrprair@sandia.gov

Marc Steffen
President, Geothermal Drilling Organization
Calpine Corporation
10350 Socrates Mine Road
Middletown, CA 95461
TEL: 707-431-6102
FAX: 707-431-6148

Raymond J. LaSala
Office of Geothermal & Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Ave.
Washington, D.C. 20585-0121
(202) 586-4198, Fax (202) 586-8185
Raymond.LaSala@ee.doe.gov

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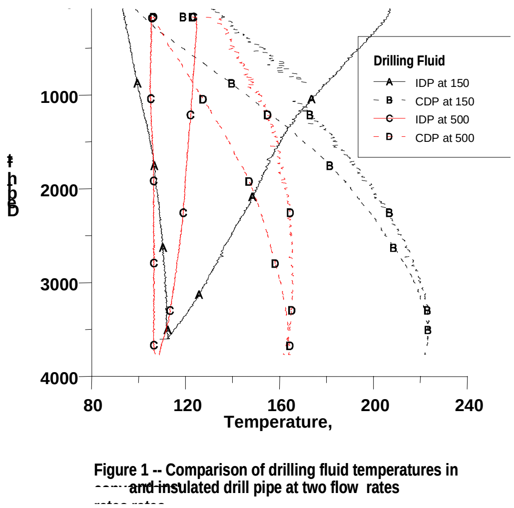


**Figure 1.** Insulated drillpipe greatly reduces bottom-hole mud temperature in an Imperial Valley field test.

**Figure 2.** Photograph of the LEAMS prototype.

# CONVERSION TECHNOLOGY

# FIELD TESTING OF THERMALLY-CONDUCTIVE, CORROSION-RESISTANT HEAT EXCHANGER LINERS

Keith Gawlik
National Renewable Energy Laboratory

## KEY WORDS

materials testing, materials development, polymer concrete lining, heat exchangers, industrial coatings

## PROJECT BACKGROUND AND STATUS

Fouling and corrosion of heat exchangers and brine service piping are major concerns to the geothermal power industry. Increased heat transfer resistance, loss of material due to corrosion, and increased maintenance to remove scale and replace piping combine to raise the cost of power produced from geothermal resources. Traditionally, heat exchangers in highly-fouling brine service have been made from corrosion-resistant, expensive materials such as titanium, monel, and stainless steel. Reducing the cost of the heat exchanger, and potentially slowing the fouling rate, can be achieved by using polymer linings applied to low-cost carbon steel.

A collaborative effort began in 1993 between the National Renewable Energy Laboratory (NREL), Brookhaven National Laboratory (BNL), and industry partners to evaluate the thermal, anti-fouling, and anti-corrosion characteristics of polymer linings. The polymer linings were BNL's polymer composite lining (PCL) and polyphenylene sulfide (PPS), with and without silicon carbide additive, and phenolic materials from a commercial coating company. The coatings were applied to plain carbon steel tubes and the performance of the lined tubes was compared to the performance of stainless steel (AL-6XN) control tubes.

An economic analysis was conducted to determine the cost savings potential of polymer-lined heat exchangers. A variety of methods of protecting the tube ends were investigated and cost comparisons made. It was found that if the entire heat exchanger is constructed of carbon steel and protective linings used in the tubes, on the tubesheets, and in the channels, significant savings can be realized. A unit made with polymer-lined tubes and using a baked phenolic coating on the balance of the wetted surfaces is 36% of the cost of a heat exchanger made with traditional corrosion-resistant materials.

Since 1993, a number of field tests have been completed at the industry partner's power plant in the Salton Sea area. Tubes lined with PCL, PPS, and phenolics have been tested. Test results for the PCL-lined tubes showed that under similar operating conditions the overall heat transfer coefficient for the PCL tubes was about 9% lower than for the AL-6XN tubes. Post field test analysis at BNL proved that the PC liner fully protected the carbon steel surfaces from the corrosive brine. PCL reformulated to improve its oxidation resistance was more successful in retarding the accumulation of scale, and fouling rates reductions of up to 19% were obtained. However, because the scale-to-PC-liner bond strength was the same order of magnitude as the liner-to-tube-wall bond strength, the PCL tubes could not be reliably hydroblasted clean without damage to the liner surface.

PPS-lined tubes have shown good fouling resistance and ability to be cleaned by hydroblasting. The results have shown reductions of fouling rate of 15% to 19% compared to stainless steel tubes. The tubes were protected from corrosion, but there was some removal of PPS during hydroblasting when a hydroblasting pressure higher than necessary for scale removal was used. The PPS formulation is being improved to enhance its bond strength to the carbon steel tube, to increase its surface hardness and resistance to damage from hydroblasting, and to further reduce the tendency of scale to adhere to it.

Phenolic-lined tubes have had mixed results. In an extended duration field test from February to July 1999, they performed very well with complete protection of the carbon steel even after repeated hydroblastings. But in a field test that started in July 1999, a number of tubes failed through perforation of the tube after only a few weeks of service. There are also concerns that the maximum temperature that phenolics can withstand appears to be lower than the production brine temperature at many binary plants.

Investigations have also been made into the use of thermally-sprayed metallic coatings to protect the ends of the tubes where the flanges and other fittings are attached. Ni-Al plasma sprayed coatings were applied to tubes to investigate the use of these metallic coatings in the region of the tube-to- tubesheet joint. These coatings failed to protect the underlying carbon steel due to cracking of the coating during the roller-expansion process to join the tube to the end fittings, and also due to the inherent porosity of these coatings. Therefore, the Ni-Al coating used can not be recommended for further use in this application.

Activities in FY99 consisted of skid improvements and two field tests. Extensive rework of the heat exchanger test apparatus and investment in equipment replacement led to improved reliability and uptime. This work took place from October 1998 to February 1999. The first field test ran from February to July 1999 and included a number of cycles of exposure to brine followed by complete hydroblast cleaning of the tubes. This extended duration test was much longer than the 45-day exposure tests performed in the past and simulated more closely the manner in which a lined tube would be used in service. The second field test started in July 1999 and ran beyond the end of the fiscal year. A number of tubes were replaced early in that test due to coating failure and tube perforation. They were replaced by stainless steel tubes or new PPS-lined tubes as they became available from BNL.

In the next fiscal year, tests of improved PPS and other coatings will likely continue at a new site where high temperature production brine is available. This site will probably be the Mammoth Lakes binary plant, where the apparatus will have access to brine at temperatures up to 350°F (177°C), much hotter than the 220°F (104°C) brine available at the current site in the Salton Sea. The higher temperature will allow the program to explore further the capabilities of PPS and other coatings. The installation of the skid at the new site will follow skid refurbishment and redesign to replace corroded components and to enable it to process the new brine and withstand the new environmental conditions. The installation of the skid at the new location will likely occur in the summer of 2000. BNL will refine their coating materials based on the outcome of the current set of tests.

## PROJECT OBJECTIVES

This project's objective is to reduce the capital and maintenance cost of brine-wetted heat exchangers and service piping at geothermal power plants by developing and testing fouling- and corrosion-resistant coating systems. These coatings are designed to be applied to low-cost carbon steel. Reducing the capital and maintenance costs of heat exchangers will lead to reduced cost of electricity generation, and increased cost competitiveness of the geothermal power industry. The coatings will be exposed to temperatures up to 356°F (180°C).

To this end, NREL has conducted field tests of PCL and PPS coatings developed by BNL to determine the heat transfer, fouling, and corrosion properties of the materials. Ni-Al tube end treatments developed by BNL were also investigated. NREL found an industry partner to collaborate on the use of phenolic coatings in brine service, and coordinated the procurement and testing of phenolic-lined tubes. Significant capital cost savings can be achieved if heat exchangers are constructed of coated carbon steel rather than traditional materials such as titanium, monel, and stainless steel. In addition, the anti-fouling properties of the coatings can reduce maintenance costs.

The long-term durability and temperature and pH limits of the coatings will also be evaluated. Tubes from previous field tests will be cleaned and reused in subsequent tests to determine how well the coatings last under repeated test and clean cycles. Through coupon tests, the phenolic coatings will be evaluated at temperatures higher than available at the current site, and at lower pH levels.

***Technical Objectives***

- Evaluate polymer coatings in actual brine service to determine the materials' abilities to prevent corrosion of the base metal, reduce fouling, transfer heat, and remain adhered to the base metal. Compare these results to the performance of traditional corrosion-resistant materials.
- Use the field test results to refine the composition of current coatings and to aid in the development of new coatings.
- Determine the manufacturing issues related to the use of promising coatings, and find ways to resolve construction problems.
- Determine the economic benefits of using coated carbon steel heat exchangers against units made of corrosion-resistant metals.

***Expected Outcome***

- Development of new heat exchanger polymer linings that will reduce the capital and maintenance costs and extend the life of equipment in geothermal brine service
- Provision of data, suitable for heat exchanger design, on the thermal and mechanical properties of polymer linings.
- Development of techniques for using the polymer linings in a commercial heat exchanger construction environment.
- Provision of estimates on the economic advantages of the coatings in reducing capital and O&M costs.

## APPROACH

NREL, in cooperation with industry partners, performs field tests of polymer coatings provided by BNL, researchers at NREL, and commercial suppliers. BNL has developed liner materials and coated appropriate lengths of heat exchanger tubing for the field tests. NREL also coordinates the coating of tubes by commercial coating companies. NREL installs the tubes in its heat exchanger test skid located at a geothermal power plant operated by the industrial partner. Temperature, pressure, and mass flow data are recorded at the site and downloaded via a modem for analysis at NREL's offices. Test skid maintenance may be performed by plant personnel or by a person under subcontract to NREL.

NREL works with industrial heat exchanger manufacturing firms to determine methods by which pre-lined heat exchanger tubes can be assembled into shell and tube heat exchangers using standard industrial processes. These manufacturing firms also help quantify the potential cost savings of using corrosion-resistant liners for carbon steel components in place of using corrosion-resistant metal components or overlays.

## RESEARCH RESULTS

The results from FY99 showed that the PPS and phenolic coatings could be easily cleaned and reused in an extended duration field test if the hydroblasting was performed carefully. There did not appear to be any significant difference in the fouling rates of polymer-lined tubes and plain stainless steel tubes in the two tests in this fiscal year. However, fouling depends heavily on the characteristics of the brine, and these characteristics have varied widely recently due to lack of control by the industry partner in the injection of a number of chemicals to control flocculation and naturally occurring radioactive material upstream of the skid.

The PPS tubes were able to be cleaned and reused a number of times, but excessive hydroblast pressure cause surface erosion of the polymer. There was a fine line between the minimum hydroblast pressure necessary for scale removal and the point at which erosion of the polymer occurred, so the acceptable hydroblast pressures were limited to a narrow range that was not simple to determine nondestructively. The development of a harder PPS surface would increase durability and practicality of this material.

The phenolics showed mixed results. In the first test, all phenolic-lined tubes performed very well. The underlying carbon steel was completely protected from corrosion and the liners were able to be cleaned completely and repeatedly of scale. In the second test, a number of new phenolic-lined tubes failed shortly after the test began.

BNL performed coupon tests of a variety of phenolic materials and improved PPS formulations and showed that the currently-available phenolics would probably not be able to accommodate high brine production temperatures encountered at many binary plants. The temperature range of PPS is much greater than that of phenolics, though, so these coatings can probably be used in the new site and at others with high temperature brines. The relocation of the skid to a new facility will enable researchers to explore the coatings' performance with high temperature brine, and will allow the testing of the coatings with brine that has a completely different chemical composition than the current brine in the Salton Sea.

## FUTURE PLANS

Additional field tests of liners from BNL, NREL, and commercial suppliers will be conducted. Tubes will be coated after joining to the end fittings to explore protection of the tube ends. New formulations of PPS will be explored, and other materials will be tested as appropriate.

NREL will refurbish, redesign, and move the skid to a new location where high temperature production brine is available to the apparatus. NREL will instrument this skid and conduct field tests with the new brine conditions.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| | |
|---|---|
| CalEnergy | Industry partner at whose plant the brine tests are being conducted. |
| Heresite Protective Coatings, Inc. | Commercial coating company that supplies and applies a variety of phenolic coatings. |
| Hughes-Anderson Heat Exchangers | The company that has conducted design and economic studies of polymer concrete lined heat exchangers. |
| Ogden Power Pacific, Inc. | Industry partner who will provide a new site for the skid. |

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## CONTACTS

Raymond LaSala
U.S. Department of Energy
Office of Geothermal and Wind Technologies, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585-0121
Tel: (202) 586-4198
Fax: (202) 586-8185
raymond.lasala@ee.doe.gov

Keith Gawlik
Tel: (303) 384-7515
Fax: (303) 384-7540
keith_gawlik@nrel.gov
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

# THERMALLY CONDUCTIVE POLYMER COMPOSITES FOR HEAT EXCHANGER TUBES

Toshifumi Sugama and Ronald P. Webster
Brookhaven National Laboratory

## KEYWORDS

corrosion protection, fouling coefficient, heat transfer, mild steel, polymer composites, antioxidant agent, silicon carbide, thermal conductivity, polyphenylene sulfide

## PROJECT BACKGROUND AND STATUS

The economic utilization of binary working fluids in geothermal energy conversion cycles would dramatically increase the size of exploitable hydrothermal resources. A significant cost in geothermal binary-cycle power plants is the shell and tube heat exchangers. Replacing the shells and tubes damaged by corrosion, erosion, and fouling due to scale deposition is very costly and time consuming. At present, heat exchangers made from titanium alloys and stainless steels are commonly used because they resist corrosion. However, these high-grade alloy metals are considerably more expensive and have much lower thermal conductivities than copper and carbon steels. If an inexpensive heat exchanger of mild carbon steel (MCS) could be coated with a thermally conductive material that confers resistance to corrosion and erosion equal to that of copper, brass, and high-grade alloy steels, and also offers anti-fouling surfaces, then the capital cost of these large heat exchangers would be markedly reduced. In addition, this would increase in energy conversion efficiency.

BNL developed a silicon carbide (SiC) thermal conductor-filled polymer composite that had excellent thermal conductivity and corrosion resistance. Further, BNL demonstrated the technical feasibility of applying it to the interior surface of MCS heat exchanger tubes, (25 mm outside diam. x 1.2 mm wall thickness x 6100 mm long). Based upon these results, field tests were begun to evaluate its performance as a low cost, thermally conductive, anti-corrosion, -erosion, and -fouling coating for MCS-based heat exchanger tubes.

In FY 1994-1995, a 75-day field test of MCS lined with a thermally conductive polymer composite consisting of trimethylolpropane trimethacylate (TMP)-crosslinked with styrene/methyl methacrylate copolymers as the binder and a SiC grit as the thermal conductor was carried out under conditions that simulated those in a bottoming cycle in a multi-stage flash geothermal process. The hypersaline brine inlet and outlet temperatures were 108° and 89°C, respectively. Concurrently, AL-6XN stainless steel tubes were also evaluated as controls. The post-field test analysis of the tubes indicated that the polymer composite liner (PCL) had a heat transfer coefficient which was only 9 % less than that of the more expensive AL-6XN, and showed that it conferred excellent corrosion resistance to the MCS tubes. However, a major drawback of the liner was the fact that the functional ester groups in the copolymer binder underwent hot brine-induced oxidation, forming a reactive carboxylate derivative. This derivative preferentially reacted with $Ba^+$ and $Ca^+$ ions present in the geothermal brines to form Ba- and Ca-complexed hydrolysates. Introducing these complexed carboxylate compounds on the copolymer surfaces not only promoted the rate of the deposition of brine-induced scales on the coating surfaces, but also caused the scales to bond strongly to the coating, making them difficult to remove. At the same time, the scales that had accumulated on the AL-6XN were easily removed by hydroblasting at pressures of > 6000 psi, thereby restoring their function as heat exchanger tubes. These results indicated the importance of identifying polymeric binders that resist hydrothermal oxidation and subsequent scale deposition. Such chemically inert binder systems would improve the surface properties of the coatings ensuring that scales could be readily removed.

To achieve this goal, a second field test was conducted in FY 1997-1998. In this test, three polymeric material systems, the 1,4-phenylene diamine (PDA) antioxidant-modified TMP-crosslinked styrene/methyl methacrylate (TMP-ST) copolymers, the polyphenylene sulfide (PPS) system, and the polytetrafluoroethylene (PTFE)-modified PPS system, were employed to evaluate their usefulness as the anti-corrosion and -oxidation coatings for heat exchanger tubes. Post-test analyses showed that although the PPS coating surface suffered some oxidation, its extent was considerably inhibited by blending PTFE into it. Such inhibition of oxidation was due to the formation of a chemically inert PTFE layer segregated from the PPS layer at the outermost surface site of coating.

A five-month field test was conducted from late FY 1996 to early FY 1999 to determine the useful lifetime of PPS- and PTFE/PPS-coating systems in repeated hydroblast clean-reuse processes. The commercial phenolic resin-based Saekaphen Si 14E coating system (prepared by Heresite Protective Coatings Inc.) was included in this field test.

## PROJECT OBJECTIVES

The objective of the research is to reduce by 30 % the cost of heat exchangers in geothermal binary power plants.

### *Technical Objectives*

The objectives of the project will be achieved by developing a material meeting the following criteria:

- Heat transfer and fluid-flow characteristics similar to those of AL-6XN tubing.
- Hydrothermal stability > 170°C: no decomposition after exposure for 10 days to brine at 200°C.
- Smooth surface texture: roughness value, Ra, < 0.15 µm by profilometer measurement.
- Low surface energy: contact angle > 80° of water droplet on coating surfaces.
- Low rate of oxidation: oxygen uptake of < 0.5 O/C atomic ratio after exposure for 10 days to acid brine at 200°C.
- Excellent adherence to metal surfaces: lap-shear bond strength of > 5.0 MPa.
- Low ionic conductivity: pore resistance, Rp, > 1 Mega ohm-$cm^2$ by AC electrochemical impedance spectroscopy.
- Coating film thickness < 8 mil.
- Cost not more than twice that of mild carbon steel.

### *Expected Outcomes*

- Electric generation capacities in geothermal flash processes could be improved by 10% with the availability of cost-effective materials for use in bottoming cycle heat exchangers.
- Low temperature geothermal resources that are currently uneconomical will become more attractive for development, thereby greatly enhancing the exploitable geothermal reserves.

- Increased plant utilization factors due to reduced scale deposition and decreased quantities of waste sludge for disposal will result from the use of binary processes with hypersaline brines.

## APPROACH

The work is being performed as a collaborative effort between BNL, the National Renewable Energy Laboratory (NREL) and private industry. BNL undertakes the fundamental and applied research necessary to define the polymer composite's formulations, determines the thickness requirements of the protective coating, and develops methods for placing thin, uniform coatings on the interior surface of the heat exchanger tubes. Post-field test evaluations also are carried out at BNL.

Engineering analyses and heat transfer tests are conducted by NREL. The work includes measuring the heat transfer coefficients, estimating costs, and managing the field tests. NREL also coordinates technology transfer.

A geothermal company provides the field test site, operating personnel, and ancillary equipment. Tests are being made in an environment typical of that in a bottoming cycle application in a flash process. The design, manufacturing methods, and economic studies then are conducted by a heat exchanger manufacturer.

## RESEARCH RESULTS AND VARIANCES

Using scale-removing hydroblasting technology, carbon steel heat exchanger tubes lined internally with SiC-filled PPS/zinc phosphate and SiC-filled PTFE/PPS/zinc phosphate coating materials were cleaned and reused to determine their useful lifetime as corrosion-protecting coatings. After nearly five-mo. field testing, there were leakages of fluid in both of the PPS- and PTFE/PPS-lined tubes, revealing corrosion of tubes brought about by the failure of the coatings.

To gain an understanding as to why the coating failed in the repeating clean-reuse processes, the tubes were examined using scanning electron microcopy (SEM) and energy-dispersive x-ray spectrometry (EDX). The SEM image revealed the destruction of the underlying steel caused by severe corrosion in conjunction with a discontinuous layer of thin PPS coating film of less then ~ 50 µm. This information clearly verified that the PPS layer underwent some wear and tear during hydroblasting. Also, the image revealed that although the PPS layer was locally eliminated, the zinc phosphate primer layer still adhered to the steel. Nevertheless, when a hostile brine came into contact with a blemished area in the coating, its attack not only promoted the rate of the steel's corrosion, but also eroded the corrosion products, such as iron oxides, thereby generating undermining-related pin holes in the tubes. Thus, the surfaces of PPS and PTFE/PPS coatings must be hard, smooth, and slippery to overcome wear- and tear-damages from hydroblasting.

The results on the commercial phenolic resin-based Saekaphen coatings showed that although the surfaces of the phenolic thermoset polymer films had the advantageous properties, such as a smoothness, low surface energy, and surface slip, for their use as anti-corrosion and -fouling coatings of heat exchanger tubes, the films peeled off from the tube's surfaces after hydroblasting. Such failure was due to the poor adherence of the Saekaphen coating to metal substrates.

## FUTURE PLANS

Assuming that hydroblasting will continue to be the primary means for removing scales, BNL will start a series of laboratory and field tests to evaluate the resistance of the coatings to wear due to this process. Coatings made with one of two wear resistant polymer systems, which are being developed at BNL in collaboration with Ticona, will be evaluated. The polymer systems are a new highly crystallized rigid PPS and PTFE-blended PPS composites containing varying amounts of a very hard polysulfone powder with a melting point of > 450°C.

A ultra fine, packed zinc phosphate crystal primer, which is being developed at BNL, will be evaluated for use with Heresite's Saekaphen coating system. A series of HX tubes will be coated with the zinc phosphate primer and then sent to Heresite Protective Coatings Co., to apply the Seakaphen coating. The tubes then will be evaluated in the field and at BNL.

## INDUSTRIAL INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type of Extent of Interest |
|---|---|
| California Energy Co. | User of heat exchanger tubes. |
| Heresite Protective Coatings, Inc. | Heat exchanger manufacture |
| Applied Surface Technology, Inc. | Heat exchanger manufacture. |
| Ticona Inc. | PPS manufacture. |

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## CONTACTS

Mr. Raymond LaSala, EE-122
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585
Tel: (202) 586 4198
Fax: (202) 586 8185
E-mail: Raymond.Lasala@ee..doe.gov.

T. Sugama and R. P. Webster
Department of Applied Science
Building 526
Brookhaven National Laboratory
Upton, NY 11973
Tel:(516) 344 4029; (516) 344 2845
Fax: (516) 344 2359
E-mail: sugama@bnl.gov; webster@bnl.gov

# COATINGS FOR HIGH TEMPERATURE APPLICATIONS

Toshifumi Sugama
Brookhaven National Laboratory

## KEYWORDS

coatings, corrosion protection, polymers, piping, well casing, cooling towers, vent gas blowers, acid condensate

## PROJECT BACKGROUND AND STATUS

Corrosion problems at The Geysers have increased as steam pressures decline. These have contributed to decreases in electric power generation, increased operating costs, and safety and environmental concerns. In FY 1997, BNL started cost-shared work with geothermal companies active at The Geysers which focuses on low cost solutions to these difficult materials problems. This joint work includes the identification of needs, performance of the prototype and full-scale field evaluations, and subsequent economic studies.

FY 1998, the cooperative test program with the Department of Scientific and Industrial Research (DSIR) in New Zealand was completed. This field test evaluated several potential coating systems being developed by BNL and also commercial coating systems for use as corrosion/wear-preventing barriers on piping systems, dry cooling towers, turbine components and vent gas blowers. The coated steel panels were exposed for 45 days to a steam at The Geysers in New Zealand.

As of October 1999, using the same coating systems as those used in New Zealand field tests, a 7-mo.-exposure test was completed in The Geysers steam- condensate at Material Integrity Solution, Inc.. In this trial, condensate's temperature was varied from 65 to 120°C. The results from both field tests suggested that the most effective coating in mitigating the corrosion of carbon steel was the BNL-developed polyphenylene sulfide-based coating (PPS) system. All the other commercial coatings, such as epoxy, polyimide, polyamide, polyurethan, and CVD-derived TiN and Ti(CN), failed during exposure. However, although the PPS coatings offered improved protection, one critical issue was their susceptibility to hydrothermal oxidation, which might allow corrosive electrolytes to permeate the PPS film during prolonged exposure.

## PROJECT OBJECTIVES

The objective of the research is to decrease the operating costs of steam production, transmission and utilization at The Geysers by the identification and subsequent demonstration of low cost materials of construction that will withstand the highly corrosive acidic environments encountered in some areas of geothermal fields.

### *Technical Objectives*

The technical objective is to select and optimize materials systems previously developed under DOE/OGT sponsorship, for specific end-use applications at The Geysers.

Design criteria for the coatings being developed are as follows:

- Ability to coat the substrate with large surface area and able to restore damaged coatings.

- Capability to protect the substrate against the attack of condensed and vaporized corrosive species at temperatures up to 200°C.

- Ability to adhere strongly to the substrate (tensile bond strength of > 10 MPa).

- Having a low coefficient of friction.

***Expected Outcomes***

Attainment of the project's objectives will result in the following:

- Wells that presently cannot be operated due to excessive maintenance costs or environmental/safety concerns may be restarted.

- Service life expectancies of fluid production, transmission and electric generation components will be increased.

- Cost-effective methods for water conservation will be available, thereby extending the reservoir's life due to an increased level of fluid reinjection.

## APPROACH

The approach being used to meet the project's objectives is to optimize the formulations of polymer, polymer composite, and ceramic materials previously developed under DOE/OGT sponsorship for specific end-use applications at The Geysers. The identification of needs, the performance of prototype and full-scale field evaluations, and subsequent economic studies are undertaken as cost-shared work with firms active at The Geysers.

The Project consists of three phases:

Phase 1 consists of the identification of specific materials problems, elucidation of the fluid environments, and the selection of candidate materials systems. Laboratory testing under simulated process conditions is then conducted to establish technical feasibility. Based upon these results, modifications to the systems are made to maximize corrosion resistance.

Phase 2 consists of small-scale field testing, and contingent upon the results, prototype component testing.

Phase 3 consists of design studies to incorporate the technology into components, cost estimates, documentation, and the identification of potential commercial suppliers of the new technology.

## RESULTS AND VARIANCES

It was evaluated the usefulness of antioxidants and their combinations to hinder the hydrothermal oxidation of polyphenylenesulfide (PPS) coatings which suffer from the attack of low pH, brine at 200°C. Among them, tetrakis[methylene, 1,3,5,-di-t-butyl-4-hydroxyhydrocinnamates] methane (TMBHM) was identified as the most effective one. Once TMBHM came into contact with a sulfur radical on an aromatic ring and the aryl radicals generated from the hydrothermally degraded PPS during the period of oxidative induction, the hindered phenol functional group in the TMBHM donated the hydrogen as radical scavenger to tie up these PPS-associated radicals. Such a radical-trapping reaction played a key role in rearranging and reconstituting the damaged PPS structure. However, TMBHM does not completely retard the rate of oxidation, which was related directly to the transformation of the sulfide group in the PPS into sulfonyl and sulfonic acid groups. Nevertheless, TMBHM's oxidation-hindering behavior had two important factors which extended the useful lifetime of PPS coatings used as corrosion-preventing coatings: The first factor was that it maximized the potential of PPS having low surface energy and hydrophobic characteristics; the second was that it retained low ion conductivity.

## FUTURE PLANS

Laboratory and field testing efforts performed as cost-shared activities with geothermal companies active at The Geysers will be continued. The current industrial partner is Material Integrity Solutions, Inc., (MIS). To date, antioxidant-modified PPS was identified as the starting material for the coatings most promising in inhibiting the rate of corrosion of the steel. However, a major drawback of these organic polymer coatings is that their surface hardness is much lower than that of the ceramic and intermetallic alloy coating surfaces, thereby resulting in a poor resistance to abrasive wear. Two ways to resolve this problem will be explored: The first will focus on developing and synthesizing well-crystallized rigid PPS polymers in collaboration with Ticona; the second will be to formulate composite material systems prepared by incorporating a very hard polysulfone powder with a melting point of > 450  C into the coatings. The coated metal substrates will be exposed to hot brine, and then tested to evaluate their potential as a corrosion/oxidation/ wear resistant coatings.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Ticona Inc. | PPS manufacture |
| MIS | Research collaborators in exploring protection against corrosion in vent gas blowers, dry cooling tower components, turbine blades, and rotor housings. |

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## CONTACTS

Raymond LaSala, EE-122
U.S. Department of Energy
1000 Independence Ave, S.W.
Washington, DC 20585-121
Phone: (202) 586-4198
Fax: (202) 586-8185
Email: Raymond.Lasala@ee.doe.gov

Toshifumi Sugama
Brookhaven National Laboratory
Upton, NY 11973-5000
Phone: (516) 344-4029
Fax: (516) 344-2359
Email: sugama@bnl.gov

# CLAD AND THERMAL SPRAYED NiCr BASE ALLOYS FOR CORROSION PROTECTION

M.L. Allan
Brookhaven National Laboratory

## KEYWORDS

corrosion, clad materials, thermal sprayed coatings, NiCrMo alloys

## PROJECT BACKGROUND AND STATUS

Clad materials are composites of a protective coating metal that is metallurgically bonded to a substrate metal. These materials are used in various industries including chemical processing, oil, electronic, and automotive. Of interest to geothermal applications is the use of corrosion resistant alloys as cladding on carbon steel. These should prove more economic than monolithic alloys provided reliable service can still be achieved. Pipes can be successfully clad, as can bends, elbows, tees, etc. The BNL survey of O&M related materials needs identified clad materials as an important area for future research to reduce O&M costs. This project was initiated in FY99 to examine the corrosion characteristics of clad NiCr base alloys. The laboratory and field data obtained in this project could be used to develop service life models that will support more detailed life cycle cost analysis as well as improve understanding of the factors controlling performance of the clad materials. Comparison is also being made with thermal sprayed corrosion resistant alloys.

## PROJECT OBJECTIVES

The objectives of this task are to optimize the use of clad NiCr base materials for corrosion protection in geothermal brine and steam transportation systems and compare the performance with thermal spray alloy coatings and bulk alloys of the same composition.

### *Technical Objectives*

- Perform electrochemical tests on clad, thermal sprayed and bulk NiCr base alloys in synthetic geothermal brines.
- Perform field tests on clad and thermal sprayed NiCr base alloys and compare results with electrochemical tests.
- Conduct cost analysis.
- Consider applicability of contemporary service life prediction models.

### *Expected Outcomes*

- Reduced capital and maintenance costs.
- Data supporting selection of clad materials.
- Increased confidence in using clad materials.
- More systematic approach to predicting service life.

## APPROACH

Clad, thermal sprayed and bulk NiCr base alloys are being subjected to electrochemical tests in synthetic 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 variation s in material behavior has been studied as this is important in service life prediction. The influence of temperature is included in the research and it is planned to also investigate the effect of brine chemistry since this is site-specific and time dependent. Field tests are intended and the performance will be compared with that predicted by electrochemical tests. 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.

## RESEARCH RESULTS

The alloys investigated included Inconel 625, Incoloy 825, Hastelloy C-276 and Anval C-22. 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. The electrochemical tests have found that Inconel 625 and Hastelloy C-276 gave the best corrosion protection for the synthetic brine chemistry and experimental conditions used to date. This generally correlates with prior experimental studies involving weight loss and pit depth measurements and field tests in brines with similar chemistry. Slight differences in pitting and repassivation potentials for the clad and bulk alloys were measured. The in-situ corrosion resistance of the clad Inconel 625 and Hastelloy C-276 is predicted to be comparable to that in solid form. The thermal sprayed coatings exhibited passivity which was encouraging and suggests that the coatings are suitable for field testing. The clad and thermal sprayed materials exhibited some variability in corrosion characteristics between test specimens, although the basic performance was similar.

## FUTURE PLANS

In FY00 critical pitting and crevice temperature tests and scratch tests to measure repassivation time for clad Inconel 625 and Hastelloy C-276 and thermal sprayed Inconel 625 will be performed. Comparisons will be made with bulk materials of the same composition. This information will be useful in determining the thermal conditions under which pitting and crevice corrosion are likely to occur. Repassivation time will be measured on the different materials to indicate relative recovery from damage to the passive film. The effect of brine chemistry on these parameters will be ascertained. Field tests on clad and thermal sprayed Inconel 625 pipes are planned and the in-situ corrosion compared with that predicted by electrochemical tests. The applicability and validity of current service life models to the observed corrosion morphologies will be investigated.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Klad, Inc. | Clad material manufacturer. |
| Sulzer Metco | Thermal sprayed coating supplier. |
| Mammoth Pacific | Potential field testing |

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## CONTACTS

Dr. Marita L. Allan
Department of Applied Science
Building 526
Brookhaven National Laboratory
Upton, NY 11973
Tel: (516) 344 3060
Fax: (516) 344 2359
E-mail: allan@bnl.gov

Mr. Raymond LaSala
U.S. Department of Energy
Office of Geothermal Technologies, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585
Tel: (202) 586 4198
Fax: (202) 586 8185
E-mail: **raymond.lasala@ee.doe.gov**

# MICROBIOLOGICALLY INFLUENCED CORROSION OF CONCRETE IN COOLING TOWERS

M.L. Allan
Brookhaven National Laboratory

## KEYWORDS

microbiologically influenced corrosion, concrete, epoxy coatings, repair, mortars, cooling towers, bond strength, durability

## PROJECT BACKGROUND AND STATUS

This project was initiated in FY99 to evaluate commercially available protective coatings and mortars for repair and prevention of microbiologically influenced corrosion (MIC) of concrete in induced draft cooling towers used in geothermal power plants. MIC and resultant degradation of concrete was identified as a research need in a prior industry survey of operation and maintenance materials needs. A laboratory testing protocol was developed for comparing the resistance of coatings and mortars to sulphur oxidizing bacteria. This was combined with acid resistance and adhesion tests. Guidelines for repair of damaged concrete were developed. Effort in FY00 will focus on testing the resistance of delineated epoxy coatings to nitrifying and heterotrophic bacteria, evaluation of calcium aluminate mortars and investigation of the performance of silica fume-modified concrete. Field tests on selected materials are also planned.

## PROJECT OBJECTIVES

The overall objective of this project is to evaluate strategies and materials for repair and prevention of microbiological attack of concrete in cooling towers in geothermal power plants and thereby reduce maintenance costs and extend service life.

### *Technical Objectives*

- Evaluate epoxy coatings and modified cementitious mortars for protection of concrete against MIC.
- Prepare recommendations and user guidelines for prevention and repair of MIC-damaged concrete with tested materials.

### *Expected Outcomes*

- Reduced concrete maintenance and repair costs.
- Decreased reliance on biocides.
- Increased service life of concrete cooling tower structures.

## APPROACH

Commercially available concrete repair and protection materials have been selected for performance comparison. To date these have included three epoxy coatings, an epoxy sealant and an epoxy-modified cement mortar. In addition, a latex-modified mortar prepared in house and representative of the type commonly used in concrete repair is being evaluated. The materials have been assessed for bond strength, acid resistance and MIC resistance. Initial testing of coating and mortar resistance to MIC is performed on a laboratory scale using an Atlas cell arrangement. Coated concrete panels are exposed to sulphur oxidizing bacteria (*Thiobacillus ferrooxidans*) at 40°C for a period of 60 days. The coatings and mortars are then evaluated for degradation due to acid attack in the form of etching, softening or decrease in bond strength. Resistance to other types of bacteria found in cooling water can be evaluated in the same manner. Such laboratory tests do not exactly reproduce field conditions and are, therefore, limited. Hence, it is planned to perform long-term field testing in collaboration with geothermal power plant operators on materials delineated from the laboratory tests as having the best potential. The experimental and field work is combined with development of recommendations and guidelines for repair and protection of concrete structures with the tested materials. The project is being extended to incorporate calcium aluminate mortars that have been used with success in concrete sewers and to consider how durability can potentially be improved through concrete mix design. Specifically, the influence of silica fume on resistance to MIC is of interest.

## RESEARCH RESULTS

Of the materials tested, the epoxy coatings gave the best overall performance. Baseline tests conducted on uncoated concrete panels to measure resistance to sulphur oxidizing bacteria in the Atlas cell arrangement revealed extensive etching of the concrete surface under a biofilm in the immersed zone. Etching was also evident in the vapor zone and was less severe. The epoxy-coated panels were free from any biofilm and adequately protected the concrete substrate for the test duration. The bond strength of the epoxy coatings was not diminished after exposure. The epoxy sealant underwent softening in both the vapor and immersed zones with the extent being greater in the latter. Bond strength was significantly reduced and the concrete substrate beneath the sealant was attacked. A biofilm grew on the epoxy-modified mortar in the immersed zone. Beneath the biofilm etching occurred and this was also evident to a lesser extent in the vapor zone. Similar results were obtained for the latex-modified mortar. Both mortars reduced the rate and extent of MIC compared with bare concrete but neither performed as well as the epoxy coatings.

## FUTURE PLANS

The coatings delineated as having the best resistance to sulphur oxidizing bacteria will be tested to determine the resistance to other bacteria prevalent in geothermal cooling towers. Specifically, nitrifying and heterotrophic bacteria will be investigated. In addition, mortars based on calcium aluminate cement will be evaluated since these have been found to possess resistance to MIC associated with sulphur oxidizing bacteria and are used for protection of concrete sewers. This will be achieved through laboratory and field tests.

Resistance of silica fume-modified concrete to sulphur oxidizing bacteria will be examined for different cement replacement levels, curing conditions and initial degree of surface carbonation. Concrete specimens will be exposed to sulphur oxidizing bacteria and monitored for biodegradation in terms of physical and chemical changes such as surface softening, leached calcium, microstructure and phase composition. From this it will be possible to predict the usefulness of silica fume as a supplementary cementing material for future cooling tower construction.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Unocal | Selection of repair materials, technical interactions and field testing in Indonesia. |

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## CONTACTS

Dr. Marita L. Allan
Department of Applied Science
Building 526
Brookhaven National Laboratory
Upton, NY 11973
Tel: (516) 344 3060
Fax: (516) 344 2359
E-mail: allan@bnl.gov

Mr. Raymond LaSala
U.S. Department of Energy
Office of Geothermal Technologies, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585
Tel: (202) 586 4198
Fax: (202) 586 8185
E-mail: **raymond.lasala@ee.doe.gov**

# ADVANCED CEMENTS

Toshifumi Sugama
Brookhaven National Laboratory

## KEYWORDS

calcium aluminate phosphate cements, sodium polyphosphate, fly ash, acid-base reactions, mechanical properties, carbonation, acid resistance, lightweight, pumpable, well completions

## PROJECT BACKGROUND AND STATUS

An identified problem that is severely reducing the lifespan of wells, and has increased costs and environmental concerns, is the deterioration of cement due to alkali metal catalyzed reactions between $CO_2$-containing brines and calcium silicate hydrate (CSH) compounds and calcium hydroxide present in conventional well cements. In the former case, the reactions between Na and K in the brines and CSH phases lead to the formation of substituted CSH compounds, such as pectolite and reyerite, both of which are susceptible to carbonation. Leaching of the resulting $CaCO_3$ and $Ca(HCO_3)_2$ leads to rapid reduction in strength, increasing permeability of cements, causing corrosion on the outside surface of the well casing. Cement failures attributed to $CO_2$ occur in less than 5 yr, and in one case, well casing collapsed within 90 days. In addition, low slurry densities (– 1.2 g/cc) are needed to minimize the frequency of lost circulation episodes when attempts are made to cement in weak unconsolidated rock zones with very fragile gradients. Solving these material's problems which can seriously constrain the development of the world's geothermal resources, is the goal of the current research on cements.

In 1996, BNL succeeded in developing a new cementitious material, so called calcium aluminate phosphate (CaP) cement that met many of the above design criteria. CaP cement was composed of four chemical components; (1) fly ash as a recycled byproduct of coal combustion, (2) calcium aluminate cement, (3) sodium polyphosphate as fertilizer intermediate, and (4) water. When the cement slurries made by mixing these components was exposed in geothermal environments, they hydrothermally reacted to form three crystalline phases, hydroxyapatite, zeolite, and alumina. These reaction products were highly resistant to deterioration due to carbonation. In fact, the laboratory tests exposing them for six months to a brine solution at 300°C with a $CO_2$ concentration of 40,000 ppm showed that CaP cement remained intact, and was carbonated only to one percent, while conventional cement was ready to crumble, with 50 percent carbonation.

Consequently, BNL recommended the use of CaP to Unocal and Halliburton in February 1997. Subsequent field testing and further development by Unocal led to full-scale tests and a field-workable CaP system which was first emplaced by Unocal in a geothermal well in northern Sumatra, Indonesia in September 1997. Four wells have been were completed using this new cement system, which has since been commercialized under the trade name "ThermaLock Cement" by Halliburton Energy Services.

Since then, $N_2$ gas-introduced foam and microsphere-filled lightweight well cementing material systems based on CaP have effectively met their primary criteria in two other full-scale field applications: Halliburton and Shell E&P Technology Co. used a CaP system in August, 1998 to cement steam injection wells in the Belridge field near Bakersfield, CA; Halliburton and Japan Petroleum Exploration Co. used one in April, 1999 to complete geothermal wells on the island of Kyushu, Japan.

Although full-scale field applications showed very promising results, there remained the following questions:

1. how durable are these downhole cements in supporting casing pipes during long-term exposures in high $CO_2$ brine at 300°C ?

2. does this cement system cured at low temperature < 90°C withstand the highly concentrated $H_2SO_4$ environments (pH <2.0) encountered in surface ground water?

Post-test analyses of Indonesian field test specimens are now needed to assess the durability of the placed cements. Specimens taken during completion of the wells were exposed in an autoclave at conditions similar to those of the downhole at 280°C in order to conduct a long-term exposure test for up to 18 mo. in the Laboratory (BNL).

Other ongoing work is to develop and modify CaP cements to confer improve resistance to the highly concentrated $H_2SO_4$ (pH ~ 1.8) environment encountered in the well's surface ground water at temperatures up to 90°C. Work was started in FY 1998 to investigate the magnitude of susceptibility of the CaP cements to acid erosion and degradation. The resulting data indicated that although the degree of acid erosion of the CaP cements was much lower than that of conventional Class G cements, the CaP specimens had a loss in weight of 29.3 % after exposure to acid for 30 days at 90°C.

## PROJECT OBJECTIVES

The objectives are to continue post-test analyses of cements which were used for completing the Indonesian geothermal wells, and also to develop acid-resistant cements at temperature of 90°C.

### *Technical Objectives*

Design criteria for the cements being developed in this program are as follows:

- Compatible with conventional field placement technologies.
- Slurry density, approximately 1.2 g/cc.
- Pumpability, 4 hr at 100°C.
- Carbonation rate, <5% after 1 yr in brine at 300 C containing 500 ppm $CO_2$.
- Compressive strength, >5 MPa at 24 hr age.
- Bond strength to steel, >70 KPa.
- Water permeability, <0.1m Darcy.
- Acid erosion rate, < 5 wt% after 25 days in pH 1.6 solution at 90°C.

### *Expected Outcomes*

Attainment of the project objectives will result in the following:

- Decreased costs for well completions due to fewer lost circulation control episodes.
- Increased well life to >20 yr.

- Reduced environmental concerns about blow-outs.
- Permit development of higher temperature, higher $CO_2$ content brines.

## APPROACH

The work is being performed as a collaborative effort between BNL, Unocal, Halliburton, and Shell E&P Technology.

**A. Post-test Analyses of the Indonesian Field Test Samples**

In monitoring the quality of downhole cements, one difficulty encountered was the fact that an ~ 5500 ft depth of these Indonesian wells was too deep to remove downhole cement specimens. To deal with this problem, we decided to conduct an 18-month-long exposure test in the laboratory (BNL) under environmental conditions simulating those at the bottom of the wells. A simulated geothermal brine containing a 20,000 ppm $CO_2$ and 400 ppm $H_2S$ was made up, composed of 11.8 wt% NaCl, 2.45 wt% KCl, 7.04 wt% $CaCl_2$, 0.12 wt% LiCl, 0.12 wt% $SrCl_2$, 0.04 wt% $BaCl_2$, 0.85 wt% $FeCl_3$, 0.43 wt% $MnCl_2$, 0.10 wt% $ZnCl_2$, and 77.05 wt% water at temperature of 280°C. The formulation of cement slurry used in the field tests consisted of 31.3 wt% calcium aluminate cement (CAC), 27.2 wt% Indonesian fly ash, 9.7 wt% sodium polyphosphate, and 31.8 wt% water. Evaluations of the quality of the exposed cement specimens include the change in compressive strength, the degree of shrinkage or expansion, the rate of carbonation, and the phase composition and transformation.

**B. Acid Resistant Cements**

To improve resistance of the CaP cements to acid, the specimens were modified with various water-born polymers and were exposed to a $CO_2$-containing acid solution (pH 1.60, 2.0 wt% $H_2SO_4$, 1 wt% $Na_2CO_3$, and 97.0 wt% water ) at 90°C. The factors to be investigated involved the change in compressive strength and porosity, the loss in weight, and the identification of reaction products yielded by the interaction between the acid and cement.

## RESEARCH RESULTS AND VARIANCES

**A. Post-Test Analyses of the Indonesian Field Test Samples**

To assess the durability of the CaP cements which were used to complete the geothermal wells in Indonesia, the specimens were exposed for up to 14 months in an autoclave containing a simulated geothermal brine with 20,000 ppm $CO_2$ and 400 ppm $H_2S$ at 280°C. Hydrothermal reactions between sodium polyphosphate (NaP) and fly ash or calcium aluminate cement (CAC) generated two major crystalline phases, hydroxyapatite (HOAp) and analcime (AN), which were responsible for developing a densified microstructure in cement bodies and offering their ultimate compressive strength. The AN phase was susceptible to a reaction with $CO_2$, transforming it into the cancrinite (CAN) phase. The AN 6 CAN phase transition continuously took place during exposure between 7 days and 4 months. This phase transition caused the alteration of a dense microtexture into a porous one, thereby resulting in some loss of strength. However, once the conversion of AN into CAN neared completion, there was no further significant change in compressive strength. After 14 months exposure, the phase composition of cements consisted of HOAp and CAN as the major phases, and AN as the minor one. No decomposition of the cements was observed, nor was there any carbonation-caused erosion, suggesting that the CaP cements have a excellent durability in a hostile geothermal environment.

### B. Acid Resistant Cements

To improve resistance of the CaP cements to a $H_2SO_4$ solution (pH 1.6) at 90°C, various different organic polymer dispersions were incorporated into the cements. Among them, the acrylic-styrene copolymer (ASC) with a pH ~ 4 exerted a best performance on mitigating acid erosion of the cements. The reasons for making them less susceptibility to the acid attack were due to the following two major roles of ACS: The first was ASC's chemical affinity for the $Ca^{2+}$ ions liberated from monocalcium aluminate (CA) and calcium dialuminate ($CA_2$) in the calcium aluminate cement (CAC) reactant, so forming Ca-complexed carboxylate compounds in the interfacial contact zone between ASC and CAC; the other role was related to the coverage of the reaction products and the unreacted CAC and fly ash particles by the ASC film, generating a network structure. These roles significantly restrained the formation of gypsum yielded by the reaction between $H_2SO_4$ and CAC. Gypsum is detrimental to the cements because it expands, making them vulnerable to acid erosion. The loss in weight of ASC-modified CaP cements after exposure for 25 days to hot acid was only 2.6%, compared with 27.3% in unmodified cements after the same exposure time.

## FUTURE PLANS

In collaboration with Unocal and Halliburton, BNL will continue to work to develop acid-inert CaP cements. The physico-chemical factors contributing to a lower magnitude of acid erosion of CaP will be investigated. This work will include 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. $Al_2O_3$-rich calcium aluminate cements, supplied from Lafarge Aluminates Co., will be used as starting materials to generate a large amount of acid-resistant reaction products, and to reduce the formation of $CaSO_4.2H_2O$. Samples of the final material will be delivered to Halliburton and Unocal for their independent evaluations.

Also, BNL will investigate ways of preventing the development of microcracks generated by the shrinkage and propagation of cracks caused by brittleness. Work will center on developing and optimizing pumpable fiber-reinforced CaP cement composite systems. One approach will be to incorporate high-temperature stable fibrous materials into the CaP cements to create a composite structure. Six different fibers, carbon, glass, alumina, boron carbide, boron nitride, and a high-temperature polymer, will be used in this work. The criterion for success will be the ASTM testing procedure on toughness-related mechanical behaviors; a fracture toughness of at least 0.06 $MN/m^{3/2}$ is desired.

## INDUSTRY INTERESTS AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Halliburton Services | Cement properties characterization, pumpability studies, economic evaluation. |
| Unocal | Field testing. |
| Shell E&P Technology Co. | Field testing. |

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## CONTACTS

Raymond LaSala, EE-122
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585-121
Phone: (202) 586-4198
FAX: (202) 586-8185
E-mail: Raymond.Lasala@ee.doe.gov

Toshifumi Sugama
Brookhaven National Laboratory
Upton, NY 11973-5000
Phone: (516) 344-4029
FAX: (516) 344-2359
E-mail: sugama@bnl.gov

# CEMENTS FOR REMEDIATION OF DEFORMED WELL CASING

A.J. Philippacopoulos and M.L. Allan
Brookhaven National Laboratory

## KEYWORDS

geothermal wells, Geysers geothermal field, casing deformation, casing remediation, cements, material testing, high-temperature, structural analysis

## PROJECT BACKGROUND AND STATUS

This current project was initiated during the last quarter of FY 99 to search for appropriate cements, which are required in geothermal casing remediation operations. Casing remediation of geothermal wells is a cost effective alternative to plugging and abandonment. The precise nature of what causes these wells to excessively deform and therefore lose their productivity is currently not known. Formation movement, which in turn, is associated 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. At least 50 wells in Calpine's portion of The Geysers field were found to be severely deformed. In response to this problem, a GDO project developed a remediation procedure. It 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. Calpine is currently undertaking remediation projects at The Geysers geothermal field. BNL is participating in these remediation efforts by focussing on the development of optimum cement for the casing patch. Cement formulations are systematically tested to obtain material properties and their range of applicability. At the same time, numerical modeling is performed to investigate the patch/formation interaction. Laboratory testing and finite element analysis are carried out interactively to achieve optimization. Failure analysis of the cement patch as well as yield surface characterization of the cement materials will be carried out in FY2000. This is needed to evaluate the long-term performance of the remediation patch.

## PROJECT OBJECTIVES

The objective is to develop and analyze optimum cement for use in geothermal well casing remediation projects.

### *Technical Objectives*

- Analyze interactions of casing, cement and formation subjected to shear deformation and determine how cement properties can mitigate casing damage.
- Analyze proposed casing remediation method and determine required patch cement properties.
- Measure relevant material properties and derive appropriate descriptive models of different geothermal well cement formulations under confining stress at elevated temperatures.

### *Expected Outcomes*

- Cost effective cements appropriate for restoring productivity and accessibility of geothermal wells.
- Material properties suitable for a removable and retrievable casing patch, if another remedial operation is required in the future.

- Evaluation of the local behavior of the stress field in the neighborhood of the remediation operations.
- Optimum material performance at high temperature and confining pressures.
- Assessment of the reliability of the patch to future shearing from formation movement.
- Increased life expectancy of wells and reduced necessity for plugging and abandonment.

## APPROACH

The technical approach combines material development, testing and modeling. It is carried out interactively in the sense that results from each of these tasks are used in dealing with the other. For example, numerical modeling leads to refinements in material behavior, which in turn requires changes in material properties. Similarly, changes in cement properties may require different modeling techniques and further testing. Technical information pertinent to casing remediation of geothermal wells at The Geysers field is also obtained through interaction with Calpine who currently is carrying on remediation projects. Prior to Calpine, BNL has interacted with Unocal on this project. Technical exchange between BNL and Unocal was concentrated on wellbore deformation surveys and geologic data pertinent to The Geysers. Additional interaction was made with other research and industry players in this area such as Sandia National Laboratories and Terralog Technologies.

## RESEARCH RESULTS

A survey on cements for potential application to casing remediation of geothermal wells was conducted and completed. It revealed similar efforts by the oil industry to treat excessive deformation problems in oil wells. The consensus is to gain the benefit the oil industry’s experience and try to apply it to the geothermal industry. While there are similarities between these two cases, geothermal wells require special attention due to the high temperatures and pressures associated with their operation. The survey concluded that without quantitative data, specific to the environment within geothermal wells, it is difficult to come up with a particular cement mix for remediation projects in geothermal fields. While some interim solutions were given at the end of this survey, the main recommendation is that material selection requires technical justification. The latter must be done on the basis of testing and analysis.

Initial site data from The Geysers geothermal field were evaluated in order to gain insights of the potential causes of the large deformations experienced by several wells. Several wells located in the central and southern area of this field were logged with caliper surveys in 1996. Some of these results seem to correlate with the subsidence in the area. Combinations of loading, interface and boundary conditions as well as material contrast between layers have produced such deformations. It is an extremely difficult task to precisely evaluate such combinations without involving a large number of uncertainties. In order to obtain a preliminary appreciation of the factors involved, a set of geomechanical models were developed using generic properties. The resulting finite element models included the upper portion of a geothermal well and its surrounding formation so that well/formation interaction effects were included in the analysis (Figure 1). Stresses and deformations were evaluated using two-dimensional plane strain analysis. We considered different potential mechanisms, i.e., shearing, tension, axial/lateral compression and bending. Preliminary results based on elastic analysis showed that stresses developed in the casing are very sensitive to the particular mode of failure considered. In addition, the results from the geomechanical analysis depend strongly on the site layering and in particular on the material property contrast between layers.

The behavior of the casing patch is investigated using finite element models of the cement, liner and surrounding formation. These models simulate the localized behavior of the geothermal well in the vicinity of the remediation. They incorporate cement/casing/formation interactions. Using these models, the structural resistance of the casing patch is investigated for shearing failure conditions. Model development is carried out interactively with material development. A variety of cement mixes are investigated with the objective to select optimum properties. Extensive laboratory testing is done to evaluate the corresponding mechanical properties which, in turn, are employed in the analysis to obtain estimates of the casing patch resistance to shearing. The first phase of the analysis utilizes elastic properties. Subsequently, failure criteria that describe the triaxial strength of the developed materials are considered. Specifically, in addition to conventional Mohr-Coulomb criteria used for concrete models, we are investigating Willam-Warnke material models to describe the plasticity behavior of the cements to be used for remediation. As done for concrete, we are augmenting these models by a tension-cutoff criterion to account for cracking in the tension regime. The development of triaxial failure criteria for the remediation cement is expected to continue in FY2000. These criteria are very valuable for assessing the long-term response of the casing patch to future deformations.

Three cement mixes were selected for initial material property determination. The baseline mix is standard Class G cement/silica flour and the variations on this are latex-modification and reinforcement with fibres. Improvements in ductility, tensile and shear properties and fracture toughness are sought through the latter mixes. The potential benefits with respect to casing remediation are analyzed in the numerical modeling component.

## FUTURE PLANS

There are three key areas that need to be investigated in FY2000. The first corresponds to experimental testing of the cements to quantify their behavior at high temperatures and pressures to limits comparable to those encountered in geothermal wells and identify how pertinent properties can be optimized. The rate of property development is also of interest. The second corresponds to the development of triaxial failure criteria required to adequately describe the behavior of the optimum cements at high strains. Such criteria are required to evaluate the long-term behavior and the structural reliability of the patch. The third area basically corresponds to refined finite element analysis of the patch resistance to failure using the results of the above two areas of investigation. In FY2001 and 2002 it is planned to analyze the high temperature and pressure mechanical behavior of other cements (e.g., foam, carbonation resistant) and investigate the use of additives such as metakaolin to improve properties. More detailed mix design to optimize both short and long term performance will be conducted. The numerical modeling activity will be refined and consideration given to other patch configurations. In addition, materials models to describe behavior of fibre reinforced cements will be incorporated in the analysis. Other activities include design and operation of an experimental arrangement replicating a section of patched well casing to better understand failure mechanisms and to verify the results from numerical modeling.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| **Organization** | **Type and Extent of Interest** |
|---|---|
| Calpine | Use of cements for casing remediation at Geysers |

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Dr. A. J. Philippacopoulos and Dr. Marita L. Allan
Department of Applied Science
Building 526
Brookhaven National Laboratory
Upton, NY 11973
Tel: (516) 344 6090; (516) 344 3060
Fax: (516) 344 2359
E-mail: ajph@bnl.gov; allan@bnl.gov

Mr. Raymond LaSala
U.S. Department of Energy
Office of Geothermal Technologies, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585
Tel: (202) 586 4198
Fax: (202) 586 8185
E-mail: **raymond.lasala@ee.doe.gov**

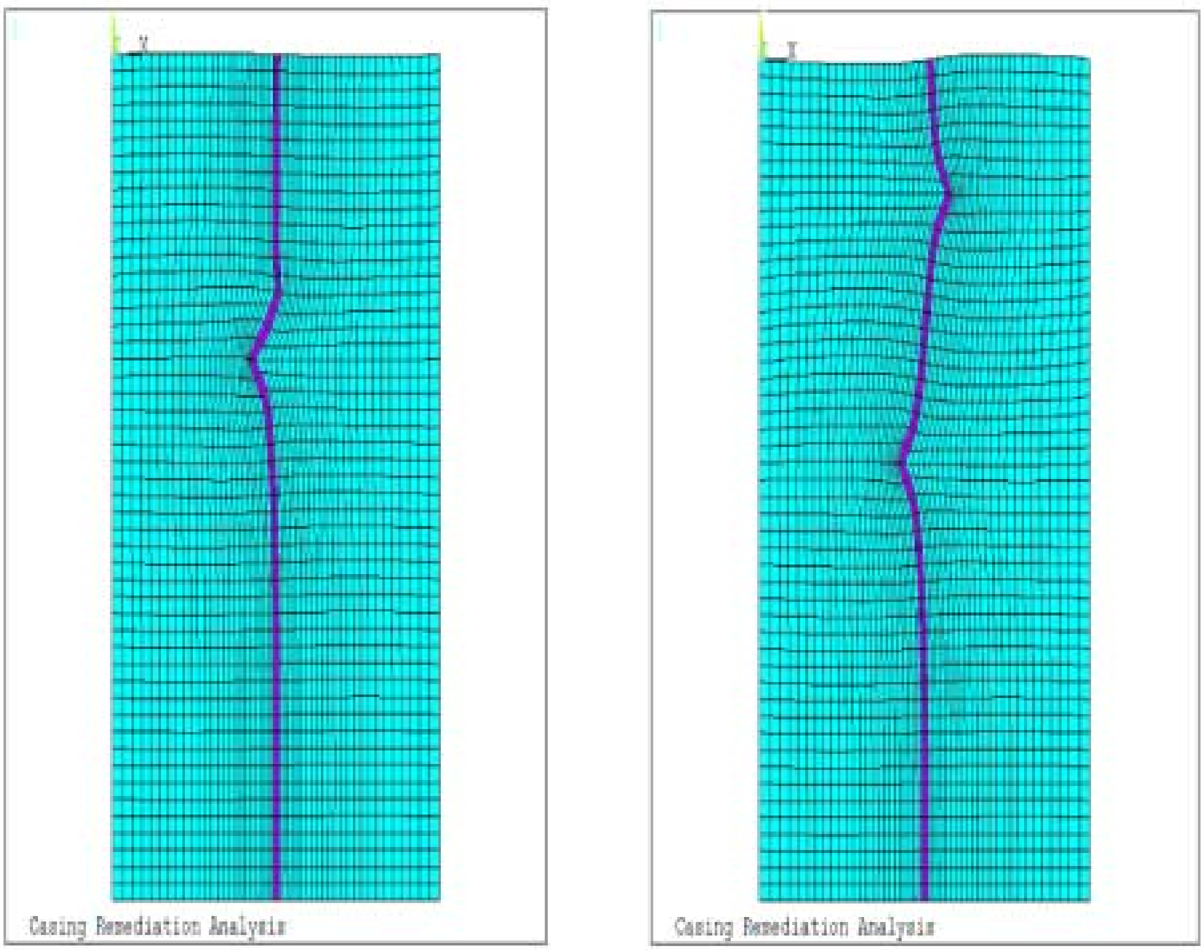


**Figure 1.** Geomechanical Models of Geothermal Wells showing Single (left) and Double (right) Modes of Casing Failures.

# THERMALLY CONDUCTIVE CEMENTITIOUS GROUTS FOR GEOTHERMAL HEAT PUMPS

M.L. Allan and A.J. Philippacopoulos
Brookhaven National Laboratory

## KEYWORDS

geothermal heat pumps, cementitious grouts, thermal conductivity, permeability, infiltration rate, heat transfer analysis, thermal stresses

## PROJECT BACKGROUND AND STATUS

This project commenced in FY 97 and investigates the performance of thermally conductive cementitious grouts for completing boreholes used with geothermal heat pumps (GHPs). Grouts were formulated to meet a number of criteria including thermal conductivity, coefficient of permeability, dimensional stability, durability, compatibility with conventional mixing and pumping equipment, environmental compliance and economics. The program has involved extensive experimental characterization of grout properties, field verification of grout performance, numerical modeling of grout behavior under thermal loads, and interaction with GHP industry and environmental regulators. The culmination of the research is successful use of the developed grout in commercial projects.

## PROJECT OBJECTIVES

The objective is to develop and demonstrate a low cost and environmentally acceptable thermally conductive cementitious grout that will result in decreased bore length requirements, decreased GHP installation costs and improved GHP performance.

### *Technical Objectives*

- Increase thermal conductivity of grout to at least 2 W/m.K so that bore length can be reduced by 20 to 30%.

- Monitor field performance of thermally conductive cementitious grouts and compare with conventional materials.

- Conduct in-situ infiltration tests to confirm sealing capability of grouts.

- Develop and use two-dimensional finite element models of grouted borehole and surrounding media to perform heat transfer and thermal stress analysis.

- Provide technical assistance to commercial users of thermally conductive cementitious grout.

### *Expected Outcomes*

- First cost installation of GHPs reduced by at least 10%.

- Thermal resistance reduced by at least 20%, particularly in dry conditions.

- Enhanced GHP long-term performance and marketability.

- Acceptance by environmental regulators.

## APPROACH

This project involves integration of laboratory testing, full-scale field work and computational analysis. Modeling of grout behavior under likely operational conditions, combined with experimental determination of material properties and verification of performance in field tests ensures a thorough and comprehensive evaluation and maximizes the level of confidence for using the developed grout. Other participants in the project are University of Alabama (thermal resistance tests, bore length calculations), Oklahoma State University (field tests) and Sandia National Laboratories (field tests). BNL has interacted with the Eastern Heating and Cooling Council and New Jersey Department of Environmental Protection to resolve concerns regarding effectiveness of grout as a hydraulic seal. Furthermore, technology transfer activities have included training for GHP installers and technical support on commercial projects using the developed grout. Details on the project and grout material and mixing specifications are available to the community at our web site (http://www.das.bnl.gov/ghpwb.htm).

## RESEARCH RESULTS

The optimized grout formulation (Mix 111) has a thermal conductivity up to three times higher than that of bentonite and neat cement grout. The grout consists of cement, water, a particular grade of silica sand, superplasticizer and a small amount of bentonite. The thermal conductivity of Mix 111 was 2.42 W/m.K (1.40 Btu/hr.ft.$^{o}$F) when mixed in the laboratory and wet cured. The mean value for field mixed grout was 2.19 W/m.K (1.27 Btu/hr.ft.$^{o}$F) This compares with 0.80 to 0.87 W/m.K (0.46 to 0.50 Btu/hr.ft.$^{o}$F) for neat cement grout, 0.75 to 0.80 W/m.K (0.43 to 0.46 Btu/hr.ft.$^{o}$F) for conventional high solids bentonite grout and 1.46 W/m.K (0.85 Btu/hr.ft.$^{o}$F) for thermally enhanced bentonite all of which refer to properties under wet conditions. The thermal conductivity of bentonite drops to 0.40 W/m.K (0.23 Btu/hr.ft.$^{o}$F) and that of thermally enhanced bentonite declines to 0.50 W/m.K (0.29 Btu/hr.ft.$^{o}$F) when dried out whereas Mix 111 only decreases to 2.16 W/m.K (1.25 Btu/hr.ft.$^{o}$F). Therefore, Mix 111 is particularly suited to conditions where drying of the grout may occur. Bore length reductions may be up to 22 to 37% based on calculations performed in FY 97 and depending on bore diameter, soil type and other variables.

Mechanical and hydraulic properties, shrinkage resistance, bond strength to U-loop and durability are also better than neat cement grouts. Of particular importance from an environmental concern is the ability of grout to act as an effective borehole sealant. Coefficient of permeability measurements and infiltration tests on grouted U-loops have confirmed that Mix 111 has acceptable sealing capability. Circulation of different temperature fluids through the U-loop was found to have a relatively small impact on infiltration rate. As fluid temperature was varied from 3 to 35$^{o}$C the infiltration rate remained of the order of $10^{7}$ cm/s. Infiltration rate was not greatly affected by partial replacement of cement with ground granulated blast furnace slag or fly ash.

The structural reliability of ground heat exchangers of GHPs was investigated for different thermal loading conditions. This task included two studies: (a) heat transfer and (b) thermal stress analysis of the system. First, the heat transfer problem was investigated. Such investigations were based on finite element modeling of the complete system i.e., the polyethylene pipes, the grout and the surrounding formation. Both pipes were incorporated into the model. Using these models, several heat transfer analyses were performed considering heating and cooling modes of operation as well as a parametric variation of the materials involved. Following the detailed evaluation of the heat response of the system, a thermal stress analysis was carried out. In the latter analysis, material properties obtained from our experimental investigations were input to the models for the grout materials. Furthermore, soils were modeled to represent a range of soft to stiffer site conditions. In addition, as part of our system reliability evaluation studies, a systematic investigation of the effects in the system response due to formation of gaps at key interfaces was undertaken. Debonding reduces the reliability of the ground heat exchangers. To quantify the impact due to debonding on the performance of GHPs, a dual approach was employed. First, a set of simple one-dimensional models were developed and used to perform variation of parameter studies considering debonding at the grout/formation interface. These results were further investigated using two-dimensional finite element analysis, which allows for a spatial variation of the gaps along the interfaces considered. The latter analysis provided additional insights into the debonding problem that cannot be obtained under one-dimensional assumptions. The above studies provided valuable conclusions regarding (a) the temperature and heat distributions in the pipe/grout/formation system, (b) the thermal stress and deformation fields in the grout and (c) the influence of debonding in the heat transfer characteristics of the system.

Field tests conducted at Oklahoma State University and Sandia National Laboratories on 250 ft deep boreholes verified the improved performance conferred by Mix 111. Thermal resistance was reduced up to 35% compared with high solids bentonite grout and 16% compared with thermally enhanced bentonite. The results confirmed the advantages of Mix 111 in different geologies and climatic conditions and will give justification for designers to specify the grout on future projects. The field test results are depicted in Figures 1 and 2.

Use of Mix 111 in consolidated and unconsolidated formations has been approved by the New Jersey Department of Environmental Protection. BNL collaborated with the DEP and GHP industry to develop permit conditions for the grout. A grout training session and field demonstration of Mix 111 were performed in New Jersey in conjunction with the Eastern Heating and Cooling Council, Geothermal Resources Group, Geothermal Services and GPU Energy. Other technology transfer activities included presentations at technical meetings and seminars, publication of research findings and news articles to reach a broad audience, establishment of a web site describing the project and provision of technical assistance and grouting guidelines to users and potential users of the grout.

The grout has been accepted and used successfully in commercial projects throughout the U.S. by companies such as Geothermal Services, Inc. and Enlink Geoenergy Services, Inc. One of the projects was for installation of a GHP system at a school and involved 130 boreholes. Interest in the material from the GHP industry has steadily grown due to the advantages in thermal conductivity, potential reductions in bore length, improved bonding characteristics, reproducible field performance and environmental compliance.

## FUTURE PLANS

DOE funding of all GHP research ended in FY99. Hence, it is not planned to pursue this project further. If funds become available there are several important areas that require investigation. These include conducting experimental tests and static and dynamic stress analysis to verify long-term stability and performance of Mix 111 grout, examination of bonding and infiltration characteristics between grout and surrounding formation under operational conditions, non-destructive testing of bond integrity and experimental verification of findings from numerical modeling.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
| --- | --- |
| Geothermal Services Inc. | Used Mix 111 grout on commercial projects. |
| Enlink Geoenergy Services Inc. | Used Mix 111 grout on commercial projects. |

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## CONTACTS

Dr. Marita L. Allan and Dr. A.J. Philippacopoulos
Department of Applied Science
Building 526
Brookhaven National Laboratory
Upton, NY 11973
Tel: (516) 344 3060; (516) 344 6090
Fax: (516) 344 2359
E-mail: allan@bnl.gov; ajph@bnl.gov

Mr. Raymond Fortuna
U.S. Department of Energy
Geothermal Division, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585
Tel: (202) 586 1711
Fax: (202) 586 8185
E-mail: raymond.fortuna@hq.doe.gov

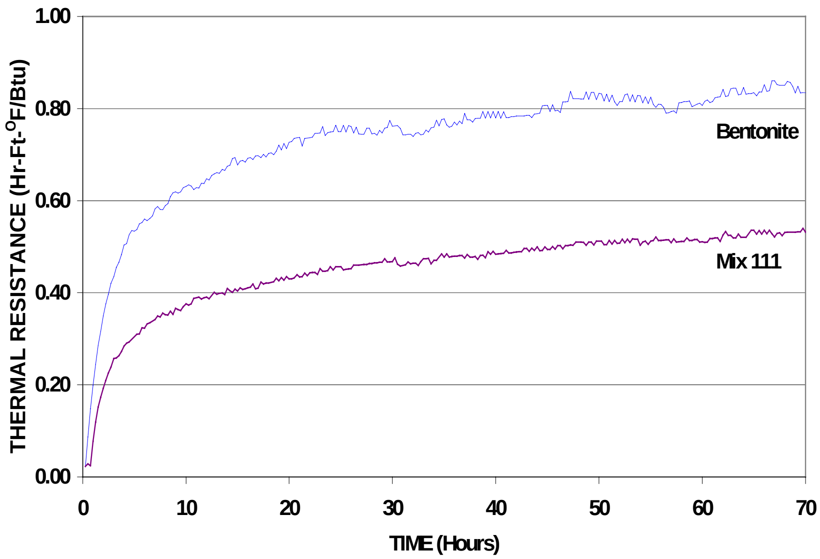


**Figure 1.** Field results from Sandia National Laboratories.

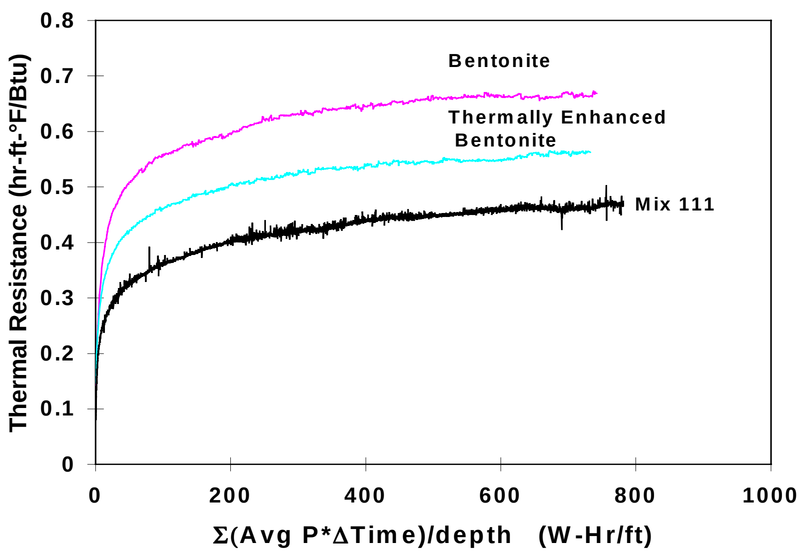


**Figure 2.** Field results from Oklahoma State University.

# SILICA EXTRACTION FROM HIGH SALINITY BRINES

William Bourcier, Molly McCutcheon,
Roald Leif and Carol Bruton
Lawrence Livermore National Laboratory

## KEY WORDS

Salton Sea geothermal system, silica precipitation, silica reinforced rubber

## PROJECT BACKGROUND AND STATUS

The problem of silica scaling in geothermal plants is now being approached as an opportunity to encourage precipitation of a useful silica byproduct. A technology that turns a waste stream of silica scale into a marketable commodity will have a favorable impact on the economics of geothermal power use. Silica, especially high surface area amorphous silica, is widely used in industry as paper and rubber additives, in cements, as pigments and inert fillers, and as chromatography adsorbates. The bulk of these specialty silicas are currently being synthesized in acid/base aqueous precipitation processes not unlike those which are induced in some spent geothermal fluids before reinjection. There is currently a considerable effort by geothermal energy producers to develop appropriate technologies for silica extraction.

CalEnergy is actively seeking a technology that produces a marketable silica precipitate from their spent fluids in the Salton Sea geothermal area. CalEnergy's Salton Sea geothermal field currently produces about 130 metric tons/day of silica. If the silica can be sold as a rubber additive at the current market price of approximately 70 cents/pound, a substantial revenue is generated, in addition to avoiding the landfill disposal costs of what was previously a waste product. Silica-enhanced rubber produces tires which bond better with steel wire, have higher tear strength, and have lower rolling resistance (Ferch and Toussaint, 1996). If successful, the amount of new geothermal silica entering the market is not large compared to the current production rate of about 3000 metric tons of precipitated silicas per day, so it should not significantly lower the price (Ferch and Toussaint, 1996).

CalEnergy uses two processes to control silica scaling (Featherstone et al., 1995). The crystallizer-reactor-clarifier (CRC) process extracts silica by encouraging precipitation on suspended seed materials. The seed materials are simply recycled silica precipitate. The solids are filtered and the fluid, which now has a reduced silica content, is reinjected. Brine acidification, the second method, takes advantage of the fact that silica precipitation rates are reduced as the acidity is increased. Dilute HCl is added to the spent geothermal brine. Lowering the pH by 0.5 to 1 units reduces scale formation in the reinjection system to nearly the same rate observed with the more expensive CRC process.

CalEnergy is currently producing silica with a modified brine acidification process in which a reactor/clarifier step is carried out before downstream zinc extraction and reinjection. This step involves adding a base to the previously acidified solution, raising the pH and inducing precipitation. Nuclei are used to enhance precipitation and accelerate settling to separate the silica precipitate from the brine. The properties of this precipitate are being optimized for use in one of the industrial applications of silica mentioned above. Another requirement is that the fluid still be suitable for the zinc extraction process that takes place immediately after silica extraction.

For reasons of price and market volume, CalEnergy prefers to produce silica suitable as a rubber additive. For this application, the silica must have a high surface area (90-250 $m^2/g$), high density of internal pores

(1.7-50 nm diameter), and an appropriate number of surface silanol (SiOH) groups in order to bond to the silane coating agent and rubber.

## PROJECT OBJECTIVES

Our objective is to use benchtop experiments, a variety of advanced characterization techniques, and geochemical modeling calculations to modify and optimize the hybrid brine acidification process to produce silica with favorable properties for commercial use. To date, CalEnergy has not produced in pilot scale tests a viable silica precipitate for use as a rubber additive, although their product appears to be adequate as a less valuable pozzolanic concrete additive. When the silica precipitate is silane treated (see Figure 1) and incorporated in rubber, the silica particles do not disperse and bond well. The rubber therefore has inferior properties in terms of torque resistance, tensile strength, hardness and viscosity.

Several possibilities exist as to why the silica fails to bond as well as commercial silicas. CalEnergy's geothermal precipitate contains substantial amounts of contaminants, in particular iron. This is a consequence of the high iron concentration in the brine. Although the precipitate can be leached to reduce the iron content from several weight percent to a fraction of one weight percent, iron and/or other trace elements may change surface properties enough that the silica does not bond well with the silane coating agent.

Another possibility is that the silica does not have enough or the right kinds of surface silanol groups which play a key role in bonding to the silane coupling agent. Some infrared spectroscopic work already performed by CalEnergy suggests that there are a similar number of silanol groups on their silica compared to commercial silicas. But it is possible that they are clustered on the surface and therefore give rise to the wrong surface charge or acidity to bond well with the coupling agent. It has already been observed that an aqueous suspension of the CalEnergy silica has a lower pH than commercial silica rubber additives.

A third possibility is that the geothermal silica has the right molecular structure but that it has the wrong physical properties. The particles may be too agglomerated, or have the wrong pore sizes, or have some other property developed during the extraction, drying, and silane treatment processes that makes it unsuitable as an additive.

Our goal is to examine these potential problems and others and resolve the reasons for the inferior behavior of the silica precipitate and formulate a method to produce the right kind of precipitate. With this goal in mind, our specific technical objectives are as follows.

### *Technical Objectives*

- Identify the key molecular properties of the precipitated silicas in terms of number and types of silanol surface sites, degree of polymerization of the silica network, and amount of adsorbed water, which are favorable for its use as a rubber additive

- Identify the key physical properties of the precipitated silicas in terms of surface area, pore size and distribution, and dispersion in oil, which are favorable for its use as a rubber additive

- Provide an optimized precipitation process methodology in terms of which base is added to increase pH, final pH of precipitation process, and type of seed added to induce precipitation

- Determine whether minor and trace elements in the silica precipitate affect its success as a rubber additive

***Expected Outcomes***

- Identify the key molecular properties that allow some precipitated silicas to function as effective rubber additives

- Help define a method of pretreatment of the solution or post-treatment of the solids to remove chemical impurities

## APPROACH

We will generate silica precipitates by performing a matrix of laboratory simulations of the brine acidification process using simulated Salton Sea brine with and without iron present. We will include in this matrix several types of bases including $Na_2CO_3$, NaOH and $Ca(OH)_2$ and vary the neutralization pH over a range of pH values within the limits provided by CalEnergy based on avoiding corrosion yet having acceptable silica precipitation rates. We will characterize the physical properties of the precipitates from the laboratory experiments in terms of their surface area, pore size distribution, and (after silane treatment) their dispersion in oil. We will also characterize the molecular properties of the precipitates using nuclear magnetic resonance (NMR) to determine the number and types of surface silanol sites, the amounts of sorbed water, and the degree of polymerization of the silica network.

If the presence of minor and trace elements in the silica precipitate are found to be a problem, we will then perform modeling calculations of the silica precipitation process to determine whether a viable and cost-effective method exists for removing iron from the brine prior to silica precipitation. These calculations will be performed using existing chemical modeling codes.

## RESEARCH RESULTS

We first performed laboratory simulations of the silica precipitation process in glassware at room temperature. This allowed us to develop procedures for preparing silica supersaturated solutions, for adding base to the solutions to promote silica precipitation, and for separating and examining the precipitate. We are now doing the experiments at elevated temperatures in a stirred pH-controlled reactor approaching the P-T conditions of CalEnergy's Salton Sea extraction site of 108$^{o}$C and 5-15 psi. These experiments generate silica precipitates that we then analyze for their suitability as rubber additives.

We analyzed several precipitated silicas furnished by CalEnergy (including both samples made by CalEnergy from Salton Sea brine and synthetic commercial products) using scanning electron microscopy (SEM), X-ray diffraction (XRD) and NMR. An SEM photomicrograph of silica manufactured by Degussa (a silica which works well as a rubber additive) is compared with a precipitate from the Elmore site in Figure 2. Although both samples have relatively high surface areas of ~100-200 $m^2$/gram as measured with BET gas adsorption, the SEM photos show that they have different textures. The Degussa material appears to be agglomerated into sub-micron sized balls, whereas the Elmore material appears to be a loose aggregate of even finer 10-50 nm balls. Pore size analysis should help to quantify the textural differences.

Preliminary NMR data on these samples shows that the average silica-oxygen bond numbers, amounts of adsorbed water, and amounts of hydrogen bonding differ between the various solids. In general, the Degussa material has a smaller degree of silica polymerization (a slightly smaller average number of Si-O bonds per silica tetrahedron) than the Salton Sea samples, but a comparable degree of hydrogen bonding of the surface silanol sites. Although at this point we are uncertain how these observations affect bonding of the silica in rubber, we can use the observations in an empirical way to produce silicas with properties that match the silicas that bond well to rubber.

We have done some modeling calculations of the silica precipitation process aimed at determining a method for removing minor and trace elements, in particular iron, present in the silica. Our first calculation simulates the effect of adding soda ash ($Na_2CO_3$) to the brine to increase the pH and induce silica precipitation (see Figure 3). We use this base rather than NaOH or lime because the soda ash should react with the dissolved iron in the brine to precipitate iron carbonate ($FeCO_3$) and perhaps other carbonates as well. Our hope is to be able to selectively remove the iron and any other metal which gives the silica unfavorable properties, but leave behind metals such as zinc which will be extracted downstream and sold. The results for the simplified Na-Ca-Mg-Fe-Zn-C-Si-Cl-$H_2O$ system (Figure 3) show favorable trends. Iron carbonate is the most insoluble carbonate and precipitates first as the $Na_2CO_3$ is added. Shortly thereafter $CaCO_3$ begins to precipitate and still later ZnO. In reality, the precipitate will probably be a single carbonate phase that contains varying amounts of Ca, Fe, Mg and some Zn. A solid solution model for carbonates that can be used to quantify the composition of the likely precipitate does not currently exist. We also were forced to approximate activity coefficients for these high salinity brines using methods appropriate for lower salinities. Nevertheless these results suggest that it will be possible to selectively lower the iron content of the brine with soda ash addition. Model results can be validated experimentally if this work is pursued.

## FUTURE PLANS

We will continue our matrix of silica precipitation experiments using the results of completed tests to guide the choice of parameters for future tests. If we find that a specific type of base or endpoint pH has a favorable impact on the properties of the precipitate, we will pursue those conditions in future tests. We will determine whether the presence of other metals in the brine, including Fe and Mn, have an impact on the precipitate. We will determine the suitability of our produced silicas for use as rubber additives by examining their dispersive properties in oils after they are treated with a silane coupling agent. We will continue to characterize the silica precipitates with the techniques mentioned above and others to provide additional insight into the problem of producing silicas with favorable properties for use in producing tires.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| CalEnergy Operating Company | Provides samples for analysis, conditions of silica precipitation process, characteristics of silicas produced, brine analyses, operational limitations of silica extraction process conditions, and consultation on organosilane chemistry. |

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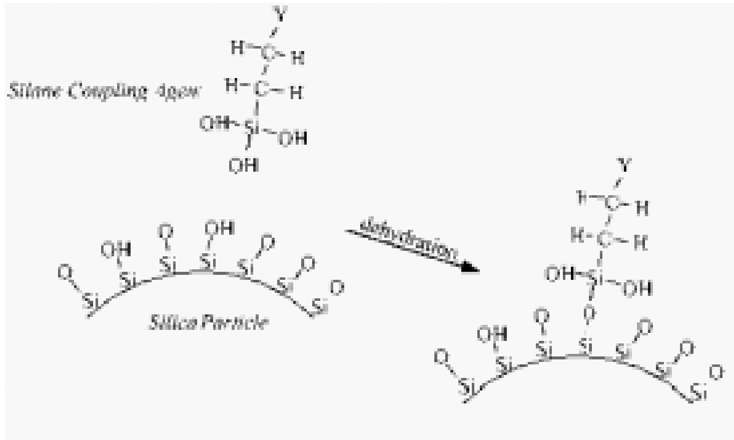


**Figure 1.** Silica particles are silane treated to enhance dispersion and bonding with rubber. The silane coupling agent reacts with a silanol group (SiOH) on the silica surface in a dehydration reaction. As a result, a chemically active 'R' group is bound to the silica surface that can then react with the rubber to increase rubber hardness and strength. The silane treatment changes the character of the silica surface from hydrophyllic to lipophyllic.

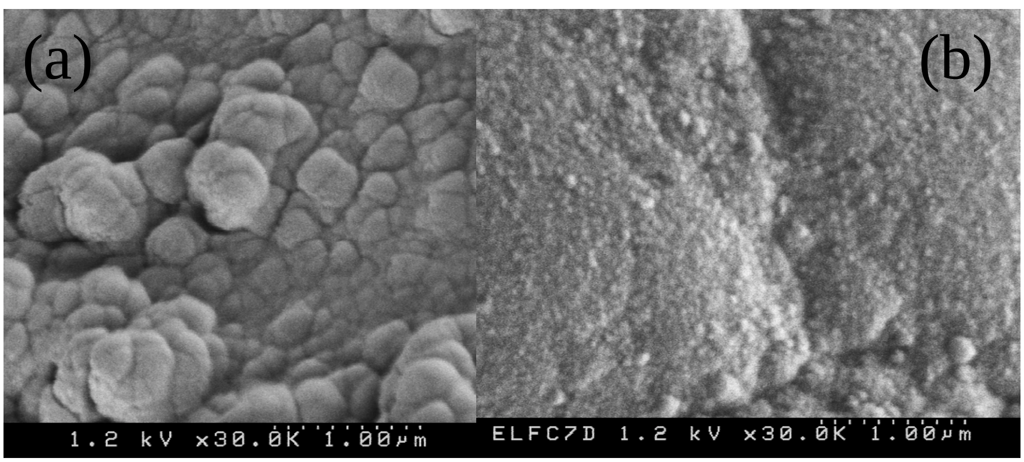


**Figure 2.** Comparison of SEM photomicrographs of (a) Degussa commercial precipitated silica and (b) silica precipitate produced at CalEnergy's Elmore region in the Salton Sea. Scale bars are one micron in both photos.

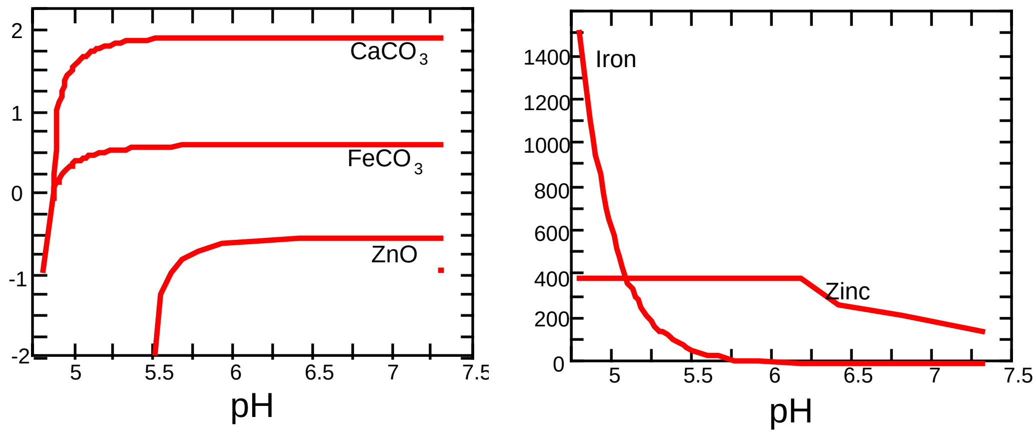


**Figure 3.** Results of modeling calculation of the effects of adding $Na_2CO_3$ to the brine to raise pH and induce mineral precipitation. The concentration of iron is selectively lowered due to iron carbonate precipitation until just above pH 5.5 where zinc oxide begins to precipitate. Calcite (calcium carbonate) also precipitates as the pH rises. Calculations performed using the React code (Bethke, 1992).

## CONTACTS


William L. Bourcier
Lawrence Livermore National Laboratory
L-219
P.O. Box 808
Livermore, CA 94550
Phone: 925-424-3745
Fax: 925-422-0208
Email: bourcier1@llnl.gov

Raymond LaSala
Office of Geothermal and Wind Technologies
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-4198
Fax: (202) 586-8185
Email: Raymond.LaSala@ee.doe.gov

# ADVANCED PROCESSES FOR GEOTHERMAL BRINES MULTIPLE RESOURCES (GMR)

## Geothermal Silica

M.S. Lin
M. Bohenek
G. Joshi-TopJ
L. Shelenkova
W.M. Zhou
Brookhaven National Laboratory
Department of Applied Science
Energy Science and Technology Division
Upton, New York 11973

## KEY WORDS

biochemical, chemical, processing, decontamination, amorphous silica

## PROJECT BACKGROUND AND STATUS

As part of the overall Geothermal Energy Research Program aimed at the development of economical geothermal resource production systems, the Advanced Processes for Geothermal Brines effort is the development of economical and environmentally friendly methods for treatment of geothermal by-products and their conversion to commercially viable products. This includes the production of silica products from geothermal mineral rich precipitates (MRPs) and mineral rich brines (MRBs). The anticipated net-result is minimum or no disposal costs and increased revenues. This R&D effort is conducted in collaboration with several industrial groups and educational institutions. This is an ongoing project which evolved from the development of a technology based on chemical and biochemical processes. This program was initiated in 1989 as a way to convert geothermal wastes from hazardous to non-hazardous wastes. The technical and economic feasibility of this technology has been demonstrated. In FY 1999, the possibility was explored of using low salinity geothermal brines as a source of silica. The chemistry and physics of these brines is quite different from that of high saline brines. The silica is present in low concentration, so new processes for recovery must be developed. However the product has the potential to be superior to that derived from high salinity brines.

- Biochemical and chemical processes are being developed in which MRP’s containing silica are converted to high quality amorphous silica. Depending on the chemical properties of the starting material and the properties of the desired end product, this material can be chemically ‘tailored’ for multiple commercial applications.

- A laboratory-scale pilot plant has been used for the optimization of processes used in the emerging technology. The process for treating high saline geothermal brines has been transferred to Unocal, MAGMA and CalEnergy.

- Process is in progress for producing silica from low salinity geothermal brine.

## PROJECT OBJECTIVES

Mineral rich precipitates (MRPs) derived from geothermal brines contain amorphous silica. This silica has a significant commercial potential. The objective of this project is to explore and chemically characterize MRPs from different geographical regions recommended by industrial partners. The properties of these silicas will determine which modifications of the patented BNL silica process and subsequent processing of the produced high grade silica will be required to meet the requirements of marketable products.

***Technical Objectives***

- Continue updating the current database dealing with the chemical and physical properties of geothermal amorphous silica.

- Expand laboratory scale experiments in which techniques that combine biochemical and chemical treatment are used to generate high quality amorphous silica.

- In the chemical composition of this product a major contribution to pigmentation is due to the presence of different chemical species of metals, especially iron. Address these properties in terms of the ultimate product (e.g., custom chemicals, fillers, etc.) for which the produced amorphous silica will be the feedstock.

***Expected Outcomes***

- Under appropriate processing conditions (patent pending) the extent and the rates of depigmentation are fast which allow a cost-efficient production of amorphous silica. The MRP source using the BNL processes becomes a new natural resource of amorphous silica produced by chemical means. The market for amorphous silica is large and varied. In 1994 the total production (global) was 2,610,000 metric tons of different types of amorphous silica, of which, precipitated silica alone (~700,000 metric tons) generated 1600 million dollars per year.

- Anticipated commercial returns will help offset the costs of geothermal power production.

## APPROACH

- The experimental strategy used at BNL for the development of a cost-efficient technology for the conversion of geothermal brines and residues into environmentally acceptable products is based on a combination of biochemical and chemical processes which separate and concentrate commercially valuable constituents of geothermal brines and precipitates.

- A laboratory-scale pilot plant has been constructed and is being used for the optimization of processes used in the emerging technology.

- In an effort to improve the physical properties of processed MRP’s, thereby enhancing their attractiveness as an industrial feedstock, BNL is conducting experiments examining the utility of additional MRP treatment process, such as reprecipitation.

## RESEARCH RESULTS

During long-term collaboration with geothermal power companies from Imperial Valley, BNL has developed processes for treating geothermal silica produced from the area. The R&D efforts have gathered significant information about the chemical and physical properties of geothermal silica produced from high saline brine. This includes (1) patented process, (2) process variables Vs properties of products, (3) product applications, (4) scaling up parameters, (5) flexible models, (6) fully operative laboratory scale pilot plant. The results were shared with UNOCAL, MAGMA and Successors (e.g., C. E. Holt, CalEnergy). Further, the current BNL process (patent pending) has been serviced recently to CalEnergy Co. through communications, visits and in-lab work-along trainings.

In FY 1999, BNL is collaborating with Oxbow, ORMAT and other Cos. in R&D for producing silica from low saline geothermal brine. Laboratory test results have showed that the low saline samples contain low concentrations of silica, about 500-ppm. Several methods have been tested for recovering the silica in low saline brine. Currently, the “ salt out” and flocculent precipitation method are selected for field test. When properly precipitated, the silica is very pure and has a very surface area. The results of chemical and physical properties tested on initial laboratory products showed the silica produced compares well with leading brands on market.

## FUTURE PLANS

- Conduct operational planning jointly with industry.
- Plan and support field tests for optimization studies and economic analysis at Oxbow plants.
- Test parameters of the processes particularly on the possible elimination of process wastes, recycling chemicals and the utilization of existing facilities in the field.
- Prepare technical reports, peer reviewed papers, monthly reports, and annual operating plans.
- NEPA review and compliance. Technology Transfer.

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Premuzic, E.T., Lin, M.S., et al. Conversion of Geothermal Brines and Sludges to Commercial Products. (Four patents pending).

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| **Organization** | **Type And Extent Of Interest** |
|---|---|
| **OXBOW**<br>Dick Benoit<br>Stewart Johnson<br>(702) 850-2248<br><br>**ORMAT**<br>Dan Schochet<br>Moshe Grassiani<br>(702) 356-9029 | Development of new feedstocks for the production of (1 ) fine chemicals from geothermal wastes. (2) Selective recovery of valuable metals. (3) Production of agricultural grade of sulfur from Stretford (and similar) waste streams. (4) Development of anti-fouling agents. Reservoir characterization and exploratory studies |
| **Florida Electric Power**<br><br>Mary McCloud<br>(561) 694-3478 | **CET Environmental Services, Inc.**<br><br>Voytek Bajsarowicz<br>Brown & Caldwell<br>P.O. Box 8045<br>Walnut Creek, CA<br>(925) 210-2510 |

## CONTACTS

Mr. Raymond LaSala
U.S. Department of Energy
Office of Geothermal Technology Division
Room 5H-048, EE-12/FORS
1000 Independence Avenue, SW
Washington, DC 20585
Phone: (202) 586-4198
FAX: (202) 586-8185

Dr. Marshall Reed
U.S. Department of Energy
Office of Geothermal Technology Division
Room 5H065-CE122/FORS
1000 Independence Avenue, SW
Washington, DC 20585
Phone: (202) 586-8076
FAX: (202) 586-8185

Dr. Allan J. Jelacic
U.S. Department of Energy
Office of Geothermal Technology Division
Room 5H065-CE122/FORS
1000 Independence Avenue, SW
Washington, DC 20585
Phone: (202) 586-6054
FAX: (202) 586-8185

Dr. Eugene T. Premuzic
Brookhaven National Laboratory
Department of Applied Science
Science and Technology Div.
Upton, NY 11973
Phone: (516) 282-2893
FAX: (516) 282-5523
**Retired at the end of FY 1999**

Participating R&D Team Contact:

Dr. Mow Lin

# INVESTIGATION OF INNOVATIVE POWER CYCLES USING MULTI-COMPONENT WORKING FLUIDS FOR MEDIUM-TEMPERATURE GEOTHERMAL APPLICATIONS

Desikan Bharathan
Vahab Hassani
National Renewable Energy Laboratory

## KEY WORDS

Ammonia/Water, Multi-component working fluids, power cycles

## PROJECT BACKGROUND AND STATUS

Many of the high-temperature (>300$^{o}$F) geothermal reservoirs have generally been identified and are already producing power using a variety of power-conversion technologies. While lower-temperature reservoirs are numerous and scattered, the cost for exploiting these resources has remained high, thus limiting their use for power production.

In order to lower the cost for power production and increase the resource utilization, the US DOE geothermal program is funding two projects to look into using multi-component working fluids (specifically ammonia and water). One of the projects, conducted by Exergy Inc. is attempting to build a nominal 6 MW electric power plant. In the other project, NIST is generating experimental data and computer models for consistent estimation of ammonia/water mixture properties.

The potential use of multi-component working fluids has been documented to yield higher utilization of the resource throughout the literature. However, the general difficulties in their use pose significant roadblocks to their wide use. The difficulties are many, starting with the lack of adequate property information for the mixtures, to analyzing the numerous heat-exchanger arrangements in the cycle (with the primary aim of reusing the heat in its different segments), to the ultimate lack of operating experience with such systems.

In this work, NREL investigated power system cycles. NREL examined in detail the use of the working fluid mixtures, specifically, ammonia/water mixtures in subcritical pressure ranges. The design of the cycles were driven by the desire to maintain the overall cost of the system and especially all recuperative and other heat exchangers to a minimum.

## PROJECT OBJECTIVES

In pursuit of its goal of reducing the cost of electricity from various geothermal resources, the Department of Energy (DOE) is conducting investigations to improve the performance and economic viability of geothermal power cycles. One of the DOE tasks, carried out by NREL, is to investigate the performance and cost-reduction potential through the use of multi-component working fluids, specifically ammonia/water, in geothermal power systems.

***Technical Objective***

- To investigate methods for improving the performance of small-scale geothermal power systems through the use of multi-component working fluids, specifically ammonia/water mixtures, in closed cycle systems.

***Expected Outcome***

- Upon completion of the task, the final report will address various innovative cycle arrangements that are designed to make the best use of the ammonia/water mixture as the working fluid and will provide a summary of the relative merits amongst the various cycles considered.

## APPROACH

The geothermal brine will be used to generate preferentially vapor of the lighter components of the mixed working fluid in the evaporator. The vapor is then allowed to pass through a turbine to generate work. It comes in contact with a cooled heavier component in the condenser. The mixing occurring at the turbine exhaust helps lower the condenser pressure to extract more power. A recuperative heat exchanger is introduced in the cycle to transfer part of the heat carried out by the evaporator effluent to the returning feed or condensate.

As opposed to the use of a pure fluid, in the case of mixed working fluids varying temperatures occur both in the evaporator and the condenser. Such a temperature variation allows these cycles to make use of a more-effective, less-irreversible heat transfer in both heat exchangers, to result in a more efficient cycle.

NREL conducted detailed exergy analyses to identify components where major losses of the availability of energy occurred in each of the cycles. Such an analysis lead to a better component arrangement in the subsequent modified cycles. NREL also examined the most-effective economical options for the components.

For the cycle investigations, NREL used the commercially available process modeling software, ASPEN.

## RESEARCH RESULTS

NREL acquired the ASPEN software necessary for conducting the analyses. NREL conducted investigations of commonly-used Rankine cycle as the base line. We also investigated two-other cycles, namely, the Kalina KCS-11cycle and the Maloney-Robertson cycle, both designed for effectively using a mixed working fluid. In addition, five different innovative cycle options were also investigated. Detailed results indicate that three of the innovative cycles yield potentially high energy conversion efficiency. These cycles remain candidates for further evaluation to arrive at cost comparisons.

## FUTURE PLANS

NREL expects to extend the results of this study to generate a suitable set of component arrangements, cycle hardware, and operating conditions for the use of ammonia/water mixtures appropriate for use with medium-temperature geothermal systems. NREL will provide detailed models for all the heat exchangers, turbine and pumps for quick evaluation of the cycle for various resource temperatures, ambient conditions and other restrictions that a site may impose. Such a model will allow one to vary component arrangements and operating conditions readily, and to quick evaluate the performance potential for the such systems. NREL plans to add cost estimates to the components to help arrive at an estimated power system cost and the cost of electricity production in various seasons of the year.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| ORMAT | Modular implementation of more efficient binary cycles |
| TIC Inc. | Construction and Modular implementation of binary cycles |
| Exergy Inc. | On evaluation of binary power cycle energy conversion potential |
| Bibb & Assoc. | Modular implementation of more efficient binary cycles |

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## CONTACTS

Desikan Bharathan
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado
Tel: (303) 384-7418
Fax: (303) 384-7495
E-mail: Desikan_Bharathan@NREL.Gov

Ray LaSala
U.S. Department of Energy
Office of Geothermal and Wind Technologies, EE-12
1000 Independence Avenue, S.W.
Washington, D.C. 20585-0121
Tel: (202) 586-4198
Fax: (202) 586-5124
E-mail: raymond.lasala@ee.doe.gov

# AMMONIA/WATER CONDENSATION: VERTICAL SHELL AND TUBE TESTS

Vahab Hassani and Judy Netter
National Renewable Energy Laboratory



## KEY WORDS

condensation, ammonia/water, shell and tube heat exchanger


## PROJECT OBJECTIVES

The objective of this work is to study condensation of ammonia/water vapor mixtures used in geothermal binary power plants. This work experimentally investigated the coupled process of heat and mass transfer in film condensation of ammonia/water binary vapor mixtures in forced flow through shell and tube condensers with condensation on the shell side. The experiments were conducted with the test condenser aligned in vertical orientation. The results of this study provide valuable information to the heat exchanger manufacturers to design the most efficient heat exchangers for application in binary geothermal power plants.

### *Technical Objectives*

- To gather experimental data on convective condensation of ammonia/water vapor mixture to understand the combined heat and mass transfer process.

### *Expected Outcome*

- The results of this study provide valuable information to the heat exchanger manufacturers to design the most efficient heat exchangers for application in binary geothermal power plants using ammonia/water as working fluid.

## BACKGROUND AND STATUS

Thermodynamic cycles using a binary mixture working fluid have attracted much attention recently because of their high thermal efficiency when used with moderate- to low-temperature geothermal resources. The Next Generation Power Plant study conducted by EPRI showed that binary systems with mixed working fluids (such as hydrocarbons or ammonia/water) are one of the best systems with low levelized cost of electricity production that can be applied to the low-temperature geothermal resources. However, the commercialization of binary cycles with mixed working fluids by U.S. industry has been very slow because of unresolved design issues one of which is lack of reliable information about the convective condensation of binary mixtures.

One of the important issues that impedes engineers in the design of heat exchangers for binary systems is the lack of understanding of the condensation characteristics of mixed fluids when applied to binary cycles. Condensation of binary mixtures is a complex process. The review of the existing literature on condensation of binary mixtures indicates that there is a major lack of understanding of the characteristics of the vapor phase mass transfer during the condensation of a non-azeotropic binary mixture. It is known that in condensers using binary mixtures, the heat transfer coefficient is lower than that of pure working fluids. This is because the less volatile component condenses more readily while the more volatile component accumulates in the vapor phase near the vapor-liquid interface. Such a layer serves as a mass diffusive resistance as well as thermal resistance which lowers the interfacial temperature resulting in reduced condensation.

In addition, the effect of mixture composition on the formation of the vapor diffusion layer, and mass and heat transfer rates that are essential for predicting the condensation rate have not been well established for the types of binary mixtures of interest for geothermal power plant applications. In general, the complexity of the heat and mass transport rapidly increases as the number of mixture components increases. Research in this area is clearly needed with special focus on geothermal binary cycle applications and with ammonia/water mixtures that are of interest to the geothermal industry.

There are only a few empirical models that have been developed to predict condensation process of limited binary mixtures. Consequently, there is a great uncertainty about applicability of the models to binary mixtures different from those on which the models were based.

## APPROACH

In this effort, NREL has designed and constructed an experimental setup that can handle various ammonia/water vapor mixtures. This setup is capable of simulating vapor mixture conditions observed in heat exchangers proposed for use in the Kalina cycle or other organic Rankine cycles. The condensing test unit is a shell and tube configuration and is sized and designed such that near-complete condensation may be achieved. The practical interest of this problem is the design and optimization of condensers. From the fundamental viewpoint, the following issues are investigated:

1. Heat transfer performance during condensation and its physical mechanisms

2. Flow characteristics and pressure drop in the condenser

3. Mass transfer in the vapor phase

The independent variables, such as the system pressure and the vapor composition, may be varied to study these effects on the transport phenomena.

The setup is designed such that, initially, the binary mixture can be passed through the shell side (annular space) while the cooling water is passed through the tube. The distribution of the vapor static pressure, the composition of the mixed vapor, and the cooling water temperature along the flow direction are measured during the tests. Capillary tubes with mini-valves are used for collecting samples of the binary vapor mixture from the test unit.

The experimental setup consists of four sections: boiler, condenser, fluid re-circulator, and a fluid bypass section. Ammonia/water vapor mixture is generated in the boiler and is condensed in the condenser section. The residual vapor and the condensate from the condenser is further condensed and cooled in the after condenser. The liquid ammonia-water mixture is then pumped back to the boiler through a fluid re-circulation pump. The boiler is also connected to a bypass system to enable system stabilization after start-up and before shutdown and provide better control of the process.

## RESEARCH RESULTS

The ammonia/water tests were carried out at various condensing pressures. Table (1) gives a list of tests conducted under different operating conditions.

**Table 1. List of Ammonia/Water Tests**

| Test # | Boiler Composition $NH_3/H_2O$ | Condensing Pressure, psia | Vapor Mass Flow Rate, kg/hr |
|---|---|---|---|
| a-719-45-0L | 70/30 | 57 | 29.9 |
| a-720-65-0L | 70/30 | 77 | 17.1 |
| a-802-40-0L | 70/30 | 52 | 21.7 |
| a-817-40-0L | 70/30 | 52 | 22.7 |
| a-719-45-30L-cone2 | 70/30 | 57 | 40.4 |
| a-720-65-30L-cone1 | 70/30 | 77 | 19.7 |
| a-817-40-45L-cone | 70/30 | 52 | 13.1 |
| a-719-45-5L-spr1 | 70/30 | 57 | 23.4 |
| a-720-65-4L-spr1 | 70/30 | 77 | 20.0 |
| a-817-34-26L-spr | 70/30 | 46 | 14.4 |
| a-817-34-55L-spr | 70/30 | 46 | 14.4 |
| a-817-34-75L-spr | 70/30 | 46 | 14.4 |
| a-817-34-112L-spr | 70/30 | 46 | 14.5 |

In some of our tests, dry vapor was introduced into the test section. These tests have been identified by a suffix of “0L” in our naming scheme as shown in Table 1. In some other tests we used aiding flow to assist the condensation process. For some tests the aiding flow was introduced into the test section through a conical reservoir built at the top of the test condenser which allowed introduction of the aiding flow as a liquid film around the tube. These tests have been identified by “cone” suffix in our numbering scheme. The rest of the tests with aiding flow consisted of using a spray nozzle to spray the liquid as fog into the top section of the test condenser. These tests have been identified by “spr” suffix in our numbering scheme. The following sample analysis is provided to allow a better understanding of the data analysis procedure.

**Ammonia/Water Test # a-817-40-0L**

The vapor, cooling water, and the condenser wall temperatures for this test are plotted in Figure 1 vs. the condenser length. The gradual decline of vapor temperature along the length of the condenser can be seen in this figure. The interface temperature for ammonia/water tests have been calculated according to the procedure outlined by Hassani and Netter (1999). This figure shows that the film resistance is the dominant resistance, however, the diffusion layer resistance is not negligible.

The cooling water and vapor mass flow rates for this test were 560 kg/hr and 22.7 kg/hr respectively. Figure 2 shows the condensing heat transfer coefficient vs. the temperature difference between the bulk vapor and the tube wall temperature. Figure 3 shows the condensing heat transfer coefficient along the axial length of the test condenser. The condensing coefficient shows an interesting trend along the condenser length. At the inlet to the test condenser, the vapor velocity is relatively high and no condensation has yet occurred. Therefore, high condensing heat transfer is observed. As the vapor flows through the test section and loses some of its mass as a result of condensation, the vapor velocity in the shell reduces considerably. The reduced flow velocity causes the heat transfer coefficient to reduce. The other fact that impacts the flow and heat transfer mode is that the driving force which is the temperature

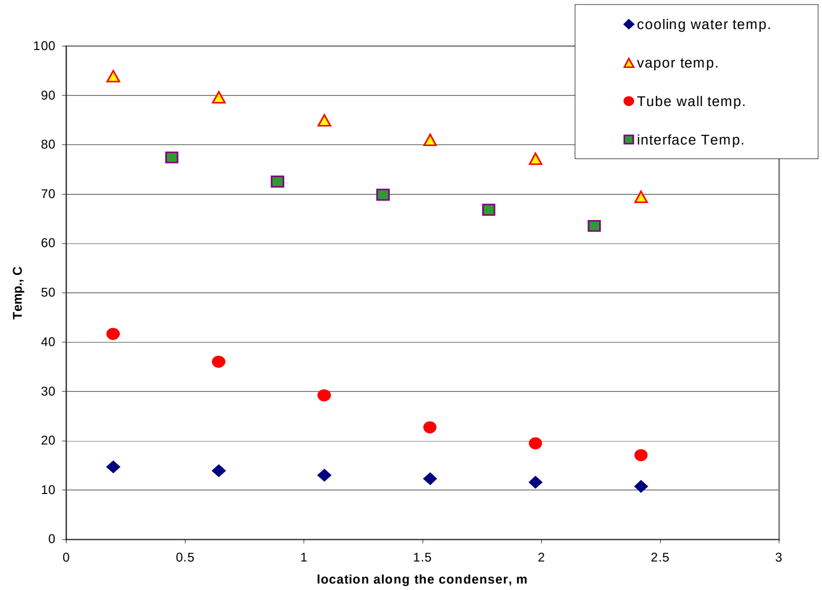


**Figure 1.** Temperature distribution in the test condenser for test a-817-40-0L.

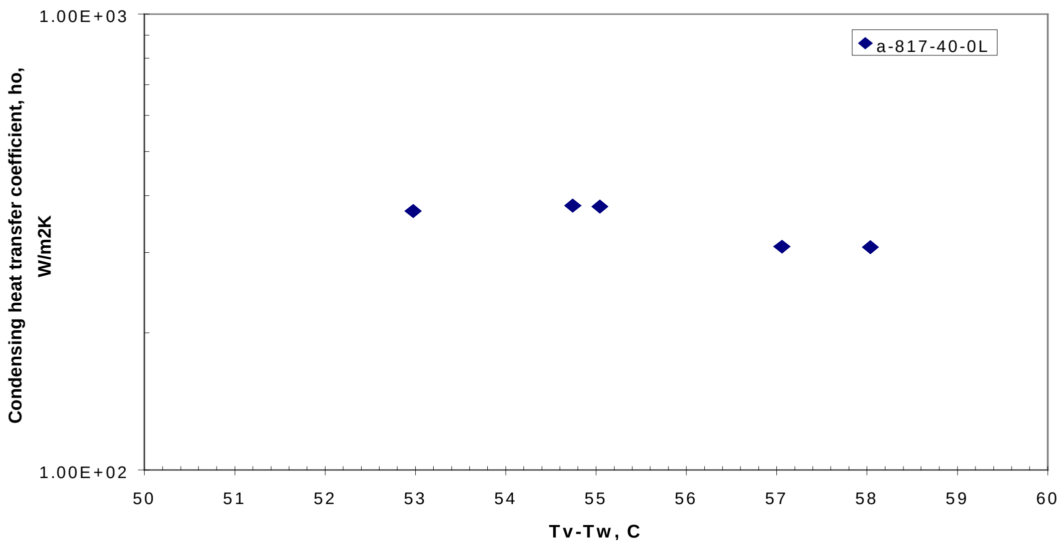


**Figure 2.** Condensing Heat Transfer Coefficient vs. Temperature Difference for test a-817-40-0L.

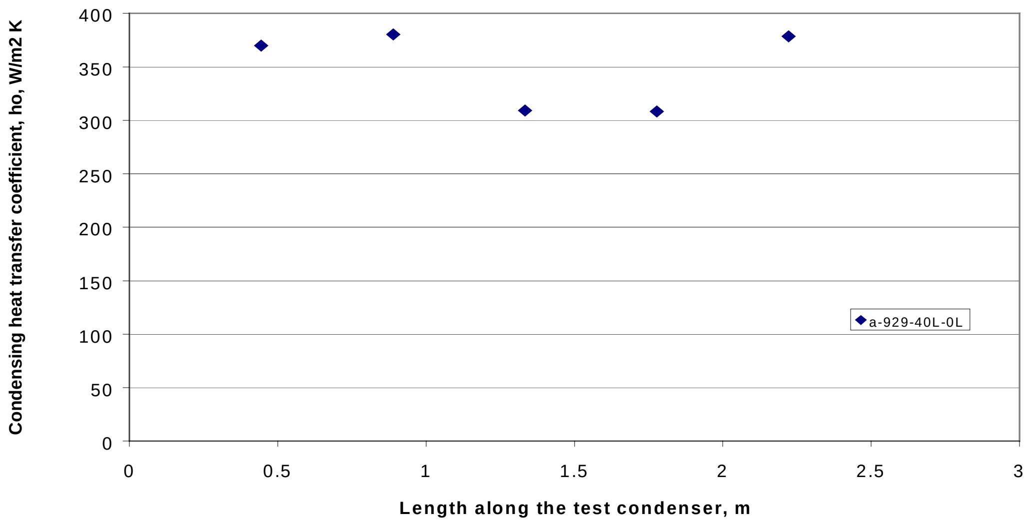


**Figure 3.** Condensing Heat Transfer Coefficient along the Condenser.

difference between the vapor bulk and the tube wall is decreasing as the vapor flows through the condenser, therefore resulting in a lower condensing heat transfer coefficient. However, Figure 3 also shows that the condensing heat transfer coefficient for the last segment of the condenser is increased. This increase may be related to the mass transfer process that is occurring along the condenser length. It is possible that as the condensate flows down the condenser, the ammonia starts evaporating back into the vapor phase.

Figure 4 shows the non-dimensional temperature difference between the interface, vapor bulk, and the tube wall temperatures, as well as the non-dimensional ammonia concentration difference between the interface and the vapor bulk along the axial length of the test condenser.

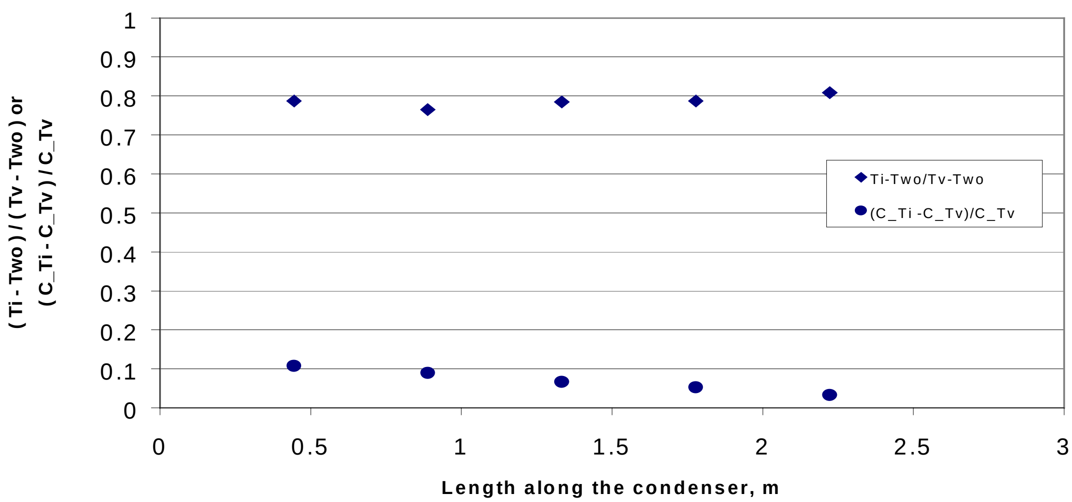


**Figure 4.** Non-dimensional ammonia concentration and temperature along the axial length of the condenser.

This figure shows the impact of the presence of the second condensing component on the whole condensing process. As is known, during the condensation of a binary mixture, a diffusion layer is produced around the condensate layer, considerably reducing the rate of heat and mass transfer. It is practically impossible to measure the resistance of the diffusion layer because the interface temperature between the condensate and the vapor is not known and cannot be directly measured. Different approaches have been used to estimate the interface temperature and hence estimate the additional resistance introduced as a result of the presence of the diffusion layer. The estimated interface temperatures were plotted in Figure 1. Using these temperatures a non-dimensional plot is provided in Figure 4. This figure shows the importance of the vapor diffusion layer resistance compared to the condensate film resistance. In the first half of the test condenser, the diffusion layer resistance constitutes more than 20% of the whole resistance. However, in the second half of the test condenser, the diffusion layer resistance is less than 18% of the total resistance.

Figure 5 shows the condensing heat transfer coefficient vs. the heat flux for each segment of the test condenser. This figure does not indicate a very clear relationship between the two, however, one can conclude that higher heat fluxes will result in higher condensing heat transfer coefficients. Figure 6 shows the variation of non-dimensional concentration with respect to the condensate mass flux along the condenser length. It is interesting to note that as the concentration difference between the interface and the vapor bulk reduces, the condensate flux increases. This may be explained by the nature of the flow of the liquid condensate film flowing over the tube.

A procedure similar to the one used for test # a-817-40-0L was used for all of the ammonia/water tests and plots similar to those shown here were generated.

Figure 7 shows the variation of the condensing heat transfer coefficient with respect to the temperature difference between the bulk vapor and tube wall for test series "817". This figure shows that the dry vapor tests have a lower condensing heat transfer coefficient compared to the spray tests and the tests with liquid film layer have the highest condensing heat transfer coefficient. It should be pointed out here that the flow rate of the aiding flow for the spray tests was much less than the liquid film tests. In our future tests, we will study the effect of lower liquid film layer flow rates on the condensing heat transfer coefficient.

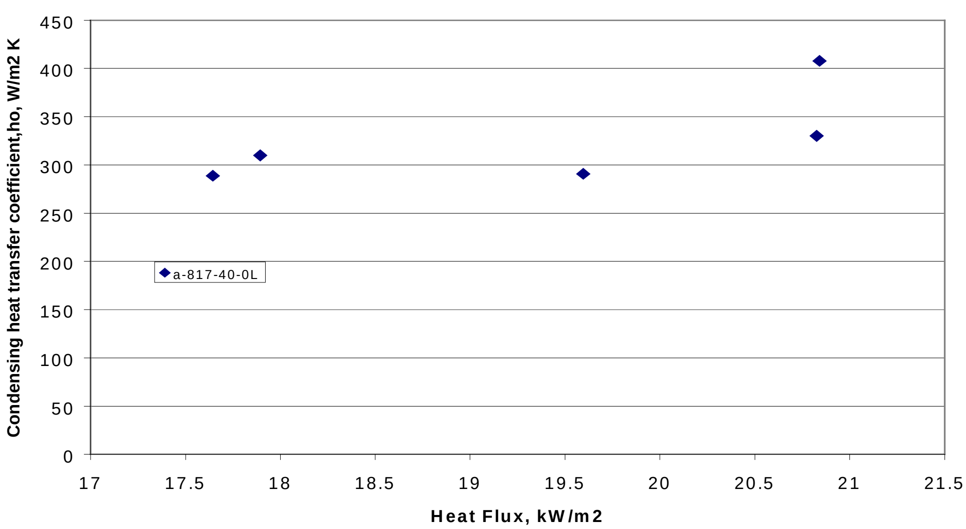


**Figure 5.** Heat Flux vs. Condensing Heat Transfer Coefficient.

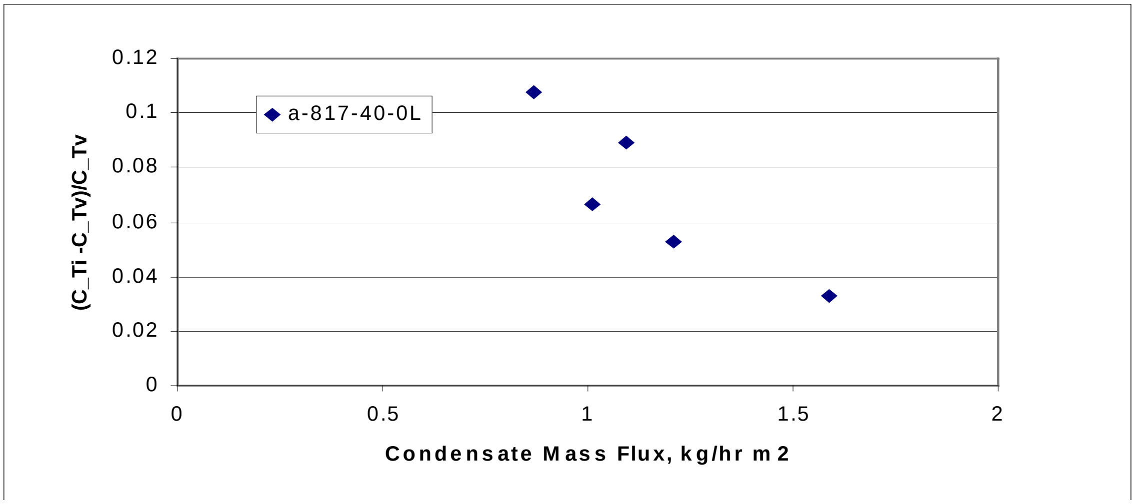


**Figure 6.** Non-dimensional ammonia concentration difference w.r.t. the condensate mass flux.

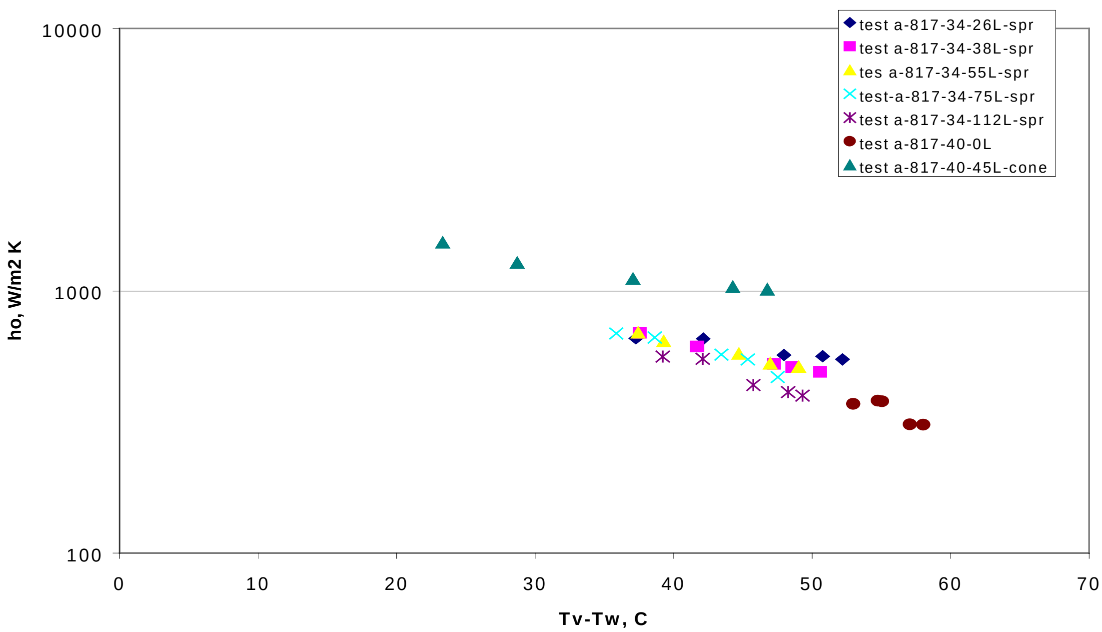


**Figure 7.** Condensing heat transfer coefficient vs. temperature difference for test series 817.

## Conclusions

This work was carried out to study condensation of ammonia/water vapor mixtures in forced flow through a vertical shell and tube condenser with condensation on the shell side. This work experimentally investigated the coupled process of heat and mass transfer in film condensation of ammonia/water mixtures. The results were presented for both dry vapor inlet conditions as well as aided flow condensation. This study clearly shows the impact of aided flow on the condensing heat transfer coefficient. The results of this study indicate that by using aided flow, condensing coefficient can be increased by as much as 3 times the dry vapor condensation.

Using heat and mass balance, the experimental results of this work were used to predict an interface temperature between the condensate film and the vapor bulk. For each test, non-dimensional concentration and temperature plots were generated which explained the relative importance and dominance of liquid film layer resistance vs. the vapor diffusion layer resistance. In most cases, where the velocity was high the liquid film layer resistance was dominant because high velocities in the vapor created a mixing condition eliminating the impact of the diffusion layer.

As part of this and future work, NREL intends to develop a methodology for predicting the condensing heat transfer coefficient as well as the vapor phase mass transfer that will be useful in predicting the condensation process of ammonia/water, as well as hydrocarbon binary mixtures.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Exergy, Inc. has expressed interest in this work because it provides important information on the lesser known issue of condensation of mixed working fluids. EFCO, a heat exchanger manufacturer, is interested in this work because it provides performance information that can be used for design and construction of shell and tube heat exchangers.

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## CONTACTS

Raymond LaSala
U.S. Department of Energy
Office of Geothermal and Wind Technologies, EE-122
1000 Independence Ave., SW
Washington, D.C., 20585-0121
Tel: (202) 586-4198
Fax: (202) 586-8185
E-mail: raymond.lasala@ee.doe.gov

Jeffrey L. Hahn
DOE-Golden Field Office
1617 Cole Blvd.
Golden, CO 80401
Tel: (303) 275-4775
Fax: (303) 275-7453
Email: jeff_hahn@nrel.gov

Vahab Hassani
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
Tel: (303) 384-7464
Fax: (303) 384-7495
E-mail: vahab_hassani@nrel.gov

# IMPROVING PERFORMANCE OF AIR-COOLED CONDENSERS

Manohar S. Sohal and James E. O'Brien
Idaho National Engineering & Environmental Laboratory, Idaho Falls, ID

## KEY WORDS

air-cooled condensers, enhancement, heat transfer, pressure drop, vortex generators, winglets, oval tubes

## PROJECT BACKGROUND AND STATUS

In a recent report on geothermal power plants[1], the costs of the air-cooled condensers in five 50 MW binary geothermal power plants are provided along with the total cost of the respective plants. As a general rule, the condenser costs are about 22 to 30% of the total plant costs. Therefore, it is desirable to improve the heat transfer coefficient in an air-cooled condenser. Most of the thermal resistance is on the air-side of the condenser tubes. The thermal resistance can be decreased by increasing air flow rate, which increases the convective heat transfer coefficient. But this also increases the pressure drop across the tube bundle and the fan pumping power. Thus, another requirement of an enhancement device(s) is that it should not significantly increase the pressure drop and the parasitic fan pumping power. The enhancement is to be accomplished without increasing the capital or operating cost of the total heat rejection system.

During an earlier study[2] it was found that oval tubes are being used for low pressure applications[3] to enhance heat transfer in other industries, especially automotive industry. The oval tubes improve the heat transfer and the pressure drop is also less than that for the circular tubes. Webb and Iyengar[3] have shown about 32% better heat transfer and 17% lower pressure drop by using oval tubes as compared to cylindrical tubes.

Another area of recent research is the application of vortex generators (also called winglets) on the tube fins. Whenever there is flow along a flat surface, which has a perpendicular cylindrical object on it (for example, a bridge support pillar in a river-bed), vortices are generated around the base of the cylinder. Same phenomenon occurs in a tube-fin arrangement. The wake behind the cylinder is a low heat transfer region, where heat transfer can be improved by generating vortices in the wake region with the help of winglets. There are mainly two common winglet shapes, rectangular and delta (triangular). The delta winglet (a triangle on its longer side) is the preferred shape for the present investigation. By optimizing the shape and placement of the winglets, the resulting vortices can minimize the wake (stagnant flow) region behind a cylinder and improve the heat transfer. As shown by Fiebig[4], the winglets enhance heat transfer by about 10-15%, but are also likely to increase pressure drop. It is anticipated that by combining both concepts, the air-side heat transfer coefficients in binary plant air-cooled condensers can be increased without imposing additional pressure drop and fan power.

The current project is investigating the application of both these developments to the specific case of air-cooled condensers. Further plans are for heat transfer enhancement and pressure drop investigations for a tube bundle (during FY-2000) and testing the application of the selected enhancement device(s) for a practical case of a tube bundle (during FY-2001).

## PROJECT OBJECTIVES

The technical objectives of this project are the following:

- Improve the air-side convective heat transfer coefficient of air-cooled condenser tubes in a geothermal power plant as compared with current practice of using finned tubes.

- Minimize the pressure drop increase across the tube bundle as a result of employing the proposed heat transfer enhancement techniques in a tube bundle.

- Collaborate with a condenser manufacturer to implement the proposed enhancement device in a cost-effective manner in a practical tube bundle case.

Expected outcomes of this project are the following.

- It is expected that the research results will demonstrate the benefits of applying vortex generators (winglets) punched out from the fins to improve the heat transfer from the air side of the tube bundle. Eventually, about 10 to 15% enhancement in heat transfer is expected.

- If oval tubes can be economically used in a bundle, it is expected that the pressure drop across the tube bundle with the application of vortex generators (winglets) will be similar to that in a conventional tube bundle. If circular tubes have to be used, the increase in pressure drop from the winglet is small enough to maintain the benefits of using vortex generators to enhance the heat transfer.

## APPROACH

1. A survey of possible enhancement techniques for air-cooled condensers was completed. From the available heat transfer techniques, two possible techniques were identified that are likely to enhance heat transfer and may even reduce the pressure drop across the tube bundle.

2. A combined experimental/computational effort is being pursued with the objective of designing and demonstrating significant improvements in the performance of air-cooled condensers. During FY-2000, heat transfer coefficient distributions will be measured in a scaled geometry of a tube bundle (round tube and oval tube).

3. A computational fluid dynamics code, FLUENT, will be used to model heat transfer and pressure drop in various tube-fin configurations of an air-cooled condenser. The purpose of the modeling effort is to: (a) verify and develop confidence in the experimental and modeling results; (b) optimize size and location of vortex generators/winglets without resorting to numerous experiments; and (c) predict trends and performance in any desired case.

4. Collaborate with a heat exchanger manufacturer to test the concept in a prototype heat exchanger and commercialize the technology.

5. Publish the results in open literature.

## RESEARCH RESULTS

During FY-1999, the INEEL investigators designed a flow duct with a tube that simulated a single passage in a fin-tube heat exchanger. Heat transfer measurements were obtained using a transient technique in which a heated airflow is suddenly introduced into a test section. The test section is a scaled-up model of the condenser tube and the narrow flow channel between two successive fins. High-resolution local fin-surface temperature distributions were obtained at several times after initiation of the flow transients using an imaging infrared camera. The Reynolds number is based on the channel height (gap between two successive fins). The heat transfer coefficients were calculated considering the temperature difference between the inlet temperature and the fin surface temperatures. Some of these results are shown in Figures given below. Figures 1 and 2 represent the same baseline case for a circular tube, Figure 1 being the digitized version of a qualitative version shown in Figure 2. The heat transfer coefficients on the fin surface at the forward stagnation point are ~10 times greater than those in a fully developed channel flow. Figure 3 shows a similar heat transfer coefficient for an oval tube having the same cross-sectional area as that of a circular tube. It is expected that using oval tubes can increase the heat transfer from the tube by about 10% as shown by the correlation for maximum heat transfer coefficient in Figure 4. Investigation of the application of vortex generators/winglets on the fins of the tube is underway.

A cylindrical tube with fins depicted in an experiment corresponding to Figure 1 was modeled using FLUENT computer code. The modeling results are shown in Figure 5. It can be noted that both qualitatively and quantitatively, the heat transfer coefficient values in Figures 5 and 1 match within normal numerical and experimental errors. The maximum heat transfer coefficient occurs in a narrow band in the forward stagnation region and is in the range 60 to 65 $W/m^2 \cdot K$.

## FUTURE PLANS

During FY-2000, a combined experimental/computational effort will be continued with the objective of significant improvements in the performance of an air-cooled condenser. A computational fluid dynamics code, FLUENT, will be used to model heat transfer and pressure drop in various enhancement configurations in a tube-fin air-cooled condenser. An appropriate sized tube bundle will be modeled and tested with four different configurations: (1) cylindrical tube bundle with plain fins, (2) cylindrical tube bundle with fins and vortex generators on the fins, (3) oval tube bundle with plain fins, and (4) oval tube bundle with vortex generators on the fins.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

During FY-2000, industrial manufacturers of condenser tubes will be contacted to collaborate on the tube-bundle testing of the concept. The tube-bundle testing will be performed in collaboration with a heat exchanger manufacturer who will provide the hardware to our specifications.

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## CONTACTS

Raymond LaSala
Office of Geothermal and Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585
Phone: (202) 586-4198
Fax: (202) 586-5124
e-Mail: *raymond.lasala@ee.doe.gov*

Peggy Brookshier
DOE Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
Phone: (208) 526-1403
Fax: (208) 526-5964
e-Mail: *brookspa@id.doe.gov*

Jay Nathwani
DOE Idaho Operations Office
850 Energy Drive, MS 1225
Idaho Falls, ID 83401-1563
Phone: (208) 526-0239
Fax: (208) 526-5964
e-Mail: nathwaj@id.doe.gov

Manohar S. Sohal
Idaho National Engineering &
Environmental Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-3815
Phone: (208) 526-9412
Fax: (208) 526-8883
e-Mail: *sohalms@inel.gov*

James E. O'Brien
Idaho National Engineering & Environmental Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-3885
Phone: (208) 526-9096
Fax: (208) 526-6971
e-Mail: *jzo@inel.gov*

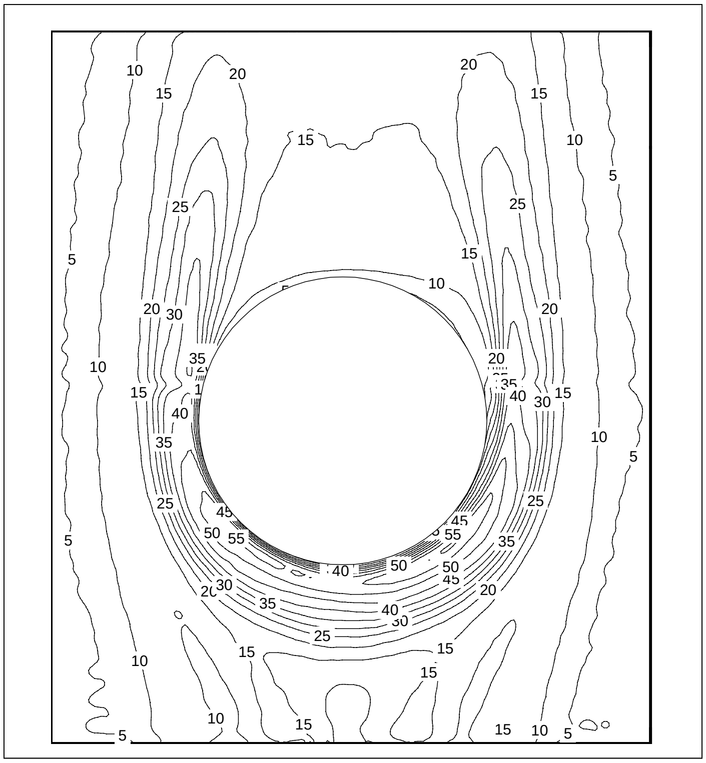

**Figure 1.** The contours represent measured values of local fin-surface heat transfer coefficient in $W/m^2 \cdot K$ for flow around a circular tube in a simulated fin/tube flow passage. Flow is from bottom to top in the figure with a mean velocity of 2.8 m/s.

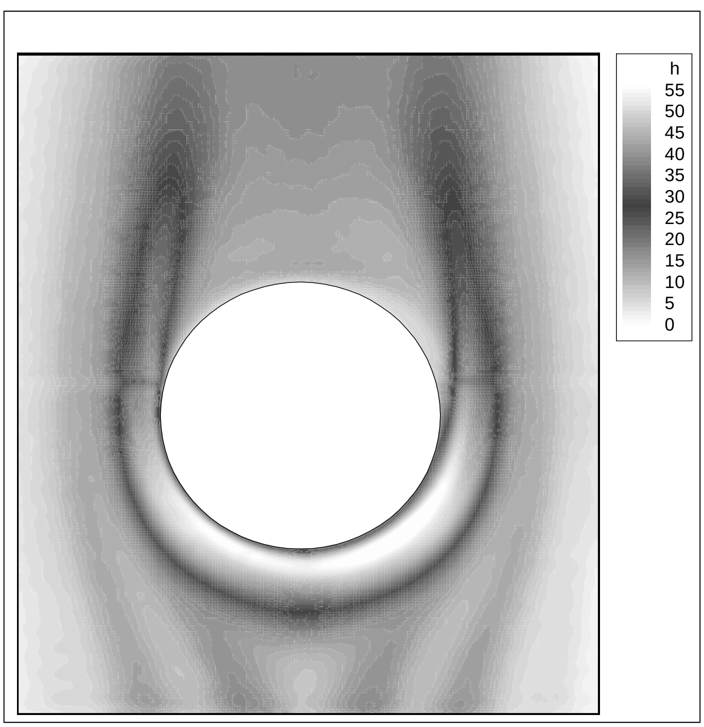


**Figure 2.** Measured fin-surface heat transfer coefficient, h ($W/m^2$ K), around a circular tube, flow velocity 2.8 m/s.

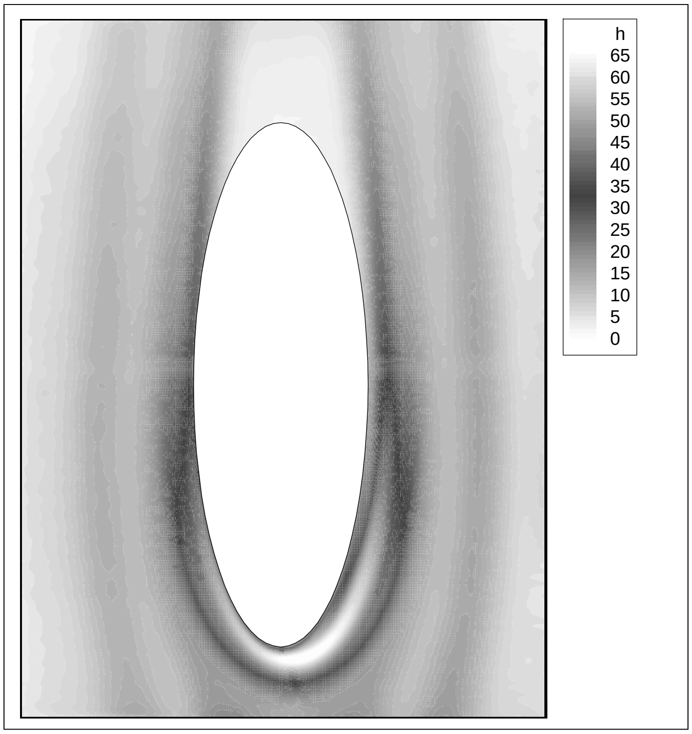


**Figure 3.** Measured fin-surface heat transfer coefficient, h ($W/m^2$ k), around an oval tube, flow velocity 2.8 m/s.

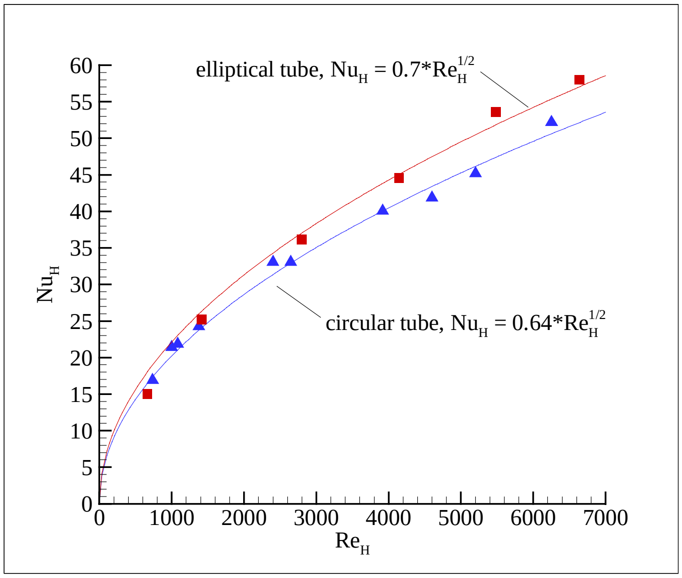


**Figure 4.** Maximum fin-surface Nusselt numbers with correlations.

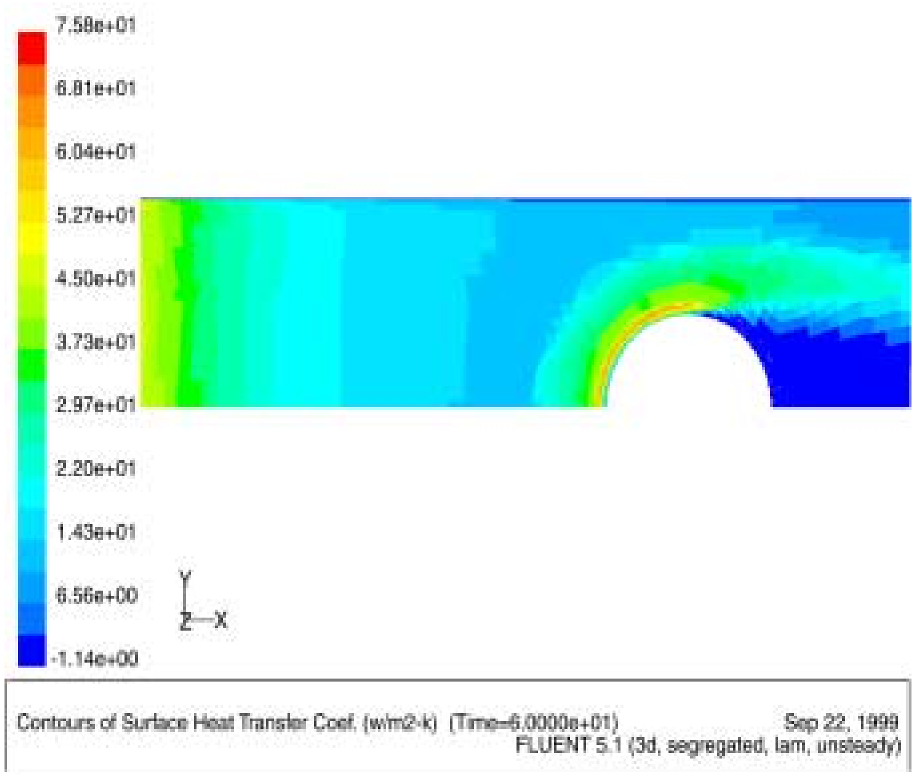


**Figure 5.** Modeling results for heat transfer coefficient on the fin surface of a circular tube corresponding to the experimental data in Figure 1.

# AIR-COOLED CONDENSER DEVELOPMENT

Charles Kutscher
Keith Gawlik
National Renewable Energy Laboratory

## KEY WORDS

air-cooled condenser, fins, transpired, heat exchanger, boundary layer

## PROJECT BACKGROUND AND STATUS

Air-cooled condensers (ACCs) are commonly used in binary-cycle geothermal power plants in arid regions and in situations where water vapor plumes are undesirable. NREL is engaged in a research program to develop better performing air-cooled condensers that can lower the delivered electric energy cost of geothermal power plants. Analysis indicates that net power increases by approximately 1% for every one degree F drop in condenser temperature. Thus improved condenser heat transfer that can allow the condensate temperature to more closely approach the ambient air temperature can have a very favorable impact on overall plant performance. The cost of the condensers and the parasitic load of the fans are also significant. A reduction of ACC capital cost by 50% can result in a cost of electricity (COE) reduction of about 1 /kWhr. A reduction of ACC fan power by 50% could lead to a COE reduction of about 0.5 /kWh.

Current finned tube condenser designs have considerable room for improvement. NREL research focuses on innovative fin geometries that increase the ratio of heat transfer to fan power. To accomplish this, we increase the overall heat transfer coefficient by reducing the average boundary layer thickness, and we also increase the effective heat transfer area. Computer models have been developed and one prototype was built and tested. A patent application has been filed.

## PROJECT OBJECTIVES

The overall objective of this work is to explore and develop improved air-cooled condenser designs that can decrease the cost of electricity from binary-cycle geothermal power plants by 0.5 cents per kWh or more.

### *Technical Objective*

- The technical objective of this work is to identify and develop new air-cooled condenser geometries that increase the ratio of heat transfer to fan power by 30% or more without incurring significant increases in capital cost.

### *Expected Outcome*

- This project will result in one or more new proven air-cooled condenser designs that can be licensed by industry for inclusion in new geothermal power plants.

## APPROACH

Air-cooled condensers and other heat exchangers that involve the use of air on one side are limited in performance by the heat transfer on the air side. This is because air is a poor heat transfer fluid, owing to its low thermal conductivity and density. In order to compensate for this, such heat exchangers typically employ extended surfaces on the air side to increase the total area for air-side heat transfer. Air-cooled condensers used in geothermal power plants typically use tubes with circular fins packed together at perhaps ten fins per inch. While the fins improve the situation, these condensers are still significantly limited in performance by the thermal resistance on the air side. Various means have been used to improve the heat transfer. These often involve the generation of vorticity or turbulence to bring cooler air to the fin surface. While these techniques can increase heat transfer, they often result in an unacceptably large increase in pressure drop, and hence fan power, as well.

The resistance to heat transfer on a surface is proportional to the thickness of the thermal boundary layer on that surface, because the boundary layer acts as an insulating layer of air. NREL research has focused on the development of innovative geometries that reduce the average thermal boundary layer thickness. Such a reduction in thermal boundary layer thickness will result in a proportional reduction in momentum boundary layer thickness and an associated increase in frictional pressure drop. However, total pressure drop is the sum of frictional pressure drop and form pressure drop (the latter being essentially independent of thermal boundary layer thickness), so it is possible to develop geometries for which the ratio of heat transfer to total pressure drop is increased.

In conventional finned tube condensers, as the air passes between the fins and flows parallel to them, the thermal boundary layer thickens along the fins, resulting in increasing heat transfer resistance. Also, the tube itself tends to block flow over the portions of the fins downstream of the tube, reducing heat transfer in the wake region. NREL designs currently under development use perforated fins in which the air flow is forced *through* the fins, instead of along the fins. We refer to these as *transpired* designs.

The flow through the holes reduces the thermal boundary layer thickness on the front of the fin. This is because the air impinges on the surface and accelerates toward the holes. (Acceleration thins a boundary layer.) Also, because there are many holes, there is not sufficient travel distance along the fin for the boundary layer to thicken. (The front surface can also be viewed as undergoing boundary layer suction, which thins the overall boundary layer.) Even more importantly, the boundary layer is very thin inside the holes. Each hole acts like the entrance region of a pipe, where the boundary layer is very thin, because it has not yet had a chance to develop. Because we use fins of high porosity, the heat transfer area inside the holes is very significant and can be several times greater than the front surface area. (Heat transfer on the back of each fin is poor, but this is more than compensated for by the large amount of heat transfer on the front surface and in the holes.) Although perforated fin designs have been used before, virtually all of these have used the holes simply to disrupt the parallel flow and have not taken advantage of transpired flow.

The geometry selected for the fins, together with the pressure drop across the fins, ensures fairly uniform flow through the entire fin surface, even in the regions behind the tubes. Thus this design also overcomes the wake problem associated with conventional finned tubes. The ratio of heat transfer to pressure drop is maximized by properly adjusting a number of available degrees of freedom: fin thickness, hole diameter, porosity, and fin face velocity (controlled by adjusting fin spacing, or the average space between fins arranged in a pleated, sawtooth-type configuration). Consideration must also be given to the fin efficiency, to ensure that sufficient heat can be transferred from the tube to the outer reaches of the fins. This constraint places an upper limit on the fin porosity.

Using the most applicable heat transfer and pressure drop correlations available, we developed a spreadsheet model to optimize performance. However, the geometries being employed fall outside the range of correlations available in the literature and required extrapolation. Small-scale samples were built and tested to provide refinements.

Based on these results, a 1 ft x 2 ft prototype was built. This consisted of six tubes with perforated fins. Electric heaters were installed inside the fins to provide a controllable and measurable heat source. The prototype was mounted at the exit of an open-circuit, low-speed wind tunnel that provided overall face velocities from 0 to 4 m/s. To allow a direct comparison with conventional technology, a conventional test unit was also constructed using finned tubes with fins spaced at 10 fins per inch. For both the conventional and the prototype units, we measured heat input and air temperature rise over a range of air velocities. Results are reported in the next section.

In order to develop improved correlations and improved geometries, we have also been performing computational fluid dynamics (CFD) simulations using the commercial code, FLUENT. This allows us to quickly examine a wide range of parameters.

## RESEARCH RESULTS

Figure 1 shows heat transfer and pressure drop results for the conventional design. At 3.5 m/s, the overall UA per unit volume of heat exchanger is about 12,000 W/C-$m^3$. The fan power is about 5 kW/$m^3$. Figure 2 shows the same results for the prototype design. Note that there is a large increase in the amount of heat transfer per unit volume (18,000 W/C-m3 at 3.5 m/s). The fan power has increased as well (to 8 kW/m3), but to get such a high rate of heat transfer with the conventional design would require much higher flow rates and much higher fan power. To allow a meaningful comparison, we can reduce the air velocity for the prototype until its fan power matches that of the conventional unit. Fan power goes as the cube of velocity and heat transfer goes as velocity raised to a power less than one, so lowering the velocity or air for the prototype will reduce fan power much more rapidly than it reduces heat transfer. If we lower the face velocity on the prototype unit until the fan power is the same as for the conventional unit, the prototype delivers 30% more heat transfer than the conventional unit. This early prototype used a porosity of only about 29%, which we now know from our computer modeling is much lower than optimum. So we believe we can increase the ratio of heat transfer to fan power in optimum designs by 50% or more.

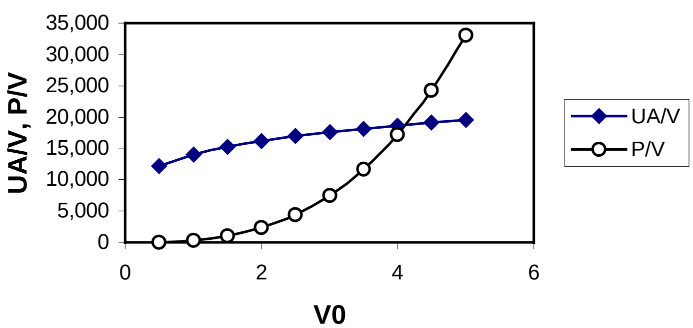


**Figure 1.** UA per unit volume and fan power per unit volume as a function of air velocity for the conventional design.

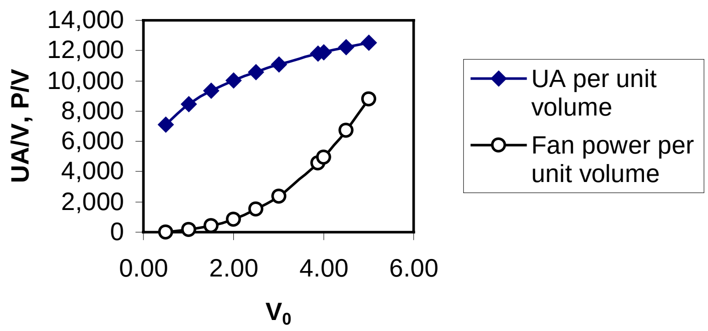


**Figure 2.** UA per unit volume and fan power per unit volume as a function of air velocity for the prototype design.

The advantage of the prototype can best be seen when costs are taken into account. Figure 3 shows cost results for the conventional 10 fin-per-inch finned tube design, the prototype (labeled as 7 fins per inch), and another perforated fin design in which the tubes lie in the plane of thick fins. (The latter is not an experimental result, but was generated using FLUENT.) In this plot, the y-axis is the capital cost per unit Watt of heat duty, and the x-axis is the total present value of fan power cost (over a 20-year plant life) per unit of heat duty. Thus at any point on the plot, the total cost is the sum of the x-coordinate (fan power cost) and the y-coordinate (capital cost of the equipment). The straight dotted lines are lines of constant total cost (i.e., the sum of x and y). Each curve was generated from a range of air velocities. The optimum velocity would be that for which the curve reaches the minimum total cost line.

Note that the two advanced concepts show significantly lower total costs over the entire range. The minimum total costs (capital plus parasitic) are as follows: \$0.20/W for the conventional design, \$0.15/W for the transpired 7 fin-per-inch, tube-through-fin design, and \$0.12/W for the transpired tube-in-fin design. These costs do not include any added material or construction costs associated with the new designs, because they will depend on the construction methods chosen. However, the results are conservative from a performance standpoint, because we believe there is considerable room for improvement of the advanced designs, as we develop better correlations for the many degrees of freedom.

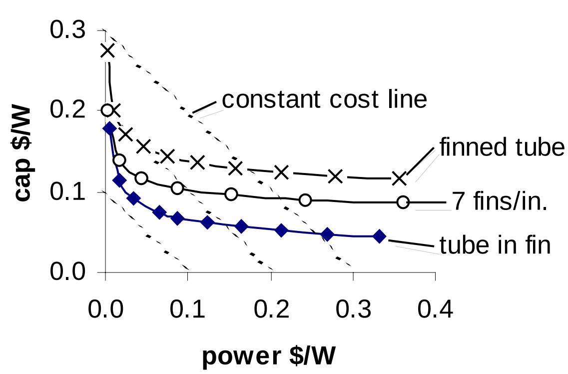


**Figure 3.** Capital and fan power costs per unit of heat duty for the conventional design and two advanced transpired fin designs.

Interestingly, this analysis showed that the minimum-cost air velocity for all designs is about 1.5 m/s. A typical design velocity for air-cooled condensers is 3.5 m/s. While this may be appropriate for many applications, our analysis suggests that this may be too high for a binary-cycle geothermal power plant, resulting in excessive fan power costs.

## FUTURE PLANS

We intend to conduct additional FLUENT simulations to develop correlations that we can use in our spreadsheet model to develop improved designs. We will then build and test a second prototype. Once we have determined the best design, we will then conduct a field test at an operating binary-cycle plant that will allow a side-by-side test with a conventional unit. We will also meet with industry to develop a relationship so that manufacturing issues can be addressed.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

A patent application was filed only recently and no formal contacts with industry have yet been made. We intend to meet with industry in the summer of 2000 to identify any interested industry partners. We ultimately intend to license this technology to ensure that it will be utilized in future geothermal plants.

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## CONTACTS

Raymond LaSala
U.S. Department of Energy
Office of Geothermal and Wind Technologies, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585-0121
Tel: (202) 586-4198
Fax: (202) 586-8185
raymond.lasala@ee.doe.gov

Charles Kutscher
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
Tel: (303) 384-7521
Fax: (303) 384-7540
Chuck_Kutscher@NREL.gov

# COMPARATIVE ANALYSIS OF ALTERNATIVE MEANS FOR REMOVING NONCONDENSABLE GASES FROM FLASH-STEAM POWER PLANTS

Martin Vorum, Eugene Fritzler
Consultants

Charles Kutscher
National Renewable Energy Laboratory

## KEY WORDS

biphase eductor, emissions abatement, gas removal alternatives, noncondensable gases, parasitic power losses, present value analysis, reboiler steam jet ejector, two-phase eductor, turbocompressor, vacuum systems

## PROJECT BACKGROUND AND STATUS

Virtually all geothermal power plants use either multi-stage steam jet ejector banks or ejectors in series with vacuum pumps to remove noncondensable gases from the systems. These conventional vacuum systems consume a considerable amount of steam or electricity. For example, in the 330 megawatt (MW) Tiwi Geothermal Field in the Philippines, roughly 20 percent of the geothermal steam is used to remove noncondensables. This not only causes a loss of salable electrical power, but when reservoir pressure drops, steam ejectors lose their efficiency (which is low to begin with, at about 20 to 30 percent). Also, the more power consumed per unit of salable product, the greater is the potential rate of decline of resource pressure, limiting resource productivity.

There are a number of alternative technologies for addressing this problem. To determine which methods are worthy of further study and commercialization, it is necessary to compare them on the basis of performance and cost.

This project has developed two computational models and a spreadsheet tool for screening the comparative benefits of the gas removal options. The project began in April 1999 and is slated to finish in March 2000. The first phase of work included a literature search, contacts with industry representatives, and analyses of the power process unit operations to formulate a figure of merit to model the performance of gas removal systems. The second phase of work defined a figure of merit to model the economics of the gas removal options. The third phase of work produced a spreadsheet to quantify and contrast the performance and economics of various options.

The work is in the end stages: the project report and the spreadsheet have been reviewed by a team of individuals from NREL, INEEL, and from industry. The process of answering comments and questions is nearly complete, and key recommendations are being incorporated. The final report will be condensed to extract a technical paper for presentations.

Two general methods of advanced gas removal were considered. One group of alternatives looks at enhancing the conventional vacuum systems. A high-efficiency turbocompressor unit by Barber-Nichols appears promising as a replacement for third-stage and perhaps second-stage jet ejectors or vacuum pumps. Two-Phase Engineering and Research has suggested that two-phase eductors might use spent brine leaving the produced-brine flash step as the motive fluid for vacuum drivers, in order to conserve the flashed steam for power generation.

The second method is the reboiler process, which would operate upstream of the power plant turbine to remove the large majority of gases from the flashed steam by physical separation.

Most gas removal methods waste steam, either to power the vacuum equipment or as component of a vent stream of concentrated gases that are separated physically in a reboiler process. The spreadsheet helps the user quantify the gas removal options with the best potential by estimating their technical and economic performance. The spreadsheet requires input data by the user to define detailed mass and energy balances for basic power plant schemes. The input is standardized into groups of five process configurations, with each setup representing one gas removal option.

The user also defines values for financial variables that control the present value analysis of the economics of each option. The user also specifies the capital and operating cost bases for each option. The flexibility of the economic model spreadsheet enables the user to check a wide range of parametric combinations of discount rates, energy pricing, tax alternatives, inflation rates, etc.

The analyses of performance and economics clearly show that there are combinations of resource properties (wellhead temperature/pressure and gas levels) for which it may well be worthwhile to conduct further site-specific analysis and implementation of the advanced gas removal alternatives. Owners and contractors may use the spreadsheet to start their own assessments and apply the results to narrow the range of gas removal choices for final design.

## PROJECT OBJECTIVES

The objective of this task was to develop a screening tool that evaluates alternative means of removing non-condensable gases, and to identify the most promising concept or concepts.

### *Technical Objective*

- The technical objective of this work was to perform a performance and cost comparison of alternative gas removal options.

### *Expected Outcomes*

- The expected outcome has two components: 1) a final report describing the results and recommendations for a particular set of cases and 2) a flexible Microsoft Excel spreadsheet that allows the user to compare their own diverse cases of different noncondensable gas removal technologies for any particular set of conditions in terms of resource produced fluid properties, process performance, and economic parameters. Both are in final review.

## APPROACH

NREL, in cooperation with industry partners, performs research on means for improving geothermal power productivity. The gas removal options considered in this project are at stages requiring both conceptual development (the biphase eductor technology) and detailed design for potential field deployment at commercial scale (turbocompressors and the reboiler process).

What has been lacking in geothermal literature is a head-to-head comparison of noncondensable gas removal options on a common basis. NREL contracted the project to develop the methods of analyzing gas removal options, and to produce a tool for future assessments of the options. This study performs a thermodynamic analysis of flash steam geothermal power plants in a way that focuses on the gas removal systems. The gas removal systems are treated as interchangeable modules within the power plant configuration. The technical process comparisons are based on common plant conditions and operating parameters defined by the user. The analysis considers the parasitic power needed to run the gas removal subsystems as a portion of the fixed generating capacity. All other power plant functions are defined as being constant.

The economic figure of merit is the net present value of each gas removal system, considered as a standalone unit. The gas removal options are ranked on the basis of equal capacity. This approach uses estimated costs of construction and operation, and claims revenue for gas removal based on the energy saved. This analysis puts the performance of all of the gas removal systems on an equal basis so that they can be rated by power production efficiency and by their dollar value as an investment.

## RESEARCH RESULTS

Figures 1 and 2 illustrate a subset of the preliminary results for the performance and economics of the alternative gas removal systems described above. These figures illustrate cases of wide ranging gas compositions for low-temperature geothermal resources. The results suggest the turbo-compressors and the reboiler process may warrant serious study for commercialization. They offer different relative advantages as a function of gas concentrations in the flashed steam. The biphase eductor technology needs further analysis to determine whether design and economic assumptions used in this study are truly realistic. If they are, then eductors show no economic benefit for low temperature cases. The variables for which eductors need better assurance of data accuracy are their thermo-mechanical efficiency and all aspects of their costs. Any future work on eductors should start with tightly focused studies to determine whether and to what degree the assumptions about eductors in this study can be improved.

## FUTURE PLANS

The results of the present work afford the user sufficient accuracy and flexibility to make meaningful comparisons of gas removal alternatives for both hypothetical and specific cases.

For future work, the spreadsheet should be considered for general use in the geothermal power industry. This analytical tool may be used for planning the new development of resources and power production facilities, or for choosing between retrofit options to improve productivity and cash flow for existing plants. The latter option could be evaluated with a goal of either reducing ongoing cost or of prolonging resource life, or both.

With industry affirmation of the methods developed for the spreadsheet, the turbocompressor and reboiler technologies should be made candidates for scaleup to commercial uses. The eductor technology should be assessed parametrically using the spreadsheet to identify the degree of improvement that is needed in the assumptions of this study in order for it to succeed. Then, as noted in the preceding section, the design and economic parameters can undergo analysis to determine whether the needed degree of improvement is feasible. Thereafter, program priorities would need to be set to justify any further funding for eductor research.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Specific industrial participants have not been contacted about using the products of this project or co-sponsoring potential future work. However, given the predominance of low-efficiency gas removal systems in existing worldwide geothermal power plants, it is expected that there may be considerable interest among both facility owners and design/construction contractors in the ability to perform the detailed and case-specific screening studies of gas removal options. This analytical method could assist the geothermal power industry in two ways regarding gas removal systems selection:

- It can support the setting of priorities and budgets for both the development and deployment of alternative gas removal technologies
- It can support the selection of key system components for planning new facilities.

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## CONTACTS

Raymond LaSala
Tel: (202) 586-4198
Fax: (202) 586-8185
raymond.lasala@ee.doe.gov
U.S. Department of Energy
Office of Geothermal and Wind
Technologies, EE-12
1000 Independence Ave., SW
Washington, D.C. 20585-0121

Martin Vorum
Phone/Fax: 303/789-0848
mvorum@chisp.net
1410 East Cornell Avenue
Englewood, Colorado 80110

**FIGURE 1**
**LOW TEMPERATURE CASES -- TECHNICAL FIGURE OF MERIT**

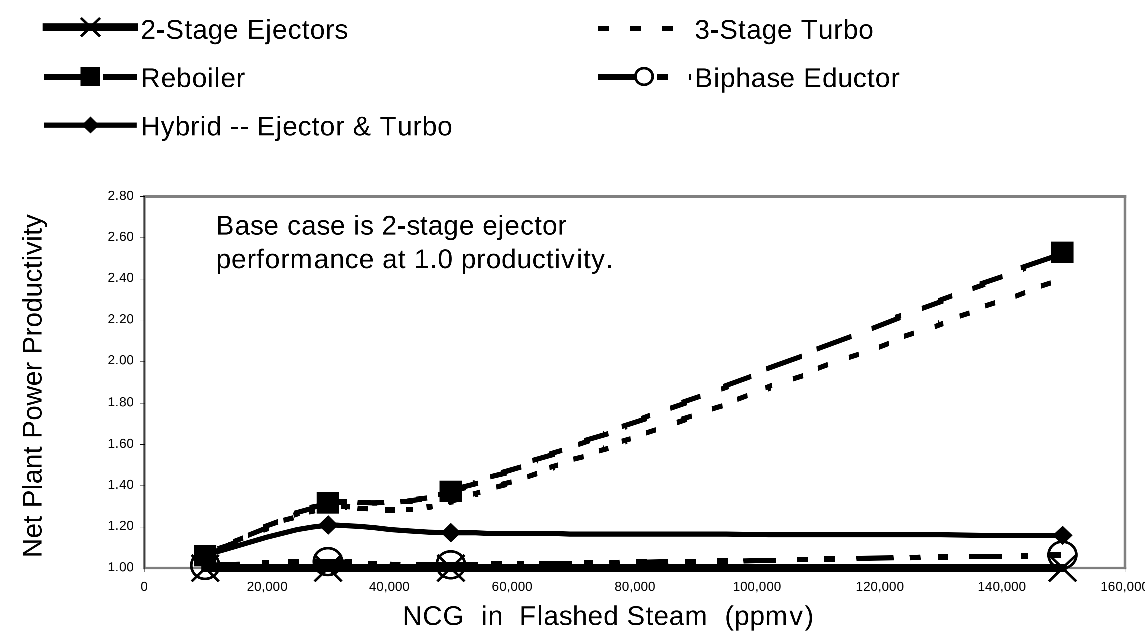
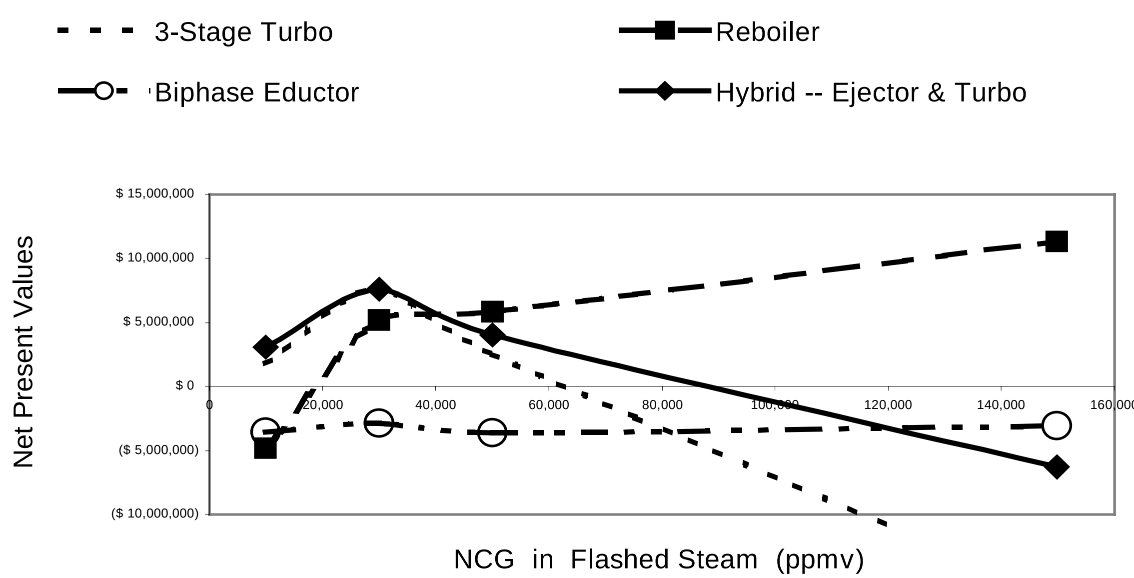



**FIGURE 2**
**LOW TEMPERATURE CASES**
**ECONOMIC FIGURE OF MERIT**



# CONTINUOUS NON-CONDENSABLE GAS REMOVAL IN BINARY POWER PLANTS

Charles Mohr
Idaho National Engineering and Environmental Laboratory

## KEY WORDS

non-condensable gas, condenser performance, turbine back-pressure

## PROJECT BACKGROUND AND STATUS

The removal of non-condensable gases (NCG's) is a problem typically associated with steam and flash-steam geothermal plants. Through discussions with the operators of binary power plants, INEEL investigators determined that systems are in place to remove non-condensable gases in most commercial binary plants. The existing systems are used to periodically vent or purge the NCG's from the condenser or vessel used to accumulate working fluid condensate. Based on a review of the operation of these binary power plants performed in mid-FY-1999 and an analysis of the effects of elevated turbine back-pressure due the NCG's, a method of continuous removal of condenser non-condensable gases was determined to have potential benefit to plant efficiency. Although the level of build varies from facility to facility, it is estimated that the reduction in the annual production of power can be as much as 2 to 4%. (The adverse effect of the NCG's is greater in the summer when a number of these plants receive a premium for power produced.)

Because membrane separation of condensable hydrocarbon vapors from non-condensables is in use in other industries, it was determined to investigate this technology for its application to binary power cycles. Membrane separations are in commercial current use for a variety of air/organic-vapor separations, including: recovery of gasoline from fumes generated during storage tank venting; recovery of dry cleaning solvents; recovery of paint solvents; recovery of halogenated solvents used in microchip and film manufacture; and separation of heavier alkanes from methane in natural gas. Use of this process should allow the condenser of a typical binary geothermal plant to operate continuously at a low NCG fraction in its condenser vapor. Although existing systems do attempt to recover working fluid from the purged vapor stream, it is anticipated that the proposed method of removal will also reduce working fluid loss to the atmosphere relative to current practice. This activity was initiated in FY-1999. With continued positive results, it will conclude in FY-2001 with testing of a prototype unit in a commercial binary plant to validate the projected performance improvement and economic benefit.

## PROJECT OBJECTIVES

The objective of this activity is to determine whether there is a cost-efficient means of continuously removing NCG's from the condensers in binary power plants and minimize the penalty on plant performance associated with their build up. Based on the project investigations, investigators are proposing to use membrane separation technology to achieve this continuous removal.

### *Technical Objectives*

- Build a database of NCG composition for various geothermal plants using binary cycles, and estimate the rate of NCG buildup from plant operating data.
- Identify probable sources of NCG's and evaluate feasibility of minimizing/eliminating introduction.

- Perform bench-scale testing of a membrane separation system for selectively separating binary-cycle working fluids from the NCG components in the database, above.

- Design and cost a full-scale system for a specific application.

- Install and direct a cost-shared demonstration of a prototype system in an operation geothermal plant.

- Analyze the test results to verify increased plant output, reduced organic emissions, and favorable economics for continued use.

- Analyze operating conditions at several other geothermal plants to verify that the system should be generally applicable to all binary-cycle operations.

***Expected Outcomes***

- Database of NCG compositions and accumulation rates for several typical geothermal plants using binary cycles.

- Successful bench tests of membrane separation system for removing NCGs from binary working fluids, and design data for implementing these membranes into separation systems for continuous NCG withdrawal from binary plant condensers.

- Engineering design for a full-scale prototype system, and analytical support for a 2 to 4 percent increase in plant output resulting from continuous operation at low NCG levels in a typical binary plant condenser.

- Preliminary arrangements for a cost-shared field test.

## APPROACH

Discussions with binary plant operators resulted in the initial identification of the NCG problem, and subsequently provided information on current operating practices and removal system configurations. The probable sources of these gases were reviewed, along with those steps operators take to minimize their introduction into the plant. Investigators then examined technologies used in other industries, and concluded the membrane separation technology could provide the desired continuous removal in the expected operating environments.

Operating data has been obtained from plant operators, and working fluid samples have been, and continue to be taken from representative plants. These samples are analyzed to determine the relative amounts of NCG's, and constituents typically found in these binary plant working fluids. This information is also correlated to operating data to determine whether the levels of NCG's in the samples are consistent with the operator's indication of gas build-up.

With the identification of the constituents of typical working fluids, bench scale tests will be conducted to determine the effectiveness, type and size of membrane required for a typical binary plant application. With this information, a prototype system will be designed and a cost estimate prepared. Based on the expected performance and cost, industry interest will be solicited. If interest is obtained, a prototype unit will be fabricated and installed in a commercial plant. The subsequent field testing will be used to validate the performance and economic benefit of this technology.

## RESEARCH RESULTS

Operators of binary power plants currently allow NCG's to build to an upper or threshold limit before activating their plant removal system. Typically this removal system involves the venting of the vapor from the region immediately over the liquid level in the condenser or a condensate accumulator vessel. The vented vapor is passed through a recovery unit, where a portion of the working fluid in this vapor stream is condensed and returned to the working fluid system. The source of the NCG's vary from plant to plant; operators have indicated that maintenance activities and recovery units on turbine lubrication systems are two major sources. Depending upon the working fluid used, air may also enter the plant during periods of cold ambient conditions if the saturation pressure of the working fluid is lower than the ambient air pressure.

Operators associate the build-up of NCG's with the increase of the excess pressure in the condenser with time. This excess pressure is the difference between the measured condenser pressure and the saturation pressure of the working fluid at the liquid temperature leaving the condenser. The partial pressure of the NCG's is added to the total condenser pressure, increasing this pressure difference as the NCG's accumulate. NCG's may also retard the heat transfer process by blanketing the tube surfaces. This produces additional sub-cooling of the condensate, and an increase in the apparent excess pressure. The level to which operators allow this excess pressure to build varies from plant to plant. In plants using an isobutane working fluid, the excess pressure can build up to 6 to 8 psid before venting is initiated. This build-up with time is illustrated in Figure 1, which is operating data from a commercial plant. Modeling of binary plants suggest that for each 1 psi increase in the turbine exhaust pressure (assuming an isobutane working fluid), the turbine power output falls by 1%.

Investigators have sampled and analyzed the isobutane vapor in an operating plant. The results of sampling have shown that there are significantly higher levels of NCG's (air) in the vapor space over the liquid condensate than in the circulating fluid. This is an expected result, based upon the Henry's constant for nitrogen in isobutane; ~32 ppm per psi of partial pressure.[1] This activity has shown that it is difficult to obtain consistent analysis between samples of the circulating fluid. This inconsistency is likely the result of the introduction of air during the sampling process, and the fact that the NCG levels in the circulating fluid are quite low. Sampling at a facility using an isopentane working fluid has been arranged, but not completed. Investigators are also evaluating the use of liquid chromatography for analysis in anticipation of removing a portion of the error associated with the sampling procedure.

Preliminary design calculations show that based on membrane performance in other NCG/organic vapor mixtures, a relatively small unit could perform the proposed continuous separation. The economics of this system cannot be completely specified without testing the membranes and separation system with a closely-simulated NCG/working-fluid mixture. However, the benefits to a commercial geothermal plant can be estimated as an increase in average output of approximately 2%. The value of this additional power should be sufficient to cover operating costs and amortization of the separation system.

## FUTURE PLANS

In FY-2000 the review of operating data and sampling at binary plants will be concluded. Bench-scale testing of membrane separations on simulated condenser vapor will subsequently be conducted. Based on the test results and estimates of NCG buildup rate derived from the plant data, a prototype system will be designed and costed. Contacts with geothermal plant operators will continue with the intent of establishing a plan for a full-scale system prototype test to be performed in FY-2001.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Ogden Power | Provide information, operating data, and indicated interest in hosting a full-size prototype test |
| SBGeo | Provide information on existing NCG removal equipment and its operation; will provide review and feedback on work |
| Membrane Technology and Research | Will provide bench-scale testing at low cost |

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## CONTACTS

Raymond LaSala
Office of Geothermal and Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585
Phone: (202) 586-4198
Fax: (202) 586-5124
e-mail: raymond.lasala@ee.doe.gov

Peggy Brookshier
DOE Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
Phone: (208) 526-1403
Fax: (208) 526-5964
e-mail: brookspa@id.doe.gov

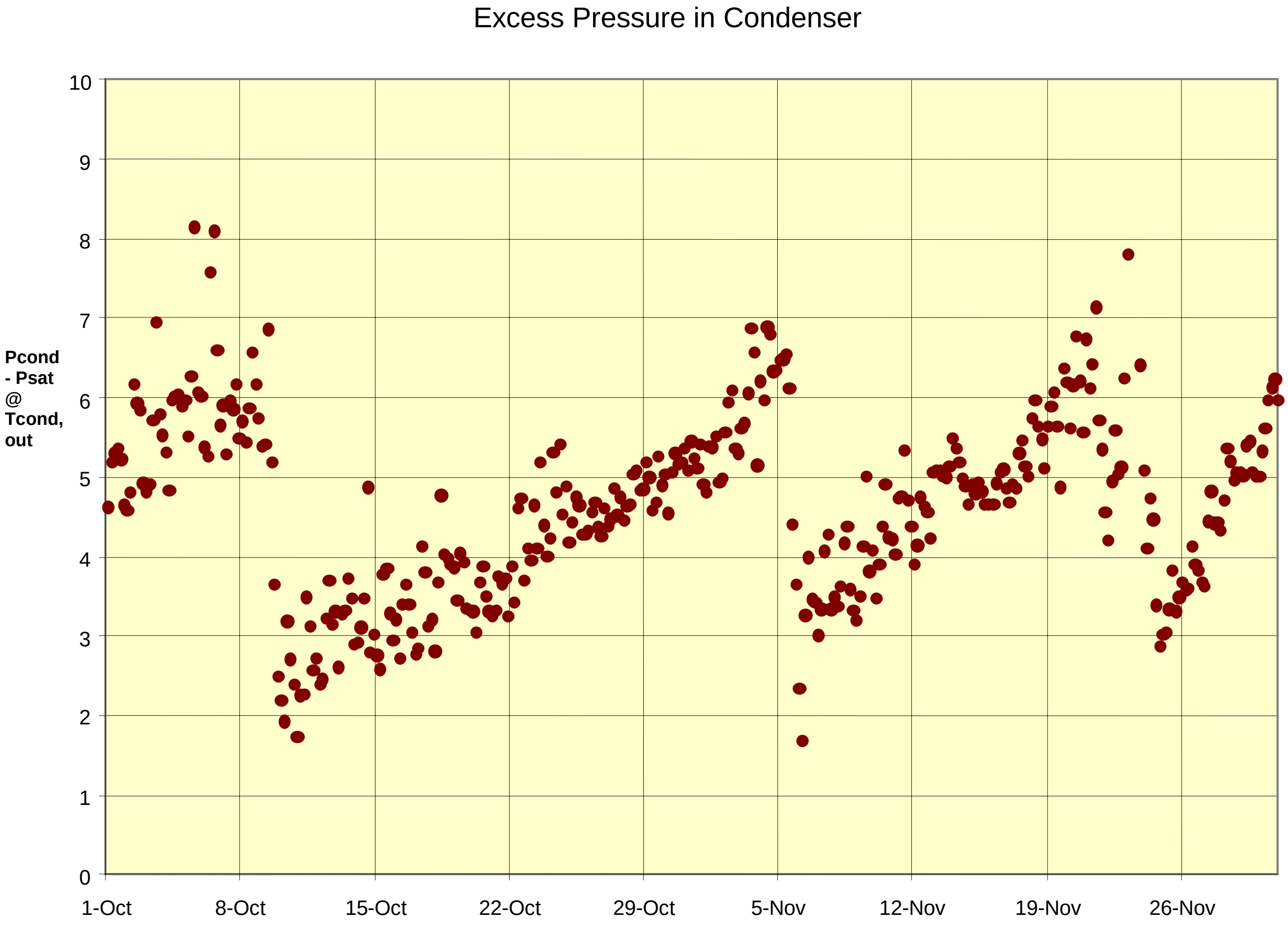
Jay Nathwani
DOE Idaho Operations Office
850 Energy Drive, MS 1225
Idaho Falls, ID 83401-1563
Phone: (208) 526-0239
Fax: (208) 526-5964
e-mail: nathwaj@id.doe.gov

Charles Mohr
Idaho National Engineering and
Environmental Laboratory
PO Box 1625
Idaho Falls, ID 83415-3625
Phone: (208) 526-9552
Fax: (208) 526-4017
email: mohrcm@inel.gov

K.K. Bloomfield
Idaho National Engineering and
Environmental Laboratory
PO Box 1625
Idaho Falls, ID 83415-3830
Phone: (208) 526-5250
Fax: (208) 526-0969
email: blookk@inel.gov

Greg Mines
Idaho National Engineering and
Environmental Laboratory
PO Box 1625
Idaho Falls, ID 83415-3830
Phone: (208) 526-0260
Fax: (208) 526-0969
email: minesgl@inel.gov

Figure 1


Excess Pressure in Condenser
Pcond - Psat @ Tcond, out
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9
8
7
6
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8-Oct
15-Oct
22-Oct
29-Oct
5-Nov
12-Nov
19-Nov
26-Nov

# GEOTHERMAL PLANT GAS DEVELOPMENT

J. K. Partin
Idaho National Engineering and Environmental Laboratory

## KEY WORDS

gas sensing, tunable diode near-infrared spectroscopy, photoacoustic spectroscopy, real-time process monitoring

## PROJECT BACKGROUND AND STATUS

The goal of this effort, initiated in 1997, is to develop and evaluate real-time, low maintenance detection systems for monitoring process gas species, such as hydrogen sulfide ($H_2S$) and hydrogen chloride (HCl). The development of new $H_2S$ monitoring systems is of interest in order to reduce the cost of abatement processes used to limit its emission into the atmosphere. These abatement processes increase the operating and maintenance costs for geothermal plants. Instrumentation currently used to control these processes is labor intensive to operate. (It is estimated that a man-week per month is required to maintain these instruments and to keep them in calibration.) At present, the $H_2S$ levels in the cooling tower stack are only measured periodically. This infrequent sampling results in a conservative use of chemical feed-stocks to ensure that regulatory limits are never exceeded. Presently, operators target chemical usage to achieve no more than 75% of allowable emissions. If this level could be raised to around 90% through the use of new continuous monitoring techniques, then annual savings on the order of $75,000 per plant might be possible from the reduced chemical usage.

HCl is also found in the steam delivered to geothermal production facilities. The washing process that reduces its concentration to acceptable levels in order to prevent corrosion of plant components also reduces the steam's energy content. The ability to perform cost-effective, real-time monitoring of HCl could also allow the optimization of this process, increasing power generation. Measurement conditions for these, and other species of interest to geothermal processes, vary from the main steam line at a temperature of about 350 °F and a pressure of 100 psig to near ambient temperature and pressure in the cooling tower stack. Concentrations of the different species vary from around 0.05 ppm to 1000's of ppms, depending upon the measurement location.

The initial emphasis of the project was concerned with the development and validation of a $H_2S$ monitoring system based upon frequency-modulated, tunable diode spectroscopy. During the past year, this instrument was modified to perform HCl measurements and tested in the laboratory as a function of process conditions. An investigation of photoacoustic spectroscopy using diode laser devices was also initiated.

## PROJECT OBJECTIVES

The objective of this project is to lower the operating costs of geothermal power production through the development and demonstration of compact, field-ready instrumentation for the real-time detection and feedback control of process gas species, such as $H_2S$ and HCl.

### *Technical Objectives*

- Demonstrate and evaluate $H_2S$ frequency-modulated spectroscopy system in the field.

- Modify frequency-modulation system to perform HCl measurement and test in the laboratory as a function of process conditions.
- Design, procure, integrate, and test a laboratory prototype based upon photoacoustic detection techniques.
- Compare performance of photoacoustic versus frequency-modulated technique and develop optimal designs for field performance.

***Expected Outcomes***

- Development of improved monitoring devices for real-time gas monitoring applications in geothermal plants.
- Optimization of process parameters to reduce chemical abatement costs and component corrosion.

## APPROACH

The development of the proposed on-line monitoring systems is based upon the use of near-infrared diode laser technology, which offers several advantages over other systems for geothermal emission and process control operations. These types of lasers produce relatively high power densities with high spectral purity for high sensitivity, high selectivity measurements. They can be manufactured to emit radiation in the 0.7 to 2.0 micron region of the electromagnetic spectrum. This region contains the overtone and combination absorption bands of a number of species of industrial interest, including $H_2S$, HCl, $CO_2$, $H_2O$, $NH_4$, $O_2$, $NO_2$ and $CH_4$. A particular diode device can be tuned to over a small range by changing its applied temperature and current. The devices are compact, operate at room temperature, and have modest power requirements. In addition, the output from these systems can be easily propagated over standard communication-grade optical fibers. This allows for the configuration of a system in which the sensitive optical and electronic components can be located in an environmentally-controlled area, and also allows the multiplexing of signals so that a single device could be used to make a number of remote measurements. This effort has been investigating two different measurement techniques incorporating these devices for geothermal process gas measurement applications. The two techniques are frequency-modulated tunable diode spectroscopy and photoacoustic spectroscopy.

For the past two years the effort has concentrated on the development and demonstration of a real-time $H_2S$ monitor based upon the frequency-modulated tunable diode spectroscopy technique. This technique determines the amount of light absorbed by the sample and relates it to concentration via Lambert's law. For the measurements, the injection current of the diode is modulated in frequency as the laser is tuned over an absorption line of the species of interest. (Hence the name frequency-modulated, tunable diode spectroscopy.) There are two principle advantages of this technique over other types of spectroscopic detection. First, the measurement can be performed in a frequency band where the signal contribution from noise is at a minimum. Second, since the laser can be precisely tuned over narrow spectral features, signal contributions from interfering species (in our application, carbon dioxide, methane and water vapor) can be also be minimized. The principle disadvantage of the technique for process application is that the broadening of the absorption line that occurs under conditions of high pressure and temperature can significantly limit the effectiveness of the technique.[1-2] Large (~ 100 m) absorption pathlengths are also required for very high sensitivity (ppb) measurements and while these can be configured using multi-pass cells, they make the measurement more sensitive to condensate, or other particulate, loading in the process streams.

In order to overcome some of the disadvantages for process gas monitoring presented by the previous technique an alternative measurement approach based upon the photoacoustic effect is also being investigated. This technique is also based upon the measurement of the absorption of radiation by the specie of interest. However, in this case, instead of measuring the change in transmittance of the probing beam, the absorbed radiation is measured directly via a calorimetric method. In this measurement, the beam is rapidly turned off and on, by either electronically pulsing or by propagating the beam through a rotating wheel with slots that "chop" the beam. This modulated beam is then directed into a sampling cell containing the material under study. When the optical frequency (wavelength) of the light is adjusted to an absorption transition, some of the molecules will be excited from lower energy levels to upper energy levels. These excited molecules then transfer the excitation to translational, rotational, or vibrational levels, which increases the thermal energy. This increase in thermal energy then produces a temperature variation, and a subsequent pressure change that can be detected by a sensitive microphone.

Unlike frequency-modulated spectroscopy, photoacoustic spectroscopy has been demonstrated on a range of samples of all phases with good sensitivity. In particular, the technique has been applied to measure trace gases in laboratory-scale, combustion reactors operating at high temperature and pressure.[3] This study demonstrated that high pressure could increase the sensitivity of the measurement since it enhances collisional deactivation. The technique also allows the use of a small measurement volume replacing the long-pass cell and its potential for problems with condensate scattering.

## RESEARCH RESULTS

Two field tests were conducted with the $H_2S$ LasIR tunable diode frequency modulation system obtained from Unisearch Associates (Ontario, Canada). The first test, which has been described in previous reports, was conducted from December $12^{th}$-$17^{th}$, 1998 at Northern California Power Agency (NCPA) Unit 1.[4] For this test, a side stream of the condenser vent gas entering the Stretford system was passed through a 10-centimeter sampling cell instrumented with the frequency-modulated spectroscopy system. The gas stream contained $H_2S$ in 2-3 mole percent concentrations along with a mixture of other gases including $H_2$, $CO_2$, $CH_4$, $N_2$, $NH_4$, and $H_2O$. The system was calibrated using a certified gas mixture of $H_2S$ in nitrogen and operated continuously for as long as 24 hours. Measured $H_2S$ levels were benchmarked against independent measurements tracking to within ±7.5%. The instrument exhibited good short operation with a typical precision on the order of ± 25 ppm (v/v) per meter, comparable to laboratory operation. Longer term stability was limited by two effects; signal modulation caused by etalon interferences and pressure variations caused by the build-up of condensate in the side stream tubing.

In order to address these issues, and to evaluate the system performance in a process stream containing a very low concentration of $H_2S$, a second field test was conducted at NCPA in July 1999. This test used a side stream taken from the treated vent gas exciting the Stretford system, containing $H_2S$ in a mixture of other gases that varied from 0-20 ppm (v/v). The stream was introduced into a multi-pass cell adjusted to a pathlength of 90 meters and calibrated with $H_2S$ in nitrogen supplied from a certified calibration gas cylinder. The system was placed on-line with the Houston Atlas system, which senses a color change in a lead-acetate tape in response to $H_2S$ concentration. (The $H_2S$ monitor is shown deployed next to this system in Figure 1.)

The data collected over a 3 1/2 day operation of the instrument at NCPA is presented in Figure 2. The system exhibited good long-term stability over this time period with a typical precision of ± 50 ppbv. It was also able to track process changes in agreement with independent measurements made by the Houston Atlas system, but with an off-set in the actual value. This is most likely due to differences in calibration between the devices. There was no evidence of interferences from other stream gases and the system exhibited minimal operational problems from condensate build-up, pressure and flow variations, or optical etalons.

A 1.793 micron laser diode was procured and installed into the Unisearch LasIR system for the detection of HCl. Laboratory experiments were conducted in which controlled quantities of HCl vapor in nitrogen from a certified gas cylinder were introduced into a stainless steel cell absorption cell with a 1 meter pathlength and observed at various pressures. These experiments indicated that HCl could be detected with this system at approximately 1 ppm (v/v) per meter at ambient conditions. This is at least 25 times more sensitive than our best measurements of $H_2S$ using near-infrared technology and is attributed to the availability of stronger absorption bands for HCl in this region. The HCl measurements also exhibited less sensitivity to increases in pressure than those performed with $H_2S$, with only a 50 % decrease in signal at 15 psig. (A 50% decrease in signal was observed at 5 psig with $H_2S$.) These results indicate that with some stream conditioning it would be feasible to detect HCl in the steam line using this technique.

Preliminary work was also completed investigating the application of photoacoustic spectroscopy for the on-line detection of plant gases. An experiment was performed using hydrogen sulfide and the 1.578 nanometer laser diode used in the frequency-modulated spectroscopy system. For the work, approximately 3.5 milliwatts of radiation from the diode was directed into a photoacoustic cell, shown in Figure 3. This cell had been modified from a design used for another application with a much higher power (several watts) carbon dioxide laser. The radiation from the laser diode was mechanically-chopped at the resonance frequency of the cell of around 2.7 kHz. The acoustic signal from an amplified condenser microphone (Bruel and Kjaer Model 4189) placed in contact with a small opening in the cell was then monitored at this frequency with an HP Model 35655A signal analyzer. Using this set-up, hydrogen sulfide at levels of 5000 ppm(v/v) could not be detected. The results of this study indicate that the cell volume will need to be made much smaller in order to increase the sensitivity of the measurement with the relatively low powers produced by the diode lasers.

## FUTURE WORK

The photoacoustic spectroscopy experiments will be continued, incorporating various system improvements suggested by the FY-99 work to increase measurement sensitivity. These upgrades include miniaturizing the photoacoustic cell volume and the use of smaller, higher sensitivity microphones. Based upon the results of this effort, an on-line measurement system for detecting HCl in the geothermal steam line will be designed either using this spectroscopy or the frequency-modulated technique.

Additional work is also planned with the $H_2S$ monitor using frequency-modulated laser spectroscopy in which the prototype will be modified to incorporate an automatic calibration system and the necessary control interfaces for unattended, long-term operation. A test location will then be solicited and the system performance validated with an extended field trial.

A new task is also being initiated to examine the feasibility of incorporating new optical devices into an instrument for measuring both steam quality and velocity. The optical measurement of fluid properties is an established technique, but it has not been widely used due to the cost and complexity of the required equipment. This effort proposes to investigate the re-engineering of these types of systems to incorporate new semiconductor emitter and detector technology that is compact, light-weight and portable (battery operation is possible). All of these components operate at room temperature and could conceivably be packaged as devices that could be directly interfaced to steam lines and used to collect and telemeter data from locations throughout the field.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Various operators at the Geysers', including Calpine and NCPA, have expressed an interest in the technology as a means of providing real-time data for improved process control and reducing the costs of operating and maintaining the existing instrumentation performing these tasks. Letters of support for the continued development of $H_2S$ monitoring system, based upon the frequency-modulated diode spectroscopy technique, were received from representatives of NCPA and the North Sonoma County Air Pollution Control District after their review of the technology during the July 1999 field validation.

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## CONTACTS

Raymond LaSala
Office of Geothermal and Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585
Phone: (202) 586-4198
Fax: (202) 586-5124
e-Mail: *raymond.lasala@ee.doe.gov*

Peggy Brookshier
DOE Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
Phone: (208) 526-1403
Fax: (208) 526-5964
Email: brookshpa@id.doe.gov

Jay Nathwani
DOE Idaho Operations Office
850 Energy Drive, MS 1225
Idaho Falls, ID 83401-1563
Phone: (208) 526-0239
Fax: (208) 526-5964
Email: nathwaj@id.doe.gov

J.K. Partin
Idaho National Engineering &
Environmental Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-3815
Phone: (208) 526-2822
Fax: (208) 526-2814
e-Mail: JK6@*inel.gov*


**Figure 1.** $H_2S$ Analyzer and Multi-Pass Sampling Cell Deployed Behind Houston Atlas Instrument at NCPA.

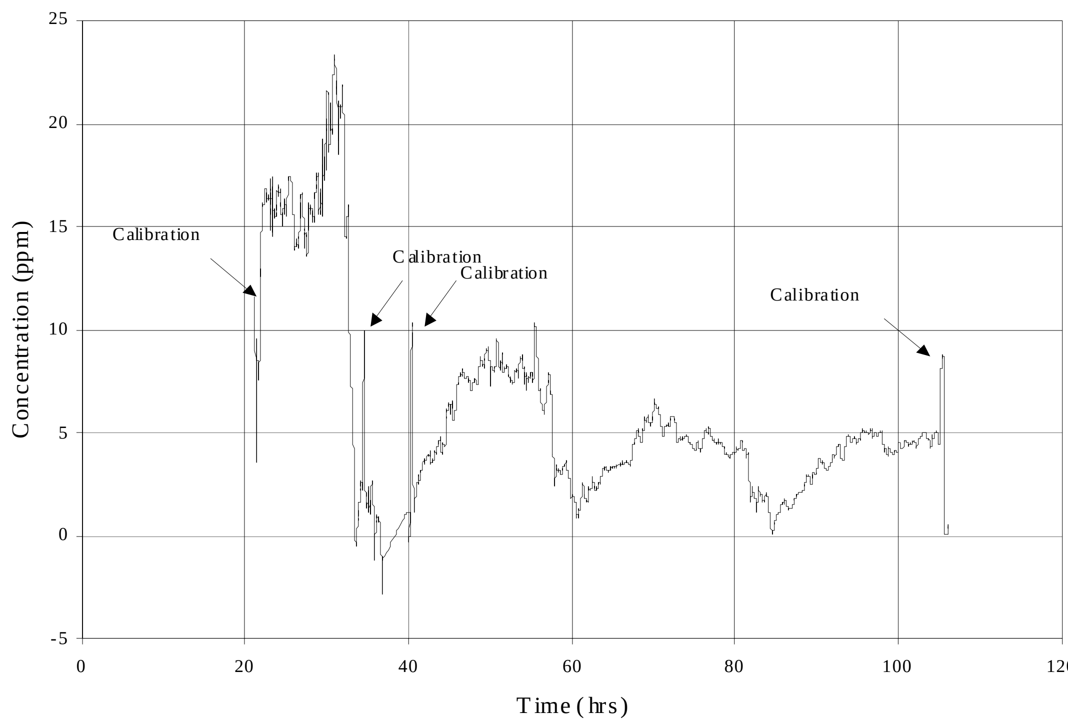


**Figure 2.** 3 1/2 Day $H_2S$ Monitor Operation in NCPA Treated Vent Gas Stream.

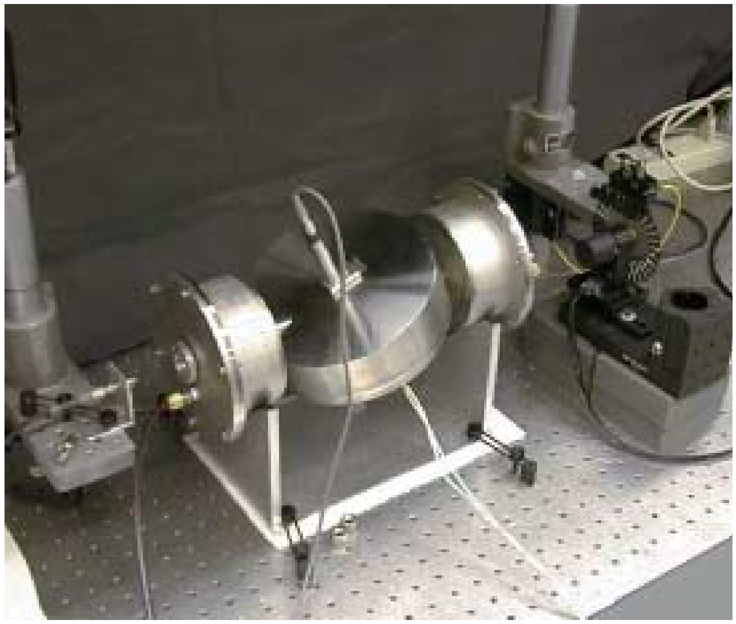

**Figure 3.** Photoacoustic Spectroscopy Laboratory Set-Up

# Scale Inhibition in geothermal power plants

Roald N. Leif, Charlene M. Schaldach and Carol J. Bruton
Lawrence Livermore National Laboratory

## KEY WORDS

amorphous silica, scale, inhibition, molecular modeling

## PROJECT BACKGROUND AND STATUS

One of the barriers to maximizing the efficiency of geothermal power plants is the problem of silica scale formation. Significant progress has been made in understanding the kinetics of monomeric silica polymerization and precipitation under a wide variety of conditions (Rothbaum and Rohde, 1979; Weres et al., 1981; Fleming, 1986). Despite this understanding, the inhibition of silica scale remains a challenge and the geothermal industry still lacks an effective and economical silica scale inhibitor that has widespread applicability. This is partly due to the diversity of geothermal brines but also due to the complex nature of aqueous silica reactivity. Therefore, the objective of this research is to provide a basic understanding of the chemical mechanisms of silica scale formation directed at the development of antiscalant technology. Experiments measuring bulk solution kinetics are complemented by tasks specifically addressing the molecular aspects of reaction mechanisms, scale characterization and computer modeling of silica molecule interactions. A knowledge of reaction mechanisms and detailed kinetic measurements may lead to new insights in controlling the silica scale reaction pathways and ultimately lead to new approaches to scale inhibition.

## PROJECT OBJECTIVES

The overall goal of this research project is to investigate methods of inhibiting scale formation in geothermal power plants. The focus is on identifying key steps in the reaction pathways by which monomeric silica polymerizes and eventually leads to silica scaling. We will determine silica polymerization/precipitation kinetics, examine how scaling rates and scale characteristics are affected by fluid chemistry and substrate composition, and model the interaction between silica molecules in an aqueous environment which provides for the effects of a background electrolyte. The effectiveness of both inorganic and organic scale inhibitors will be tested. 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.

### *Technical Objectives*

- Provide high precision quantitative data on the kinetics of monomeric silica polymerization and amorphous silica precipitation necessary for the evaluation of chemical scale inhibitors

- Determine the enhancements of scale formation due to cations (i.e. $Al^{3+}$) and measure enrichment factors of these cations in scales from batch and mixed flow reactor systems

- Probe the structures of reactive species in solution and characterize scale deposits using nuclear magnetic resonance (NMR)

- Measure the effect of the substrate on the rate of nucleation and deposition using hydrothermal atomic force microscopy

- Determine the minimum energy molecular configuration and induced surface charge density of neutral and ionic molecules of monomeric aqueous silica in water using a 6-31G** basis set at the MP2 level of correlation

- Evaluate inorganic and organic molecules as potential scale inhibitors by measuring their effectiveness under a variety of conditions

***Expected Outcomes***

- Determine accurately the kinetic behavior of the loss of monomeric silica under a range of experimental conditions and correlate the scale amount and composition with solution composition

- Characterize the structure and bonding between aluminum ion and both monomeric and polymeric silica in solution

- Determine the molecular single and double layer charge distributions surrounding neutral and ionic molecules of monomeric aqueous silica to better understand the formation of silica polymers

- Identify chemical additives that can be used to inhibit the growth rate of silica scale

## APPROACH

To determine the reactivity of silica in simulated geothermal brines, we measured the concentrations of monomeric and polymeric silica as a function of time in batch experiments. These initial experiments have focused on silica polymerization kinetics in low ionic strength solutions, with particular attention to the initial rates and nature of the induction periods. This determination provided essential baseline information on the kinetics of polymerization and polymer aggregation under these controlled conditions. We also performed initial NMR analyses on silicon-rich brine solutions with the goal of characterizing the oligomers formed during the initial stage of silica polymerization.

Quantum mechanical geometry optimizations were performed on $Si(OH)_4$ and $Si(OH)_3O^-$ molecules. At 100°C , $Si(OH)_4$ is the dominant monomeric aqueous species of Si at pH values less than about 9, and $Si(OH)_3O^-$ (which is sometimes referred to as $H_3SiO_4^-$ or $HSiO_3^-$) is dominant at pH values greater than about 9. The determined electronic structure was used to provide source terms for an iterative solution of the Poisson-Boltzmann equations (Wilson et al., 1997). To facilitate this calculation, a solvent-accessible molecular surface is constructed at the van der Waals radii of the atoms comprising the molecule. The electronic distribution of the molecule is allowed to rearrange in response to the polarization of its interface with an aqueous environment. The polarization charge induced on these surface elements is mapped onto the nodes (“dots”) from which the surface is comprised. These calculations were performed at the 6-31G**/MP2 level of theory allowing for an accurate depiction of the induced surface charge density.

By combining the results from the bulk solution kinetic measurements with computer modeling of aqueous silica molecular interactions and NMR determinations of the molecular/polymer structures, we can obtain a better understanding of silica reaction pathways.

## RESEARCH RESULTS

In the early stages of the project we began with batch experiments in low ionic strength solutions spanning a range of pH values. Monomeric silica polymerization was measured and both the timing and degree of amorphous silica precipitation were determined. These results are shown in Figure 1. Rapid polymerization of monomeric silica with no induction period was observed in the runs with pH > 7.0, whereas pronounced induction periods were observed in the runs with pH < 7.0. In experiments with pH < 7, the silica was either monomeric silica or in an amorphous silica precipitate; no polymeric silica was present. In experiments with pH > 7, the silica remained completely soluble, either as monomeric or polymeric silica. No measurable amorphous precipitated silica was found in the pH > 7 experiments. These experiments provided a baseline data set to evaluate both the effects of specific cations and the effectiveness of potential inhibitors.

The solvent-accessible surfaces of the $Si(OH)_4$ and $Si(OH)_3O^-$ molecules are shown in Figures 2a and 2b, respectively. These figures provide a direct comparison of the polarization-induced charge on the solvent-accessible surface due to the aqueous environment. The results show a more even pattern of charge distribution on the neutral molecule (Figure 2a) than on the ionic species (Figure 2b). The charge pattern on the ionic $Si(OH)_3O^-$ molecule is mostly positive (indicated in blue), with the surface covering the hydrogen atoms being primarily neutral and only slightly negative (neutral is shown in white; negative is indicated in red). On the neutral $Si(OH)_4$ molecule, there is greater negative surface charge, again on the surface surrounding the hydrogen atoms. The sign of the surface charge is essentially opposite that of the charge on the atom below the surface.

## FUTURE PLANS

Characterization of the critical stages of scale formation are essential for identifying means of limiting silica scale in geothermal power plants. We plan to extend our kinetic and mechanistic characterization of aqueous silica chemistry and silica scale formation by the combined efforts of laboratory measurements and quantum mechanical modeling of aqueous silica interactions. This approach will aid in predicting the reactivity of aqueous silica in geothermal systems.

We will conduct a number of kinetic studies using simulated geothermal brine compositions at moderate pHs and at temperatures up to 110°C. Of central importance are flow-through experiments at conditions simulating conditions found at geothermal power plants. We will continue the NMR investigation of soluble aluminum silicate species that are likely intermediates in the formation of aluminum-rich silica scales. Characterization of solids using magic angle spinning–NMR will identify the chemical state of aluminum in the scales. Influence of the substrate on silica deposition will also be evaluated using hydrothermal atomic force microscopy by directly imaging silica deposition at elevated temperatures using a flow-through cell. We also plan to develop and implement an algorithm to allow overlap of interacting silica molecules, providing the energy of interaction as a function of intermolecular separation. This will allow us to better simulate the interactions between potential scale inhibitors and silica in solution.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Geothermal energy producers interested in the development and implementation of new antiscalant technology will benefit from the findings of this project because of the potential economical benefits of silica scale control. The potential for silica scaling often limits heat extraction from the geothermal resource, and significant costs can be incurred in removing and disposing silica scale.

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## CONTACTS

Roald N. Leif
Lawrence Livermore National Laboratory
L-219
P.O. Box 808
Livermore, CA 94550
Phone: 925-422-2469
Fax: 925-422-0208
Email: leif1@llnl.gov

Raymond LaSala
Office of Geothermal and Wind Technologies
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585
Phone: (202) 586-4198
Fax: (202) 586-8185
Email: Raymond.LaSala@ee.doe.gov

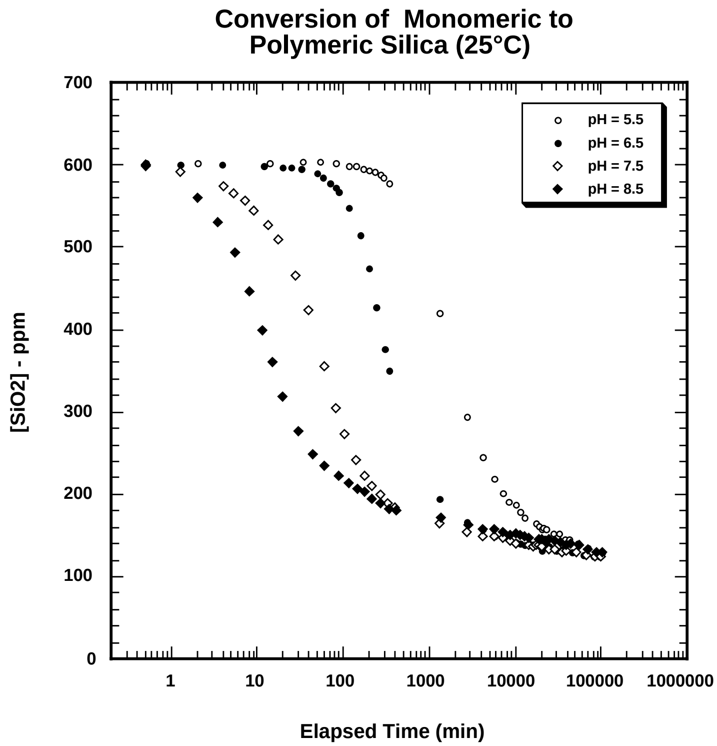


**Figure 1.** Conversion of monomeric silica to polymeric silica with time at 25°C at pH values of 5.5, 6.5, 7.5 and 8.5 in the chemical system $SiO_2$-$H_2O$.

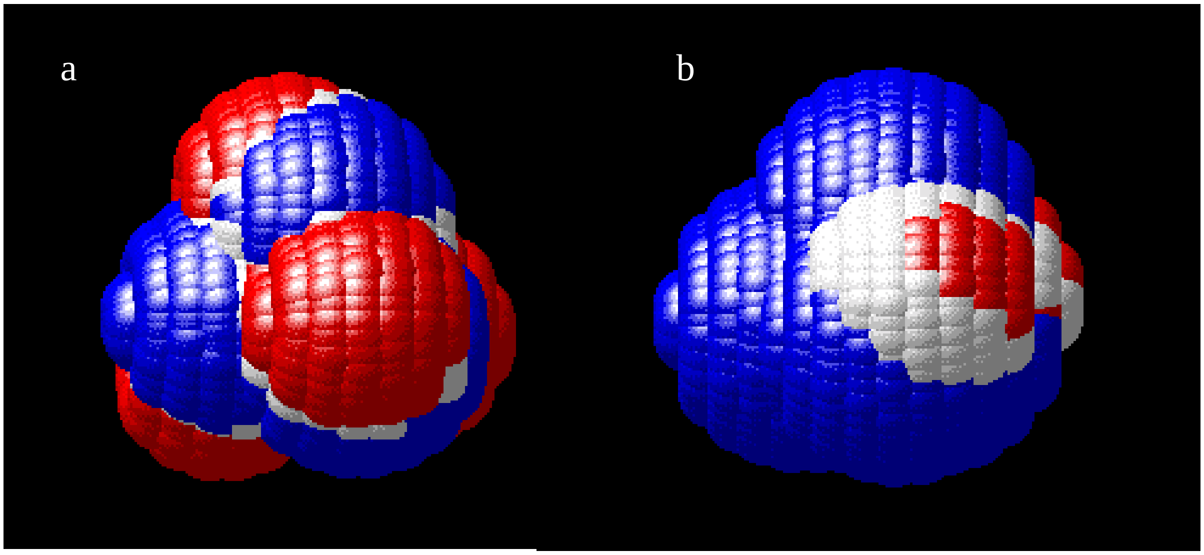


**Figure 2.** Charge distribution of solvent accessible surfaces of (a) $Si(OH)_4$ and (b) $Si(OH)_3O^-$ molecules. Blue=positive charge, neutral=white, red=negative.

# IMPACT OF MICROBIOLOGICAL ACTIVITY UPON THE OPERATING EFFICIENCY OF GEOTHERMAL PLANTS

Peter A. Pryfogle
Idaho National Engineering and Environmental Laboratory

## KEY WORDS

biofouling, microbially-influenced corrosion, microbial activity monitoring

## PROJECT BACKGROUND STATUS

The purpose of this project is to determine the impact of microbial activity on the performance and operation of geothermal plants, and to support the industry in identifying and mitigating these impacts. Significant densities of aerobic and anaerobic bacteria are found in geothermal power plant cooling water systems, which can produce complex structures called biofilms on the surfaces of critical components. These biofilms can degrade the plant operational efficiency. The annual cost to a geothermal plant resulting from the lost power production due to fouling of heat exchange surfaces, corrosion of components, and from chemical usage to control biological growth has been estimated to be as high as $500,000 for a 100MWe plant.

This effort, initiated in 1997, involves the integration of established sampling and analyses procedures with new analytical techniques for predicting the on-set and severity of microbial activity in geothermal plants. These measurements are directed at minimizing the over- or under-treatment of facilities with chemicals, which may accentuate growth and require costly countermeasures. Consequently, a multi-year study has been conducted to characterize and evaluate microbiological activity in geothermal plants at The Geysers in northern California in order to provide a baseline for comparing the impacts of varying process parameters and the benefits of various treatment alternatives.

In addition to the on-going maintenance of the baseline database of microbial activity, various methods and techniques of identifying and quantifying levels of microbial activity are being conducted. The initial effort focused on the use of a specially designed electrochemical cell for partitioning between biological and chemical attack of substrates. Investigations in 1999 evaluated the feasibility of using adenosine triphosphate (ATP) analyses as an indicator of increased microbial activity in geothermal cooling water. Experiments were also performed during 1999 to investigate the microbial degradation of the iron chelate used in the $H_2S$ abatement process.

## PROJECT OBJECTIVES

The goals of this program are:

- Investigate the impacts of microbiological activity upon the efficient operation of geothermal power production facilities.
- Support the industry in identifying and mitigating these effects.

### *Technical Objectives*

- Establish what levels of activity might be expected for a typical exposure
- Determine how this activity changes with environmental or process conditions

- Identify which analytical techniques is the most productive for elucidating differences in microbiologically and chemically-induced degradation in the plants.

- Perform baseline characterization of geothermal fields to determine microbial densities and metabolic diversity, and to perform baseline chemical analyses to evaluate nutrient availability for microbial growth and chemical corrosion potential.

- Develop and evaluate monitoring techniques for detecting the on-set, type, and level of microbial activity in plant environments.

- Evaluate the impact of microbial activity on the effectiveness of process chemicals such as the iron chelate used in the $H_2S$ abatement.

- Develop and test new methods for monitoring biocide efficacy.

***Expected Outcomes***

- Cross-field characterization of chemical and microbial activity

- Monitoring techniques for tracking microbial activity in plants

- Development of more efficient and cost-effective treatment protocols for biofouling problems

## APPROACH

This project has investigated a number of analytical techniques with measurements being performed on both biofilm samples exposed at the facilities and materials isolated and cultured in the laboratory. Techniques applied include most probable number analyses, total carbon analyses, various surface analyses of coupons, and electrochemical methods. [1-2] These techniques have been used to establish the typical level of microbial activity and its impact on component material surface and to maintain a baseline database for evaluating the effectiveness of techniques developed to mitigate the impact of the microbial activity.

In order to develop methods for mitigating the impact of microbial activity, it is necessary to develop techniques for plant operators to establish microbe levels in circulating waters. One of the methods being investigated is the use of an electrochemical split cell arrangement. The technique developed by Brenda Little and her colleagues, uses a double cell configuration in which one of the cells contains process fluid and bacteria while the second cell is sterilized. The cells share a common internal pathway having a semi-permeable membrane that permits the exchange of ions, but does not allow the passage of bacteria into the sterile side. Each cell contains an electrode made of the material of interest. The detection of a current flow between the electrodes is indicative of microbial interaction with the electrode material.

Coupons pulled from the biotic and abiotic compartments of the electrochemical cell have been examined using a variety of techniques including scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS) to identify chemical changes occurring at film interfaces and to identify corrosion products. Other techniques such as fluorescence staining coupled with confocal laser scanning microscopy (CLSM) and atomic force microscopy (AFM) were also used for detailed visualization of the physical properties of the biofilm and individual bacteria, respectively. The results of these examinations correlated very closely with those from coupons that were exposed to the circulating waters at The Geysers' plants, retrieved at monthly intervals, and shipped to the INEEL for analyses. The correlation of results between the laboratory and field studies adds validity to our use of the split-cells for controlled evaluation and testing of biocides and other process chemicals of interest.

Investigators are also evaluating a simpler, indirect technique based upon adenosine triphosphate (ATP) analysis as a means of establishing microbial activity. ATP is a high-energy molecule generated by living cells to perform metabolic functions. It is measured through the luciferin-luciferase reaction in which luminescence is generated that can be correlated to the amount of living biomass in the sample. The measurement is straightforward and could be performed in minutes as a daily sampling procedure in a plant. The technique requires evaluation to determine compatibility with this application since it can be sensitive to sulfide and some types of biocides, which may quench the reaction.

A preliminary investigation was also conducted to determine if the iron chelating compound used in $H_2S$ abatement processes was subject to microbial degradation. For these experiments, bacteria collected from the geothermal facilities were introduced into water samples containing small quantities of the chelate. Total organic carbon (TOC) analyses were then used to measure chelate loss and changes in the iron valence, i.e. the distribution and mass balance of ferrous ($Fe^{+2}$) and ferric ($Fe^{+3}$) components, were determined by atomic emission spectroscopy. Changes in biomass were also tracked through microscopic observations, selective media (MPN) inoculations, and ATP measurements.

## RESEARCH RESULTS

The sampling and analysis of cooling waters collected from the influent and effluent condenser lines of different facilities located at The Geysers has been regularly conducted since the spring of 1997. In addition, samples have been collected at the beginning of the Clear Lake pipeline and at the NCPA field distribution water line. The purpose of the latter effort is to determine if there are significant differences in microbial densities as this water travels through the pipeline. Samples from these locations were collected in November 1998, April 1999 and September 1999, providing seasonal indicators for late fall/winter, spring and summer. Gross changes in microbial activity were measured using the most probable number (MPN) technique, with the presence of heterotrophic, de-nitrifying, sulfate-reducing and acid-producing bacteria detected. Water temperature, conductivity, pH, and dissolved oxygen levels were measured and recorded as the samples were collected. Both seasonal and process change variations have been detected in some of this data during the past year. In particular, the sulfate-reducing bacteria were seen to exhibit seasonal variances with the highest number densities recorded during warmer weather. The data collected establishes baseline levels and the degree of variation in these systems as a function of environmental or process conditions. This information is required in designing monitoring techniques or devices, and in evaluating the effectiveness of mitigation methods.

The laboratory studies with the electrochemical-split cell indicate that biofilm development and colonization in the cell containing the inoculated process fluid occur in a relatively short period of time (~ one month). The film becomes more complex with exposure incorporating higher cell densities of micro-organisms with an increase in film thickness on the order of 15 microns over a three-month period. The chemical analyses of electrode surfaces indicate a general reduction of materials with the presence of more complex organic structure being detected with longer exposures. Although the electrochemical split-cell has proved to be a good laboratory tool, there are several problems with its application as a field instrument. It may be difficult to establish the required measurement stability in a plant environment since the proper operation of the device is dependent upon maintaining sterility of the abiotic compartment over time. (This was difficult to achieve even in the laboratory environment.) Ideally, the plant operator would like to have a detection method system that provides an indication of microbial activity in advance of the formation of a biofilm. The electrochemical-split cell provides an indication of microbial activity after the formation of the biofilm and resulting corrosion.

In 1999, an ATP luminometer, pictured in Figure 1, was purchased from Turner Designs Inc., Sunnyvale, CA and tested. Initial investigations were conducted in the laboratory on composite (mixed from the various plants) water samples collected during previous field trips. The instrument was subsequently tested at The Geysers' facilities during the April 1999 field trip. Measurements were taken at both the Aidlin and Unit 16 facilities over a two-day period using water samples collected from the water circulation system. While the technique gave good results at Unit 16, it was determined that high sulfate concentrations found at facilities such as Aidlin could interfere with the measurement, producing back-ground fluorescence that obscures the ATP signal for low cell numbers. (The sulfate concentrations in these fluids ranged from 1300 ppm at Unit 16, which uses a Stretford process for abatement, to 12,000 ppm at the Aidlin plant, which uses incineration for sulfide abatement.) Subsequent laboratory testing was conducted to determine the relationship between the sulfate concentration and the quenching of the ATP signal, and to identify a protocol for minimizing this interference. The laboratory work identified the approach of dilution as a means of minimizing this interference, as illustrated in Figure 2. A second field evaluation of the technique was performed in September 1999 in which the instrument was set-up and operated for two days at three different facilities, including Aidlin, Unit 16, and NCPA3. Samples were again pulled from the condenser circulation and tested for the presence of ATP. The ATP level was then correlated with a microbial cell density determined via a visual observation using a phase contrast microscope at the site. The application of the dilution method at the Aidlin plant was not successful because of the low initial microbial densities. The experiments at Unit 16 and NCPA3 did result in measurable levels of ATP that remained fairly constant over the two-day testing period. The concentration of ATP in three and four level dilutions of samples from these facilities also gave consistent results, indicating the dilution scheme has merit above a microbial density threshold level.

Experiments were also performed to examine the possible degradation of iron chelating materials by the bacteria from geothermal power plants. Investigators suspect that under circumstances where carbon may be limited to support biological growth, the chelate materials may be attacked by the bacteria and serve as a carbon source. Laboratory investigations were conducted by exposing iron chelate from a sample obtained from an operating plant, and bacteria from water samples collected during field trips. The results of the initial testing were somewhat ambiguous, and suggest refinement in the sampling times is required. Additional testing is planned with more frequent sampling during the initial period of inoculation.

## FUTURE WORK

Based upon the proof-of-concept studies completed this year, ATP appears to be a promising technique for detecting changes in microbial activity in geothermal systems. Consequently, a protocol is being developed for using this technique in a plant and incorporating it into a treatment program. FY-00 goals include soliciting facilities for performing an extended field trial using this protocol. If successful, efforts will be expanded to use the technique for determining the optimal timing for biocide applications.

In addition, an electrochemical-based biofilm monitor that has recently become commercially available will be tested and evaluated for application in geothermal plants. This monitor, the BIoGEORGE Monitor (Structural Integrity Associates, San Jose, CA) pictured in Figure 3, incorporates two electrodes, each of which is comprised of a series of stainless steel discs. These discs are subjected to intermittent polarization to a preset DC current. Biofilm activity is detected as an increase in the applied current required for achieving that potential. Traditionally, the difficulty with the application of these types of instruments has been limitations in distinguishing signals caused by scaling from those generated by biofilms. Testing will be performed in both the laboratory and plant facilities to determine if this device can successfully serve as a geothermal bioactivity monitor.

The chelate degradation studies will also be continued. During the next phase of testing ion chromatography will be used to look for changes in the chelating compound, and identify secondary degradation products of this compound. If significant degradation is unambiguously established to be occurring this work will be also be expanded a field study in an operating plant.

The sampling and analyses activities will also be expanded to include two additional procedures with the capability of providing a more detailed characterization of microbial activity at the geothermal plants. The first technique is a DNA analysis procedure using gradient gel electrophoresis (DGGE). The second procedure involves the measurement of phospholipid ester-linked fatty acids (PLFA), which serve as "signature" lipid markers from cell membranes and walls of microorganisms. These analysis procedures promise to provide more detailed information on the viable biomass, the characterization of bacterial types and the physiological status of the organisms. This more specific characterization of the microbial community may allow for the identification of particular species that have an adverse impact on the plant and equipment, as well as the operating parameters that are affecting growth. This could eventually lead to the development of activity probes that target specific microbial species, allow a plant operator to optimize chemical treatment for that species.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Calpine, NCPA and Unocal have expressed interest in various aspects of the work, and have participated in the project by allowing investigators access to their facilities. These organizations are interested in better sampling and monitoring protocols for predicting the on-set of growth, evaluating new biocide products, determining the optimal timing and doses for application, and in determining the impact of microbial growth and treatments of this growth on other process parameters.

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## CONTACTS

Raymond LaSala
Office of Geothermal and Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585
Phone: (202) 586-4198
Fax: (202) 586-5124
e-Mail: *raymond.lasala@ee.doe.gov*

Jay Nathwani
DOE Idaho Operations Office
850 Energy Drive, MS 1225
Idaho Falls, ID 83401-1563
Phone: (208) 526-0239
Fax: (208) 526-5964
e-Mail: *nathwaj@id.doe.gov*

Peggy Brookshier
DOE Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
Phone: (208) 526-1403
Fax: (208) 526-5964
e-Mail: brookspa@id.doe.gov

Peter Pryfogle
Idaho National Engineering &
Environmental Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-2203
Phone: (208) 526-0373
Fax: (208) 526-0828
e-Mail: *wck2@inel.gov*

**Figure 1.** Turner Designs ATP Luminometer.

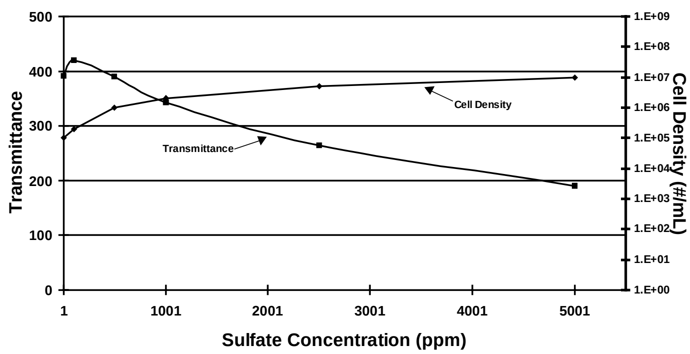


**Figure 2.** ATP Signal as a Function of Sulfate and Biomass Concentration.

**Figure 3.** BIoGEORGE Biofilm Monitor.

# FEASIBILITY OF ADJUSTABLE SPEED DRIVES FOR GEOTHERMAL POWER PRODUCTION

K. K. Bloomfield
Idaho National Engineering and Environmental Laboratory

## KEY WORDS

operations, maintenance, sustainability, energy demand

## PROJECT BACKGROUND AND STATUS

The continued success of the domestic geothermal industry is contingent upon reducing operating and maintenance cost, maximizing revenues and sustaining the resource for geothermal power generation operations. In FY-99, INEEL investigators initiated a study to examine the use of variable speed motors in binary power plant applications as a means of maximizing the plant revenue stream during periods when the price for power generated was the highest. Of specific interest was the use of these motors with the brine production pumps. Investigators believe that this application could improve the management of house power or parasitic loads, lower the maintenance cost of brine pumps and motors, provide the flexibility to curtail power production during off peak energy demand, and optimize the power production from the maturing resources due to exploitation. Once the variable devices are successfully used applied to the brine production pump motors, it is anticipated they can have additional application, and compounded benefit throughout a binary plant.

## PROJECT OBJECTIVES

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

### *Technical Objectives*

- Incorporate developed methods of assessing the benefits of cycling power compared to base load operations.

- Develop numerical simulation as a dependable method for estimating reservoir response to cycling operation.

- Develop models of plant performance is response to cycling operation of the geothermal resource. Expand models to include response of various motor-driven devices to variable speed motors.

- Transfer knowledge and technology to power producers to enhance their incorporation of reservoir and plant management with energy markets.

### *Expected Outcomes*

- Identify key parameters that reduce the risk of cycling such as the spread in on- and off-peak energy prices.

- Develop computationally efficient models to validate cycling benefits.
- Improve the understanding of cycling resource and plant operation to in response to energy markets.

## APPROACH

In order to evaluate the effect of cycling the performance of a power plant, investigators first collected historical on-peak, off-peak, wholesale power prices from the California Power Exchange. Investigators then used both historical data from power plants and modeled plant performance to obtain the variation of plant performance with brine flow rate and ambient air temperature. A generic pump curve with a 450 horsepower motor operating at 1780 rpm was obtained from a binary plant operator. The affinity or similarity laws for centrifugal pumps were applied to the pump curve to determine the flow from the pump with the available horsepower.

Affinity Laws:

$$\frac{flow_1}{flow_2} = \frac{rpm_1}{rpm_2}; \quad \frac{head_1}{head_2} = \left(\frac{rpm_1}{rpm_2}\right)^2; \quad \frac{hp_1}{hp_2} = \left(\frac{rpm_1}{rpm_2}\right)^3$$

The brine well production from the reservoir was then simulated using the TETRAD numerical simulator to test if the reservoir could support the increased production. The reservoir model was constructed as being three-dimension and having a single-component, single-phase fluid (water). This well performance model was constructed based upon information obtained from a binary plant operator on both well configuration and reservoir characteristics.

The model was given a temperature of 315 degrees F and a pressure of 70 psia at the pump suction; the operator indicated this was consistent with an observation well at depth. To match the modeled well production of 1,500 gpm, an aquifer was attached to the model and its properties adjusted until its flow matched the modeled well production. Once a suitable match was obtained, the brine production rate was varied to simulate effect of curtailed (off-peak) and increased (on-peak) production on the resource, and to predict the amount of variation in flow that the reservoir could sustain.

Investigators then examined the financial viability of curtailing output during off-peak hours and operating above pump motor design during on-peak hours to maximize output. The hourly historical market clearing price obtained from the California Power Exchange was applied to the performance of a binary plant having an annual ambient temperature profile expected for a typical Basin and Range plant. Based upon historical operating data from an existing plant, a correlation of brine effectiveness (net power per unit mass of fluid) as a function of the ambient temperature was derived. The cost data, temperature profile, and brine effectiveness correlation were then used to calculate the effect of cycling the reservoir on the plant revenues.

## RESEARCH RESULTS

This study was initiated under the premise that a DC motor would be used to provide the desired variable-speed, operating characteristic for brine production pumps in binary power plants. Subsequent to initiating this study, investigators concluded the more feasible approach would be the use of variable-frequency drives (VFD's). The VFD allows the frequency and voltage to an AC motor to be varied, thus adjusting the motor speed, torque, and horsepower to meet a specific pumping requirement. These drives allow existing motors to utilized, and though they require separate purchase and installation, the price of these devices is decreasing, while their performance is improving.

Because these devices allow an existing AC motor to be used, they have application beyond that for brine production pumps in both new and existing geothermal power plants. They should have application in both steam and binary power plants, though investigators believe the application will be greater in binary plants, which typically utilize more fluid drivers with higher parasitic power consumption. The ability to vary the speed of these fluid drivers provides added flexibility, allowing component performance to match required performance for different ambient and brine conditions. This should allow a plant operator to boost the performance of that component(s) limiting plant output during on-peak periods, while minimizing the power consumption of the remaining components. It is also expected that these devices would simplify control schemes, allowing control valves to be eliminated along with the parasitic losses associated with throttling flow through these valves.

Although there appears to be significant potential for use in a binary plant, the initial phase of this study examined the use of the variable speed motors as initially proposed; to vary the production of geothermal fluid for a binary power plant. Based upon the results of the well/reservoir simulation, investigators determined that the simulated reservoir would support 8 hours of off-peak production of 75% of the design flow, with 16 hours of on-peak production at 108% of design flow. This production scenario would result in ~3% less brine usage annually. If the reservoir is experiencing a production decline, this lower usage should off-set, in part, the effect of the resource decline on plant performance. This off-set would be more significant in out-year operation, and was not considered in this initial study.

The base-load plant design was 11.6 MWe (net) for binary plant using air-cooled condensers designed for a typical mean ambient temperature (~45 degrees Fahrenheit). Using historical operating data from a commercial power plant, a correlation was derived that provided the brine effectiveness as a function of the ambient air temperature. This correlation was then combined with the hourly temperature data from Reno NV to generate the hourly output from the plant at the design, or base, plant brine flow rate. This same procedure was then used to calculate the expected power performance from the plant when the brine flow was varied as described for off- and on-peak periods. Using the hourly price data obtained from the California Power Exchange for a one-year period in 1998 and 1999, revenue streams were generated for the two operating scenarios. These revenue streams are summarized in the following table.

| | Base load revenues | Cycle revenues | Difference |
|---|---|---|---|
| January | $195,973 | $197,744 | $1,771 |
| February | $195,325 | $197,384 | $2,059 |
| March | $196,342 | $200,225 | $3,883 |
| April | $234,294 | $236,634 | $2,339 |
| May | $170,833 | $173,220 | $2,386 |
| June | $148,174 | $153,031 | $4,857 |
| July | $152,941 | $153,769 | $828 |
| August | $227,224 | $230,918 | $3,694 |
| September | $275,176 | $273,972 | -$1,204 |
| October | $240,983 | $244,626 | $3,643 |
| November | $282,134 | $278,366 | -$3,768 |
| December | $301,069 | $301,647 | $578 |

Under this off- and on-peak pricing scenario, the cycling of the brine production (using the variable speed devices) would produce an additional $21K annually (excluding the potential decrease in maintenance costs). The months with the negative revenues indicates that there would not be advantage of cycling because there is little difference in on and off peak power prices during those months. (The assumption that flow would be cycled as indicated was consistently used over the entire year; in an actual application, brine production might not be cycled during periods when there was minimal difference between off- and on-peak power prices, and no advantage to cycling production.)

The increased revenue stream of $21K is considered a minimum, and will likely be larger with optimization of the scheme for cycling production. The pay-back for installing these devices on production well pumps will vary with the final production optimization scheme, the number of devices required (it may not be necessary to install them on each well), and with the price of the VFD. The prices of the VFD's continue to fall; over a period of a few months in 1999, a vendor's quoted price fell by a factor of 25%.

## FUTURE PLANS

Investigators will complete the modeling activity to include the impact of using the VFD's throughout a binary plant. Using input obtained from the operators of binary plants, this modeling activity will attempt to incorporate these devices in those applications that typically limit the performance of these plants. Investigators will also continue to identify and evaluate other technologies with the potential to maximize plant revenues, as well as minimize the impact of operating a geothermal plant at off-design conditions (resource decline and off-design ambient conditions). The investigation will also attempt to quantify the apparent benefit of using the VFD's on reducing maintenance costs by extending pump and motor life, and maintenance intervals.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

There is significant interest in this project from binary plant operators as a means of increasing their revenue stream and possibly extending the life of equipment and the resource. Mammoth Pacific, in particular, has been very cooperative in providing investigators with plant and equipment data, and with feedback relative to the probable uses of these devices. The Baldor Electric Company has been very helpful and willing to demonstrate the advantages of variable frequency drives in probable applications in binary power plants.

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Raymond LaSala
Office of Geothermal and Wind Technologies, EE-12
U. S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585
Phone: (202) 586-4198
Fax: (202) 586-5124
e-mail: raymond.lasala@ee.doe.gov

Peggy Brookshier
DOE Idaho Operations Office
850 Energy Drive, MS 1220
Idaho Falls, ID 83401-1563
Phone: (208) 526-1403
Fax: (208) 526-5964
e-mail: brookspa@id.doe.gov

Jay Nathwani
DOE Idaho Operations Office
850 Energy Drive, MS 1225
Idaho Falls, ID 83401-1563
Phone: (208) 526-0239
Fax: (208) 526-5964
e-mail: nathwaj@id.doe.gov

K.K. Bloomfield
Idaho National Engineering and
Environmental Laboratory
PO Box 1625
Idaho Falls, ID 83415-3830
Phone: (208) 526-5250
Fax: (208) 526-0969
email: blookk@inel.gov

R. J. Turk
Idaho National Engineering Laboratory
P. O. Box 1625
Idaho Falls, ID 83415-3878
Tel: (208) 526-3611
Fax: (208) 526-8363
email: turkbj@inel.gov

# GEOTHERMAL TWO-PHASE FLOW MEASUREMENT

Robert P. Evans, Joe G. Keller
Idaho National Engineering and Environmental Laboratory

Jonathan Blotter, Alan G. Stephens
Idaho State University

## KEY WORDS

two-Phase, mass flow, sensor, flow measurement, instrumentation

## PROJECT BACKGROUND AND STATUS

Transducer noise analysis is a technology initiated at the INEEL that shows promise in providing two-phase flow measurement in steam/water mixtures. The method was first used at the INEEL as a diagnostic tool for pump performance under two-phase flow conditions for nuclear applications. Experimental tests were conducted in FY-1998 to determine the feasibility of predicting two-phase mass flow rate using the noise signal from an accelerometer for geothermal applications. Expanded bench-scale testing was completed in early FY-1999 and a limited field test was conducted at the Coso BLM West geothermal power plant on the China Lake Naval Weapons Center north of Ridgecrest, California.

## PROJECT OBJECTIVES

The objective of this work is to develop a low cost, non-intrusive, mass flow measurement sensor for two-phase flow conditions. The device is intended to monitor steam delivered from individual wells that feed flashed-steam power plants. When liquid brine flashes in the well, the potential for the precipitation of solids, or scale, on those surfaces exposed to the two-phase fluid, increases significantly and can render intrusive measurement devices ineffective. In addition, flow meters ordinarily used to measure single-phase flow rates do not provide an accurate measurement of the mass flow under two-phase flow conditions.

### *Technical Objectives*

- Establish the parameters defining the relationship of the flow noise signal to the mass flow rate of two-phase geothermal mixtures.

- Perform laboratory testing and field testing to verify the technology.

- Results of these tests would be used to develop algorithms.

### Expected Outcomes

- The end product of this research is the development of a low cost, non-intrusive, mass flow measurement sensor for two-phase flow conditions. Improved flow monitoring is expected to enhance plant performance through improved management of the steam delivery to the plant turbine and to improve understanding of the resource production.

## APPROACH

Signal noise methods were first used at the INEEL as a diagnostic tool. It was noticed that in turbulent single-phase flow, the standard deviation increased with flowrate for flow measuring instrumentation. This phenomenon was also observed in homogeneous two-phase flow.

Equations of motions for free vibration of a fluid filled pipe and forces due to changes in direction of flow were examined to initially determine the forces behind flow-induced noise (Blevins, R.D. Flow-Induced Vibration, Litton Education Publishing, Inc., 1977, ISN 0-442-20828-6), and Dimarogonas A.D. and Haddad S., Vibration for Engineers, Prentice-Hall, Inc. 1992, ISBN 0-13-950841-4). These references and equations confirm the notion of flow induced vibration and that the vibration or response of the pipe is a function of the mass velocity of the fluid in the pipe. Changes in velocity can be detected by changes in the acceleration. The random impact of the flow on the pipe wall produces a noise signal on an accelerometer or other transducer sensing element that can be correlate to mass flow. Laboratory and initial field testing has shown that there is a relationship between the noise on the signal from an accelerometer mounted on the outside of a pipe and the mass flow rate of a fluid through the pipe.

Any transducer used to sense a condition related to flow will have, in addition to its usual signal, various noise components superimposed upon the primary signal. Fast Fourier Transform (FFT) analysis techniques allow these superimposed noise signals to be separated and identified for correlation with the flow parameters. These vibrations can be measured using an accelerometer mounted to the wall of the pipe. With an accelerometer, the mean is meaningless; therefore only the noise part of the signal would be used to indicate the flow.

## RESEARCH RESULTS

With the observation made in the initial proof-of-concept testing that the accelerometer signal noise increased with flow, the testing was expanded to identify those parameters important to this measurement. For these scoping tests, the effects of two parameters, felt to be important to the measurement, were evaluated; i.e. mass flow rate and steam fraction (or quality). Two separate test sequences were conducted, each where one of these parameters was held constant and the other varied.

The accelerometer data were analyzed by first transforming the data into the frequency domain and performing a power spectral density (PSD) analysis. The 60-Hz component with its associated harmonics was notch filtered to eliminate noise components associated with electrical components. The notch extended about 5 Hertz above and below the filtered frequency. After transforming back into the time domain, the standard deviation (SD) was calculated for the resulting time-series data. For this investigation the magnitude of the accelerator noise is represented by ratio of the standard of the accelerometer signal to the mean value for a time series of data.

Comparisons of the accelerometer noise with the mass flow rate, show a definite relationship between them. A least squares regression produced a standard error of 3 kg/min, which is about 8% of range. This is considered quite good for a scoping test. Because it is difficult to actually hold either the mass flow or the quality constant, it is difficult to remove all of the effects of either mass flow or quality when evaluating the effect of the other on the accelerometer noise. From the data analysis performed, it would appear that mass flow has the greater effect on accelerometer noise. It should also be noted that the range of quality conditions was quite small (up to ~10%). The analysis of the relations between the accelerometer standard deviation and the fluid quality was much less clear. At low quality, there appeared to be a correlation, but as the quality increased, the relationship appeared to go away. Testing was also conducted with liquid water, both hot and cold.

During FY1999, two papers describing this phenomena were presented. "Two-phase Mass Flow Measurement Using Noise Analysis," was presented at the 45th International Instrumentation Symposium in Albuquerque, New Mexico and "Two-Phase Flow Meter" was presented at the U.S. Department of Energy Geothermal Program Review XVII at Berkeley, California. In addition, an Invention Disclosure (LIT-PI-523) and a United States Patent Application (Case Number S-92,166) have been filed.

Field testing was conducted at the Coso BLM West plant location. A series of five tests were performed. Accelerometers and a dynamic fluid pressure transducer were installed at several locations on the two-phase and single phase flow hot brine pipelines. The data collected from a two-phase flow at a single well outlet was considered the most successful of the two-phase flow tests. The accelerometer was installed near an orifice plate and this data compared well with the output of the differential pressure transducer. Data measurement locations are represented in Figure 1. Figure 2 is a scatter plot of the accelerometer standard deviation versus the square root of the differential pressure for the two-phase flow. The data comes from an accelerometer mounted on the top of the pipe about 5 to 7 feet upstream of the orifice in that line.

The field tests show a definite relationship between the standard deviation of the signal from an externally mounted accelerometer and the mass flow through the pipe on which the accelerometer is mounted. Although there is considerable scatter in the accelerometer standard deviation data against the reference two-phase mass flow, this scatter lies well within the uncertainty of the reference flow measurement for the two-phase flow.

## FUTURE PLANS

The next step to further confirm this concept would concentrate on establishing a firm theoretical basis for using noise analysis to determine two-phase mass flow and then additional field testing as required. Research would focus upon developing a mathematical understanding of flow-induced noise, examination of the frequency and magnitude component of the noise, and pipe configuration inter-relationships. This work would lead to the understanding of the driving forces that create noise within piping configurations and form the basis of future testing. A thorough literature search would be conducted of work performed in the area of two-phase flow, noise analysis, two-phase modeling techniques, and measurement techniques. Along with the literature search, a mathematical model of two-phase flow in a pipe would be developed. This model would allow for simulation of various flow conditions and pipe parameters. It is theorized that if measurable parameters such as support conditions, wall thickness, pipe material, etc are used, a calibration curve for different pipe configurations can be developed. Data collected during previous laboratory and field tests would be used as test cases to further understand the driving forces, and to confirm the mathematical model.

Following the work to get a firm understanding of the theoretical foundation for this technique, additional testing is needed. Testing to date has been conducted in a limited environment. There are site specific requirements that will vary from field to field, but the general requirements have been established – a device that costs less than $10K and has an accuracy approaching those of single-phase flow measuring devices. The objective of these tests would be to assess the viability of this measurement technique in an actual geothermal environment and identify those modifications and/or parameters that will have to be incorporated into a prototype unit that can be subsequently field tested. Investigators would also consider the use of other signal processors that may be more sensitive than accelerometers at frequencies expected to produce flow noise.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

While a non-invasive two-phase mass flow measuring device may have many applications, this work was done to investigate applications to the geothermal power industry where flow measurement must be made using intrusive devices subject to fouling or infringing on pressure boundaries. Initial tests were conducted with Caithness, who continues to explore additional field tests. A second geothermal operating company, Oxbow Power Services, Inc. has expressed interest and information is being exchanged. A Seattle based instrument supply company that specializes in flow meters, and a Colorado based flow meter testing company have both indicated interest in the technology and commercialization aspects.

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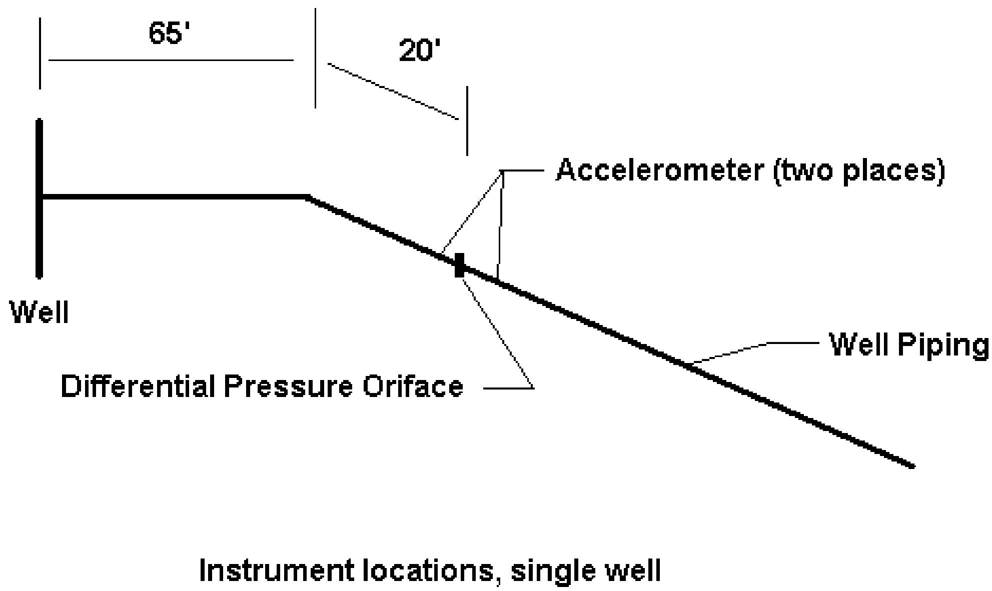


**Figure 1.** Process flow loop.

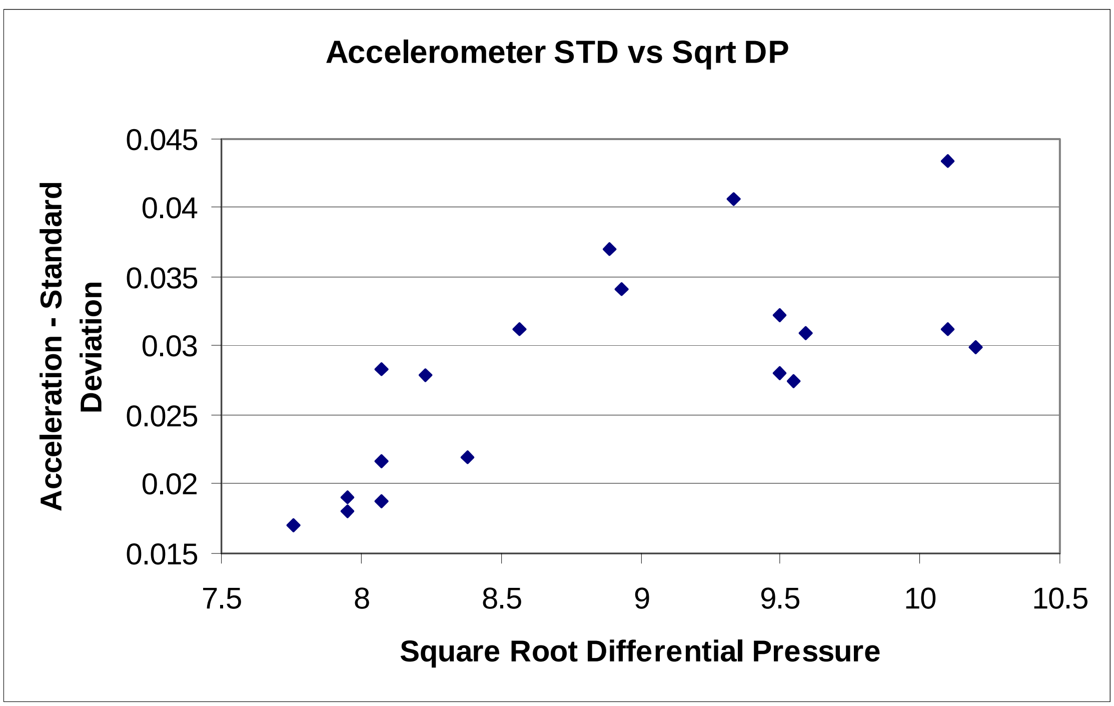


**Figure 2.** Scatter Plot.

## CONTACTS


Jay Nathwani
Advanced Technologies Division
U. S. Department of Energy
Idaho Operations Office
785 DOE Place, MS 1225
Idaho Falls, ID 83404
Phone: (208) 526-0239
Fax: (208) 526-5964
Email: nathwaj@inel.gov

Peggy Brookshier
Office of Program Management
U. S. Department of Energy
Idaho Operations Office
785 DOE Place, MS 1220
Idaho Falls, ID 83402
Phone: (208) 526-1403
Fax: (208) 526-6249
Email: brookspa@inel.gov

Robert P. Evans
Idaho National Engineering and
Environmental Laboratory
P.O. Box 1625, MS 3790
Idaho Falls, ID 83415-3790
Phone: (208) 526-0852
Fax: (208) 526-2818
Email: rpe@inel.gov

Joe G. Keller
Idaho National Engineering and
Environmental Laboratory
P.O. Box 1625, MS 3815
Idaho Falls, ID 83415-3815
Phone: (208) 526-1533
Fax: (208) 526-8883
Email: kellerjg@inel.gov

Greg L. Mines
Idaho National Engineering and
Environmental Laboratory
P.O. Box 1625, MS 3830
Idaho Falls, ID 83415-3830
Phone: (208) 526-0260
Fax: (208) 526-0969
Email: minesgl@inel.gov

Raymond LaSala
Office of Geothermal and Wind Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave. SW
Washington, DC 20585
Phone: (202) 586-4198
Fax: (202) 586-8185
Email: Raymond.LaSala@ee.doe.gov

# DIRECT USE AND GEOTHERMAL HEAT PUMPS

# GEOTHERMAL HEAT PUMP CASE STUDIES, MAINTENANCE COSTS, AND OPERATION HISTORY

R. Gordon Bloomquist, Ph.D.
Washington State University Energy Program

## KEY WORDS

Geothermal, Heat Pumps, GeoExchange Technology, Operation & Maintenance, Open Loop, Closed Loop

## PROJECT BACKGROUND AND STATUS

This project began in February 1998 and ran through September 1999. For the past 18 years, the Washington State University has been actively involved in analysis, design, and promotion of the use of geothermal/groundwater heat pumps. Although geothermal heat pumps have become increasingly popular over the past 20 years, little work had been done to establish or document operation, especially maintenance histories and costs. At the close of this contract, WSU had produced a document entitled "Commercial Geothermal Heat Pumps" that contained several case studies of systems now in use.

## PROJECT OBJECTIVES

WSU proposed to survey existing geothermal heat pump systems, identify equipment suppliers, determine equipment operating characteristics and availability, and interview system operators to assess operating reliability. System performance was assessed for both the heating and cooling modes. Ten geothermal heat pump systems throughout the U.S. were to be evaluated in detail, including several that have been in operation for over 30 years.

WSU would document the performance and operational and reliability characteristics of the systems investigated, and would develop detailed maintenance cost histories of the systems selected for detailed analysis. The results of these studies would be included in a report to be presented at conferences detailing the benefits of geothermal heat pumps to utilities and the commercial sector. WSU would also send several copies of the report to interested parties who were looking for more information on geothermal heat pumps.

### *Technical Objectives*

- To collect information on the operation and maintenance of existing geothermal heat pumps being used in commercial facilities.
- To document maintenance costs, equipment longevity and reliability, cost of replacement of critical components.
- To identify critical components, maintenance requirements, and intervals.

### *Expected Outcomes*

- Report that can be presented at conferences and sent to parties seeking more information on the technology.

- Case studies detailing geothermal heat pump installations, selection criteria, development trends, building and heat pump system characteristics, equipment and design problems, and operation and maintenance at existing heat pump facilities.

- To develop convincing information that will help satisfy potential customers of the reliability of geothermal heat pumps and the low cost of maintaining such equipment.

## APPROACH

WSU personnel visited various sites and talked with owners and operators about their existing systems. A check list was filled out at each visit. Follow-up phone calls were made to obtain any missing information. From this information gathered, the final document and case studies were produced.

The present study was conducted in two phases. The first began with a look at a number of installations in Washington State with an emphasis on obtaining information on building size and use, type and size of geothermal heat pump system, reasons for selecting geothermal heat pump technology, and owner/operator satisfaction with the system. The second phase of the study expanded the geographic area to include systems in several additional parts of the country and the scope to include much more concentration on operational, maintenance, and reliability issues.

Systems were first identified through conversations with equipment sales representatives, architectural and engineering firms, well drillers, ground loop installers, HVAC contractors, and utilities. Once a substantial number of systems had been identified, the owner/operator of each system was contacted by phone and an interview conducted to determine whether or not the system should or could be further considered. Every effort was made to include as many systems as possible with 20+ years of operating history, and as few as possible with five years or less of operating history. It is interesting to note that of all the systems that were identified, only a very few geothermal heat pump systems had been abandoned in favor of another system type, and in all such cases, the cause was related to open loop systems that had either excessive production well drawn down problems or injection well problems, and in no case due to problems with or dissatisfaction with the heat pumps.

Once the systems had been selected, detailed interviews were conducted with the owner/ operator, maintenance staff, and, when possible, the system designer. The interviews were conducted by phone and often required discussions with several individuals. Once the interviews were completed, all systems were visited, additional interviews conducted, and each system gone through in as much detail as possible. If it was determined that additional information was needed, phone interviews were again conducted with system designers, well drillers, or loop installers. When energy consumption data was not readily available from the owner/operator, every attempt was made to obtain such information from the serving utility.

As a baseline for a comparison of the results of this study, ASHRAE operation and maintenance estimates were reviewed as well as findings of work sponsored by the Geothermal Heat Pump Consortium were reviewed. The ASHRAE Handbook provides a standard method for calculating maintenance cost for commercial-size HVAC systems.

A number of the GSHP systems that date back to the 1950s were installed as a result of the building owners' wish to adopt a unique, quality design that would create a positive impression in the community. This was also at a time when air conditioning was becoming more and more of an issue and a driving force in selection of the geothermal systems. In the mid to late 1970s and early 1980s, a number of systems were built as a direct result of the oil crises of the early 1970s. The availability of a secure, locally available, indigenous resource was extremely important in the decision-making process, especially in a time of rapidly escalating energy costs and concerns over fossil fuel availability. Many owners of the more recently-developed systems contributed their decisions to go with geothermal heat pumps to past experience with such systems, very high quality of the installation, energy efficiency, and cost savings. Other reasons given included: environmental considerations, compatibility with building design or retrofit requirements, utility incentives, reputation of engineering design firm, need for individual temperature control, reduced space for mechanical equipment, and life cycle cost savings. Another important factor in many cases was the recommendation of the serving utility or advice provided by the state energy office.

## RESEARCH RESULTS

Because of the age of many of the installations, no actual capital cost data was available for most systems. For the 22 systems that are covered in this paper, the installed heat pump capacity varies from a low of 1.36-tons per 1,000 square feet to a high of 6.00-tons per 1,000 square feet. For the water source systems, flows range from 1.30 gpm per ton of installed capacity to 7.50 gpm per ton of installed capacity with an average of 3.43 gpm per ton. Required flow is, of course, very dependent upon water temperature and heating and cooling requirements. The horsepower of the well pump is totally dependent upon well construction, pumping head, and whether or not the well is equipped with a fixed or variable speed pump. For closed loop systems, the heat exchanger circuit pipe length ranged from 236 feet per ton to 600 feet per ton, with an average of 454 feet per ton. Of those with vertical bores, the range is 166 feet of bore per ton to 204 feet.

Building electrical energy use ranges from 9.40 kWh per square meter per year to 24.47 kWh per square foot per year, with an average of 18.7 kWh per square foot per year. For those systems where it was possible to determine electrical load for the mechanical system, the range was 8.43 kWh per square foot per year to 10.14 kWh per square foot per year.

As was mentioned earlier, open systems dominated the geothermal heat pump market from 1946 until approximately 1980 when horizontal and vertical closed loop systems became readily available. A majority of open loop systems rely on one or more wells, although some systems are based on other water sources, such as lake water, sewage effluent, or even municipal water. Water is withdrawn from the well or other source and disposed of through the use of injection wells, through surface discharge, or, in the case of standing column wells, the water is returned to the outer annulus of the production well.

There is little doubt that well problems dominate when it comes to open loop systems. The two most often encountered problems are inadequate flow in the production well and plugging that causes pressure build-up in the injection well. Production problems are most often a result of excessive draw down of the acquifer due to over use or severe drought. It can also be a result of sedimentation in the bottom of the well. In many cases, the wells are simply not drilled deep enough or completed correctly. Many such problems can be corrected by deepening the production well or by reworking. In those cases where sedimentation is a problem, correct screening can provide a relative straightforward solution. However, the vast majority of problems associated with open loop systems are caused by the injection well. The principal cause appears to be iron bacteria and, where a mature colony is established, extremely difficult to eliminate. The problem can be minimized by regular maintenance including chlorination (once every 3-6 months) and back pumping of the well. In some cases, the pressure build up problem is caused by scaling (often calcium carbonate, $CaCO_3$). Again, the problem can be minimized through the use of chemical treatment, although in some severe cases, some reworking of the well on a regular basis may be required. Of course, excessive injection pressure may also be the result of poor well completion or an inadequate injection horizon.

The next most common problem associated with open loop systems is pump failure. Both open shaft, vertical down-hole pumps; and submersible pumps are regularly employed and, at least for those cases where high volume is desired, the down-hole shaft system appears to dominate. Principal problems seem to be with bearings and seals, often resulting in the need for major maintenance and, in a worse case scenario, resulting in a broken shaft. Major pump problems seem to be avoided through proper sand screening and by ensuring adequate lubrication. Another commonly-encountered problem associated with pumped wells is the lack of a variable speed drive. The sudden stopping and starting of the pump appears to generate excessive turbulence in the well, and often results in considerable amounts of sand being drawn into the system. This can have an adverse impact on the pump itself, often cause bearing problems and, in addition, can result in accumulation of sand in the heat exchanger(s). The use of a variable speed drive appears to minimize this problem, and the use of sand filters or traps is often a prudent safeguard for the system.

Finally, the lack of a heat exchanger to isolate the production flow from the in-building equipment can result in major system problems. Most systems are now moving from shell and tube to plate and frame exchangers due to the closer approach temperature, the ease of maintenance, and the flexibility they offer in terms of ease of expansion. Wherever there is any concern over cross contamination, a double-walled plate and frame heat exchanger provides a means to safeguard the system as well as early leak detection.

Closed-loop systems began to challenge the dominance of the open-loop systems in the late 1970s/early 1980s. Unlike open-loop systems where required flow can easily be determined based on load, source temperature, and equipment performance, loop length is much more difficult to calculate and is highly dependent upon soil characteristics including temperature, moisture content, particle size and shape, and heat transfer coefficients. Correct sizing of the ground loop continues to be a cause for continued design problems and special attention should be placed on minimizing inference between loops, whether they be horizontal or vertical.

Other problems associated with loop design and installation include improper header design, inadequate system purging, leaks associated with corrosion of fittings, or poor workmanship. All of the above problems can be minimized through proper system analysis and design, and the use of well-trained and experienced installation personnel. One of the most often encountered problems is related to the circulated heat transfer fluid. Major problems, including severe corrosion, have been encountered with the use of potassium acetate. Some system operators also report problems with systems that use glycol. On the other hand, others using glycol do not seem to have experienced such problems. Some feel that problems in glycol-based systems stem from inadequate flushing and purging. Some systems have replaced the glycol with water and, although they have continued to experience some problems related to inadequate purging, the system is now operating in a much more satisfactory manner. In other systems, methanol is used and it is well as Environol seems to be the least problematic and best heat transfer fluid choices.

There seems to be very few problems associated with either the choice to employ a centralized or decentralized heat pump arrangement. Both afford the capability to provide supplemental heating or cooling through the use of boilers or cooling towers. The only major design problems that seem to be somewhat common in many centralized heat pump systems is the use of a two-pipe system to circulate hot or chilled water. Because the two-pipe system does not allow for the simultaneous supply of both heating and cooling, the building owner/system operator must choose which service will be provided at any given time. Because most such systems are difficult to reverse once the decision is made to go from heating to cooling, the system can not readily be changed back should a late spring cold spell come unexpectedly. Because the provision of heating is almost always more critical than cooling, operators most often choose to error on the side of having heat available.

Most maintenance problems associated with open-loop systems are well related. The problems include problems with pumps, including bearings and seals, and often as a result of bearing problems, severe shaft problems including, in at least one instance, a broken shaft. Other maintenance issues include the need to clean or even rework production and injection wells and the need for chemical treatment of injected water to control scaling or bacterial growth. Another potentially major maintenance issue is removal of sand from the heat exchanger(s) if adequate filters and/or sand traps are not used.

Maintenance of closed-loop systems appears to be extremely minimal and restricted to circulating pumps unless the heat transfer fluid results in corrosion of fittings and other system components.

Central heat pump systems seem to require very limited maintenance, and because all major pieces of equipment are located in a central location, most maintenance chores can be carried out easily. In one system, the change-over of R11 to 124A in the central heat pump has, however, resulted in major maintenance concerns and at least an initial loss of system reliability.

Decentralized systems, on the other hand, do require considerably more routine maintenance, including changing filter every three to six months. Care should be taken when installing a decentralized system to ensure that maintenance personnel have adequate access to each unit for routine maintenance and also for repairs when they become necessary.

Despite the maintenance issues mentioned, maintenance costs are relatively low in all but a few cases. In only three of the cases evaluated was maintenance considered a major concern. In one of these, the equipment was in definite need of replacement after nearly 35 years of service, and with the others, problems with the heat transfer fluid had resulted in serious corrosion problems and leaks as well as control problems due to the leaks. Anonymously high maintenance costs were a result of, in one case, a poorly structured maintenance contract; in another, lack of local maintenance providers; and in two cases, to relatively high in-house personnel costs assigned to the HVAC system.

Geothermal heat pump systems are an increasingly attractive option for commercial buildings. Based on over 50 years of operating experience, it is safe to say that earlier concerns over long-term reliability, operation, and maintenance costs were, to a large extent, unfounded. A majority of the systems have proven to be extremely reliable, with many having been in service over 25 years, and maintenance problems and costs have been acceptably low.

Advancements in equipment, installation techniques, and control systems as well as knowledge of heat transfer continues to reduce equipment and design problems. Increasing knowledge and use of a wide variety of water sources as well as ground loop designs and configurations, together with the number of in-building systems that are now possible allow that geothermal heat pump technology can be tailored to fit almost any possible building need.

## FUTURE PLANS

This effort has been terminated, but materials are being used to support remaining geothermal heat pump initiatives, e.g., Geothermal Heat Pump Consortium Super ESPC FEMP program, etc.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Geothermal Heat Pump Consortium | All |
| International Ground Source Heat Pump Association | All |
| U.S. Army CRREL | All |
| Bonneville Power Administration | Equipment reliability and maintenance cost issues |

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## CONTACTS

Ray Fortuna, USDOE, Washington, DC
Lew Pratsch, USDOE, Washington, DC, (202) 586-1512
Joe Keller, Idaho Falls, ID, (208) 526-1533
Gary Phetteplace, CRREL, Hanover, NH, (603) 646-4248

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| LLNL | Considered as alternative for new construction |
| DOE | Discussing next phase of this project |
| Heat pump industry | Would increase their customer base and improve economics |

# RESEARCH & INFORMATION DISSEMINATION AT THE GEO-HEAT CENTER 1999

Dr. John W. Lund, PE
Geo-Heat Center
Oregon Institute of Technology
Klamath Falls, OR 97601

## KEY WORDS

Direct-use, real property appraisal, scaling in ground-source heat pumps, low-temperature resources, technical assistance

## PROJECT BACKGROUND AND STATUS

The Geo-Heat Center, established in 1975 at Oregon Institute of Technology, conducts research, provides technical assistance and distributes general information on a wide range of applications in the area of geothermal energy. This program, the only one of its kind in the nation, provides rapid response, unbiased information to designers, developers and owners of systems ranging from geothermal heat pumps, through direct use, to small-scale power generation projects.

The main thrusts of the Center are to conduct direct-heat applied research and development, and to provide assistance to stimulate utilization of the nation's large low-to-moderate temperature (20 to 150°C) geothermal resource base. Research and development tasks are conceived carefully to address current industry needs in the areas of cost containment, equipment performance and application, and system design.

The technical assistance program, designed to augment, not compete with private engineering firms and developers, offers technical support for system design, equipment selection and troubleshooting for geothermal systems. This program places the unique technical expertise of the Center's staff at the disposal of potential developers and designers around the country.

A major obstacle to wider use of geothermal energy is lack of awareness. The Center's outreach program addresses this issue with a variety of information sources. Through the publication of a Quarterly Bulletin (2,200 subscribers), handbooks, software, Internet web page (http://www.oit.edu/~geoheat), a dedicated geothermal technical library (5,650 volumes), and many professional papers and technical reports, a broad spectrum of information is available to the public. Staff activity with professional groups such as GRC, IGA, and ASHRAE greatly enhances technology transfer efforts.

The U.S. geothermal resource base is currently the largest of all renewables. Though growing, the use of this immense resource remains distressingly small. Continued, aggressive and cost effective support of geothermal is the key to unlocking it's potential.

## PROJECT OBJECTIVES

The objectives of this project are to conduct direct-heat applied research and development, and to provide assistance to stimulate utilization of the nation's large low-to-moderate temperature (20 to 150°C) geothermal resource base.

### *Technical Objectives*

- To provide technical assistance to developers of geothermal direct-use projects for space heating, greenhouse, aquaculture, industrial applications and geothermal heat pumps;

- To perform appropriate R&D to reduce the cost of installing and operating direct-use projects; and

- To publish information and educational materials, maintain a web page and library to aid research and developers of geothermal direct-use projects.

The success of these projects will mean more rapid penetration of geothermal direct-use into the energy sector.

### *Expected Outcomes*

- Energy savings and reduced emissions of airborne pollutants and greenhouse gases due to more geothermal direct-heat projects on-line. For example an 82°C geothermal well producing 3 MWt (500 gpm) saves 28 TJ/yr of energy and reduces $CO_2$ by 687 kg per year compared to a natural gas boiler plant.

- Geothermal heated greenhouse and aquaculture projects developed in cold areas where using conventional fuels would not be economical, enhancing the economics and employment opportunities of the adjacent communities.

- Increased awareness of geothermal direct-heat developments and opportunities through a Quarterly Bulletin detailing geothermal projects, “Outside the Loop” newsletter for designers of geothermal heat pumps projects, along with a handbook, geothermal web page information, technical papers, software, tours of local geothermal installations, and other educational materials.

## APPROACH

The Geo-Heat Center’s approach is to provide technical assistance to prospective geothermal users on resource data, preliminary engineering design, analysis of operational problems and technical information. The program is designed to introduce the potential user and engineering consultant to geothermal direct-heat applications. The presence of a proven and reliable source of technical advice to the consultant is critical in promoting their initial involvement with an unfamiliar resource. The Oregon Institute of Technology provides a cost share of 10% on the project. Further, the Geo-Heat Center publishes educational materials to aid engineers in the design of direct-use projects.

## RESEARCH RESULTS

### *Technical Assistance Program*

Engineering and economic assistance has been provided to a broad range of clients, from the homeowner interested in geothermal space heating and municipalities engaged in geothermal district heating projects, to industrial concerns adapting geothermal resources to meet their process energy needs. During FY99, the program handled 984 requests for technical and development assistance on geothermal direct-use projects and for various types of technical information. This is an increase of 4% over FY98, with most (52%) of the requests coming by e-mail. Eighteen percent (18%) of the inquiries were international.

The program's R&D accomplishments included: (1) Scaling Considerations for Geothermal Heat Pump Systems, (2) Information for the Prospective Geothermal Home Buyer, and (3) Geothermal Snow Melting.

***Scaling Considerations for Geothermal Heat Pump Systems (K. Rafferty, 1999)***

This report investigates the problems associated with calcium carbonate scale deposited by hard water--the number one water quality problem in the U.S. When hard water is supplied to an open loop heat pump operating in the cooling mode, or to a desuperheater (for domestic hot water heating) scale can occur on the heat exchanger surfaces. This scale can reduce the performance of the heat pump and in some cases has rendered desuperheaters inoperable. Water chemistry, as it relates to scaling, is discussed along with how this issue impacts geothermal heat pumps. The report topics include: Water Chemistry and Scaling, Scaling in Heat Pump Applications, Predicting Scale Formation, and References.

Under the Water Chemistry and Scaling section, water hardness classification and its relationship to alkalinity is discussed. Two indices commonly used are also discussed--the Langelier Saturation Index and the Ryznar Stability Index. Both indices are based upon a calculated pH of saturation for calcium carbonate, and provide an indication of scale forming and possible corrosion. Sample calculation are provided along with the impact of scale thickness on the performance (EER) of heat pumps.

Finally, maps of all 50 states are included showing the principal groundwater aquifer scaling potential by color coding as follows: (1) Low (<100 ppm hardness as $CaCO_3$), (2)Moderate (100 - 200 ppm hardness as $CaCO_3$), and (3) High (>200 ppm hardness as $CaCO_3$).

***Information for the Prospective Geothermal Home Buyer (K. Rafferty, 1999)***

This study was undertaken based on requests from new and existing homeowners in Klamath Falls who have a home supplied with geothermal heat from a downhole heat exchanger (DHE). The study provides the homeowner with a detailed description of common DHE systems, answers to typical questions, troubleshooting, and maintenance and repairs. The following items were investigated and discussed: Wells, Downhole Heat Exchanger, Homes Connected to a Multi-Home System, Controls and Sequence of Operation, and Domestic Hot Water.

***Geothermal Snow Melting (John W. Lund, 1999)***

The design of pavement snow-melting systems is presented based on criteria established by ASHRAE. The heating requirements depend on rate of snow fall, air temperature, relative humidity and wind velocity. Piping materials are either metal or plastic; however, due to corrosion problems, cross-linked polyethylene pipe is now generally used instead of iron. Geothermal energy is supplied to systems either through the use of heat pipes, directly from a well to the circulating pipes, through a heat exchanger or by allowing water to flow directly over the pavement. Examples of systems in New Jersey, Wyoming, Japan, Argentina and Oregon are presented.

The investigation describes the following: General Design Criteria, Canadian Experience, Piping Material and Pavement Installations, Geothermal Heat Supply and Example Installations (Heat Pipes, Pavement Sprinkling, Geothermal Steam, and Geothermal Hot Water), and References.

## FUTURE PLANS

The Geo-Heat Center will continue to act as a clearinghouse to provide project technical assistance and information on geothermal direct-use projects. The Geothermal Direct-Use Engineering and Design

Guidebook, revised in early 1998, is our main publication on the details of direct utilization of geothermal energy. It consists of 19 chapters including details on equipment, and greenhouse and aquaculture pond heating design. The 460-page Guide is available from the Geo-Heat Center for $50 plus shipping.

The GHC Bulletin will be distributed quarterly, the home page will be maintained, new software will be developed, and information about geothermal projects and resources will be gathered and distributed.

R&D activities for FY00 include: (1) Completion of Standard Design and Short Report, (2) Appraisal Method for Real Property Containing Geothermal Resources, and (3) Inventory of Geothermal Resource Sites and Creating a Database.

The first activity (1) will focus on development of standard designs for the applications which are most often requested by homeowners and small developers. Based on past experience this will include: (a) home space heating with coils (forced air), (b) home space heating with a hydronic radiant slab system, (c) domestic hot water heating, and (d) small greenhouse (30' x 100') designs.

The second activity (2) will provide procedures for identifying the necessary costs, generating the life-cycle analysis and evaluating the results. The completed package will provide appraisers the necessary tools to successfully address the issue of geothermal resource valuation in cases where the resource is supplying heat to a specific use.

The third activity (3) will consist of: (a) collecting and assembling into a common database, existing resource and well information from Alaska, North and South Dakota, Wyoming, Texas and Nebraska, and identifying collocated resources, and (b) identifying and contacting potential users by promoting geothermal energy at regional and national meetings of the greenhouse and aquaculture industry.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Engineering and economic assistance has been provided to a broad range of clients, from the homeowner interested in geothermal space heating and municipalities engaged in geothermal district heating projects, to industrial concerns adapting geothermal resources to meet their process energy needs. With the advent of the Internet, we also get many requests from grade school, junior high and high school students to assist them in writing paper, preparing for debates and building projects associated with geothermal energy. In calendar year 1999, we had a total of 1029 requests for information and technical assistance. These requests have tripled since we went on-line with our web page in February of 1996. A breakdown of requests relative to applications for 1999 calendar year are: geothermal heat pumps (25%), general (30%), resource/wells (17%), space heating/cooling (3%), equipment (6%), greenhouses (2%), aquaculture (4%), district heating (3%), electric power (4%), resorts/spas (2%), industrial (3%), and snow melt (1%).

### *Technology Transfer*

#### Guidebook

"Geothermal Direct-Use Engineering and Design Guidebook" - 3rd edition (Lund, Lienau and Lunis, editors, 1998). This is an update of the popular direct use guidebook, last published in 1991. All of the 19 chapters have been revised based on technical assistance experience at the Geo-Heat Center and reflecting current trends in the industry.

**Other Popular Publications**

The following publications are the ones most frequently requested by the public:

- Geothermal Greenhouse Information Package (K. Rafferty and T. Boyd, 1997)
- An Information Survival Kit for the Prospective Geothermal Heat Pump Owner (K. Rafferty, ‘97)
- Aquaculture Information Package (T. Boyd and K. Rafferty, 1998)
- Direct Heat Utilization of Geothermal Resources (J. Lund, 1998).

**Outside the Loop Newsletter**

Volume 2, Number 1-3 of a newsletter, “Outside the Loop,” written for the geothermal heat pump designers and engineers, were issued in 1999. This 8-page newsletter, written by Kevin Rafferty and Stephen Kavanaugh, is available free of charge from either the Geo-Heat Center or the University of Alabama. The primary purpose of this publication is to assist engineers in finding the tools and information needed to design larger ground-source heat pump (GSHP) systems. The newsletter also includes a listing of publications, meeting schedules, and other sources that are of interest to GSHP designers. It is funded in part by the Geothermal Heat Pump Consortium.

**Quarterly Bulletin**

Four issues of the Geo-Heat Center Quarterly Bulletin were published in FY99: Vol. 19, No. 4 (December 1998) was devoted to Geo-Heat Center technical assistance and international activities; Vol. 20, No. 1 (March 1999) was devoted to direct-use activity in Oregon and California; Vol. 20, No. 2 (June, 1999) is devoted entirely to small geothermal power projects; Vol. 20, No. 3 (September, 1999) was devoted entirely to downhole heat exchangers.

**Library**

A geothermal library of over 5, 600 volumes was maintained and can be accessed through the Internet on the GRC home page. A total of 1,316 publications were requested during the fiscal years, 17 technical papers were prepared, 21 presentations were made both nationally and internationally, and 12 groups were given tours of local geothermal facilities.

**Web Site**

The Geo-Heat Center web page, maintained by Toni Boyd, has been extremely successful in communication with the public on the direct utilization of geothermal energy. It presently has almost 2,000 files, and contains GHC Quarterly Bulletins for the last five years, our major reports and papers, our publication list, and general information on geothermal energy.

Users of the site have increased from 220 users/day and 1745 hits/day in the first quarter of FY99 to 381 users/day and 2898 hits/day for the last quarter of FY99, about at 70% increase in activity. Approximately 5% of our users are international with Canada, UK, Australia, Germany, Singapore, Japan, New Zealand, and the Netherlands being the most frequent country users.

**International Geothermal Days - Oregon 1999**

The Geo-Heat Center, in cooperation with the International Summer School, offered a series of workshops, courses and seminar on the Oregon Institute of Technology campus in October of 1999. “The International Geothermal Days, Oregon 1999" include sessions on: (1) Small-Scale Power Projects, (2) Geothermal Heat Pumps, (3) Direct Utilization of Geothermal Energy, (4) evening seminars on Computer Software for Geothermal Heat Pumps and HEATMAP Computer Software Utilization, and (5) three field trips of geothermal electric power and direct-use installations.

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## CONTACTS

John W. Lund
Geo-Heat Center
Oregon Institute of Technology
Klamath Falls, OR 97601
phone: 541-885-1750
fax: 541-885-1754
email: **lundj@oit.edu**

Kevin Rafferty
Geo-Heat Center
Oregon Institute of Technology
Klamath Falls, OR 97601
phone: 541-885-1750
fax: 541-885-1754
email: **raffertk@oit.edu**

Tonya “Toni” L. Boyd
Geo-Heat Center
Oregon Institute of Technology
Klamath Falls, OR 97601
phone: 541-885-1750
fax: 541-885-1754
email: **boydt@oit.edu**

Raymond Fortuna
Office of Geothermal and Wind Technologies, EE-12
U.S. Department of Energy
1000 Independence Ave, SW,
Washington, D.C. 20585
phone: 202-586-1711
fax: 202-586-8185
email: raymond.fortuna@hq.doe.gov.

# NATIONAL EARTH COMFORT PROGRAM: GEOTHERMAL HEAT PUMP MOBILIZATION FISCAL YEAR 1999

Wael El-Sharif
Business Development Director
Geothermal Heat Pump Consortium

## KEY WORDS

GeoExchange, geothermal heat pump, Geothermal Heating & Cooling, National Earth Comfort Program, heating ventilation & air conditioning (HVAC), technology transfer, market transformation, market mobilization, public-private partnership

## PROJECT BACKGROUND AND STATUS

In 1994, the Edison Electric Institute, Electric Power Research Institute, National Rural Electric Cooperative Association and the U.S. Environmental Protection Agency joined DOE in forming the Geothermal Heat Pump Consortium (GHPC). GHPC's program was part of the Administration's Climate Challenge with the utility industry; DOE pledged $35 million toward a $100 million partnership for geothermal heat pump (also known as GeoExchange or Geothermal Heating & Cooling) market deployment. DOE has funded its commitment to the Geothermal Heat Pump Consortium since FY1995 through a research grant that was converted to a cooperative agreement during FY 1998. Total DOE funding of the Consortium, including FY 1999, has been about $19 million, with the industry (largely utility) pledging more than $65 million. Currently this project is in its final phases with completion planned by September 30, 2000.

## PROJECT OBJECTIVES

The National Earth Comfort Program is pursuing the following objectives:

### *Technical Objectives*

- Increase awareness of the technology among residential and commercial customers;
- Increase participation in the industry by architects, engineers, drillers and mechanical contractors;
- Assist utilities in designing effective programs to promote the technology in a deregulated and restructured power market environment;
- Provide technical support and effective technology transfer through research projects, design assistance, and technical workshops; and
- Set the conditions for growth in the market to 400,000 unit annual sales by 2005 – based on a 3-ton unit equivalent.

### *Expected Outcomes*

- Public awareness program results in 50 million reader/listener impressions;

- Deliver 40 workshops for architects, engineers or other professionals;
- Continue to assist utilities in business planning, and co-funded programs with utilities and other partners result in over 40,000 tons of GHP installations;
- Technology transfer programs for customers and their A&E firms result in selection of successful GHP projects totaling 45,000 tons; and
- Technology transfer programs for the federal government result in over 15,000 tons of successful GHP project commitments in federal facilities.

## APPROACH

GHPC administers a wide array of subcontracts to attain the program objectives. Exhibit 1 lists major contracts in the areas of public awareness and education, technical projects, and strategic outreach. Each entry provides information on the project, subcontractor and the objective.

Exhibit 2 provides a list of all co-funded demonstration programs with utilities and/or other parties. Each entry in Exhibit 2 lists the principal project partner (in many cases there are additional industry participants working with the principle partner), GHPC's cost share commitment, and the cost share commitment from the program partner(s). Bolded entries indicate projects with major activity in FY 1999.

## RESEARCH RESULTS

GHPC's overall programs have helped the industry grow in a difficult period of utility restructuring, during which utility promotion of energy-efficient and renewable technologies has been on a drastic downswing throughout the nation. According to DOE's Energy Information Administration's (EIA's) survey of manufacturers, the GHP industry experienced a growth of 23% in total tonnage shipped during 1997. While EIA data for 1998 and 1999 are not yet available, discussions with manufacturers and ARI data indicate strong growth for both years.

GHPC's co-funded programs continued to operate in 1999, providing demonstrations of program designs that utilities and their subsidiary energy service companies can use successfully in a restructured utility environment. The programs continued to expand markets for GHPs during 1999, with total market penetration exceeding 45,000 tons by year's end. They also continued to produce useful lessons learned reports, public education materials, technical reports, and other deliverables. Two new target market mobilization projects were awarded in 1999, American Electric Power and the GT Company, committing nearly $2 million against over $10 million from these two new partners. Despite early successes, the GT Company project was later cancelled by the parent company, OG&E Electric Services, due to changes in corporate direction and utility deregulation.

In 1999, GHPC launched its Business Planning & Business Development Initiative where GHPC uses the experience and lessons it has learned to date to provide business planning assistance for utilities, helping them select program designs that are profitable and can be implemented in a deregulated utility market environment. GHPC has provided this service to three utilities and one energy service company with several more planned for FY 2000.

In the area of public awareness and education, GHPC continues to implement its public education plan with its contractor, Al Paul Lefton Company of Philadelphia, PA. The plan emphasizes education aimed at specific market segments and media outlets, in order to obtain as much exposure as possible without having to pay for advertising space. The public awareness campaign resulted in more than 194 articles in trade publications, 163 in daily newspapers, 148 in weekly newspaper, 31 in consumer magazines, 4 major radio interviews and 2 major television segments. GHPC's first satellite feed of its Video News Release resulted in 9 news stories. The articles and media coverage provided over 49 million viewer or listener impressions by the end of 1999. GHPC also cosponsored the Federal Energy Management's June 22, 1999, teleconference: "TeleFEMP VII." GHPC produced a 30-minute segment on GHPs for the 2-hour event.

In the area of design assistance, GHPC granted limited assistance on design and feasibility analysis for over 157 projects in 1999. At year's end, the program was showing good results. By that time, of all the projects that had arrived at a decision on whether to use GHPs or not, 79% had said "yes." These projects total over 78,000 tons of HVAC capacity, and represent a rapidly expanding commercial and institutional market for GHPs.

As a complement to its Design Assistance Program, GHPC supports technology transfer workshops delivered to architects and engineers. During 1998, GHPC initiated continuing education courses with both the American Institute of Architecture (AIA) and the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). By the end of 1999, GHPC had co-sponsored more than 30 seminars to over 1200 attendees, most of whom were architects and engineers.

GHPC continued to sign Memoranda of Understanding (MOUs) with key organizations bringing the total to over twenty-one. Most significantly, the US General Services Administration (GSA) joined the U.S. Postal Service (USPS), the Department of State, the State of Maryland, and the State of North Dakota by signing an MOU. Under the terms of the MOU, the organization pledges to consider GHPs in all of its projects, while GHPC pledges to give priority to the organization in providing design assistance, technical workshops and publicity.

In the area of data collection, GHPC continued the final phases of performance monitoring at about a dozen sites in 1999. Important lessons on proper commissioning of GHP systems have been learned, and performance data for future case studies was collected.

During 1999, GHPC did not place much emphasis on technical research projects instead the emphasis was on deployment of the research results to help increase market penetration and create a self-sustainable market for GHPs.

This year, GHPC worked with selected financial organizations to offer a package of financing products to overcome capital cost and technology risk barriers among private and public sector customers. A new homes program was developed along with a commercial financing program that has been launched.

## FUTURE PLANS

With this project nearing completion, GHPC plans to finalize all active subcontracts and ensure documentation and transfer of the knowledge and lessons learned.

In the area of co-funded demonstration programs, GHPC will continue to use the experience and lessons it has learned to date to place more emphasis on business planning assistance for utilities, helping them select program designs that are profitable and can be implemented in a deregulated utility market environment. The goals is to have 6-12 active utility or energy service company programs operating permanently and, in some cases, nationally at the end of this program. GHPC will also continuing to implement a small number of co-funded programs still active. No additional funds will be committed for co-funding beyond what has already been awarded.

In the public awareness area, GHPC will continue implementation of the Al Paul Lefton Company plan developed in 1998 and deployed in 1999. GHPC's goal is to reach 50,000,000 reader/listener impressions by the end of the project.

In the area of technology transfer, GHPC is continuing both its Design Assistance Program and its co-sponsored technology training workshops during 2000, building on the success experienced in 1998 and 1999. While a good deal of its technology transfer efforts in 1999 were targeted at schools and federal facilities, GHPC anticipates expanding the efforts towards other commercial and institutional segments.

GHPC will continue to work with the winners of FEMP's Super-ESPC on Geothermal Heat Pump Technology. The following FEMP awardees can now offer 100% financing and turnkey design, installation, and maintenance in four to eight months: Trane Company, Enron, Duke Energy Services, Exelon, and Constellation Energy Services. GHPC will continue to work with these entities, FEMP, Oak Ridge National Lab, and DOE RSOs in the following areas: coordination of technical specifications for GHP systems; strategic outreach, design assistance, and technical workshops for federal facility managers.

During 2000 GHPC will continue to deploy the financing initiatives launched in 1999. GHPC will market the new homes program to utilities to be implemented in their service territories. GHPC will also deploy its commercial financing program developed in 1999 to help further overcome the first cost barrier.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

GHPC's projects are of general interest to a large number of utility, manufacturer and trade ally members (GHPC membership totals over 750 organizations). Lists of organizations directly involved in key GHPC projects are contained in Exhibits 1 and 2.

**Exhibit 1 – Major Subcontracts During 1999**

| Project Title | Subcontractor | Objective(s) Addressed |
|---|---|---|
| Field Monitoring Projects | CDH and AIL (two contractors) | Increase public awareness<br>Technology Transfer - lower first cost<br>Technology Transfer - improved design and commissioning |
| Ventilation Strategies for GeoExchange Systems | University of Alabama | Technology Transfer - improved design |
| Soil Conductivity Probe for Horizontal Systems | South Dakota State University | Technology Transfer - improved design |
| National Public Awareness and Education Initiative | Al Paul Lefton Company | Increase public awareness |
| National Teleconference Series | Casuals and Associates | Increase participation in industry<br>Increase customer awareness (usually aimed at selected market segments) |
| Co-funded Utility and Trade Ally Demonstration Programs | Various - see Exhibit 2 | Technology Transfer - successful program designs |
| Design Assistance Program | Various pre-qualified design experts | Technology Transfer - improved design and commissioning |
| Strategic Outreach Program | Jack DiEnna<br>Michael Bell<br>Quest Consulting<br>Dick Brown<br>Tom Migliaccio<br>Doug Rye | Technology Transfer<br>Increase customer awareness<br>Increase participation by architects |
| Training Workshops for Architects and Engineers | Various pre-qualified design experts | Increase participation in industry by architects and engineers |
| Compilation of State and Local Regulations and Codes | University of Idaho | Increase participation in industry by drillers; Educate state regulators |
| Annual Sales Survey | Penton Research | Program Evaluation |

**Exhibit 2**
**Co-funded Demonstration Programs**

| Project Sponsor | Project Area | Cost Share | | Ratio | Total Cost |
|---|---|---|---|---|---|
| | | GHPC | Partner | | |
| Colorado Springs Utilities | Colorado Springs, CO | $49,725 | $129,460 | 2.60 | $179,185 |
| FirstEnergy | Ohio | $27,300 | $180,600 | 6.62 | $207,900 |
| Georgia Geothermal | Georgia | $50,000 | $302,800 | 6.06 | $352,800 |
| Northern States Power | Minnesota | $47,000 | $143,000 | 3.04 | $190,000 |
| Sound Geothermal | Utah (Ute Indians Tribe) | $50,000 | $212,000 | 4.24 | $262,000 |
| Autumn Oaks | Northern Arkansas | $200,000 | $1,152,355 | 5.76 | $1,352,355 |
| **Central Hudson Gas & Electric** | **New York** | **$62,825** | **$254,775** | **4.06** | **$317,600** |
| **Delta Montrose Electric Assoc.** | **Colorado** | **$121,573** | **$364,720** | **3.00** | **$486,293** |
| Duke Power | South Carolina | $200,000 | $510,591 | 2.55 | $710,591 |
| **East Kentucky Power Coop.** | **Kentucky** | **$165,000** | **$345,000** | **2.09** | **$510,000** |
| **Gulf Power** | **Florida (Gulf)** | **$164,500** | **$426,200** | **2.59** | **$590,700** |
| John Geyer & Associates | OR, WA, UT, CA | $116,900 | $416,300 | 3.56 | $533,200 |
| Minnesota Power | Minnesota | $40,000 | $40,000 | 1.00 | $80,000 |
| Northeast Utilities | CT, MA | $86,400 | $161,000 | 1.86 | $247,400 |
| Potomac Electric Power Co. | DC, Maryland | $195,000 | $200,000 | 1.03 | $395,000 |
| **PFG Capital/Charles St. Apts.** | **York, PA** | **$113,115** | **$541,735** | **4.79** | **$654,850** |
| Plumas Sierra | Plumas County, CA | $58,830 | $97,250 | 1.65 | $156,080 |
| PP&L Buried Treasure | Pennsylvania | $23,500 | $50,920 | 2.17 | $74,420 |
| PP&L Accelerating the Pace | Pennsylvania | $175,037 | $200,878 | 1.15 | $375,915 |
| TVA Alternative Farming Ctr. | Tennessee | $60,000 | $435,840 | 7.26 | $495,840 |
| Virginia Power | Virginia | $177,000 | $509,037 | 2.88 | $686,037 |
| **American Electric Power** | **Northern Ohio** | **$1,250,000** | **$4,877,200** | **3.90** | **$6,127,200** |
| **Geothermal Resource Group** | **New Jersey** | **$700,000** | **$5,319,000** | **7.60** | **$6,019,000** |
| GT Company | Michigan | $700,000 | $5,200,000 | 7.43 | $5,900,000 |
| **OG&E Electric Services** | **Oklahoma** | **$1,250,000** | **$6,566,192** | **5.25** | **$7,816,192** |
| Oglethorpe Power | Georgia | $557,760 | $3,248,651 | 5.82 | $3,806,411 |
| **Pacific Gas & Electric** | **Northern California** | **$524,000** | **$1,560,000** | **2.98** | **$2,084,000** |
| **Southern Company** | **AL, FL, GA, MS** | **$633,100** | **$3,639,550** | **5.75** | **$4,272,650** |
| | | **$7,798,565** | **$37,085,054** | **4.76** | **$44,883,619** |

## CONTACTS

Conn Abnee
Executive Director
Geothermal Heat Pump Consortium, Inc.
701 Pennsylvania Ave, NW
Washington, DC 20004
(202) 508-5500
abnee@ghpc.org

Wael El-Sharif
Business Development Director
Geothermal Heat Pump Consortium, Inc.
701 Pennsylvania Ave, NW
Washington, DC 20004
(202) 508-5013
elsharif@ghpc.org

Raymond Fortuna
Program Manager
Office of Wind & Geothermal Technologies
1000 Independence Ave, SW
Washington, DC 20585
(202) 586-1711
raymond.fortuna@hq.doe.gov

# REFINEMENT AND VALIDATION OF IN SITU PARAMETER ESTIMATION MODELS

Jeffrey D. Spitler Ph.D., P.E., Simon J. Rees, Cenk Yavuzturk Ph.D.
Oklahoma State University
School of Mechanical and Aerospace Engineering
Stillwater, OK

## KEY WORDS

geothermal energy, ground coupled, heat pump, heat exchanger, in situ testing, simulation, thermal response, thermal storage, thermal conductivity

## PROJECT BACKGROUND AND STATUS

Determination of the thermal conductivity of the ground formation is a significant challenge facing designers of Ground Source Heat Pump (GSHP) systems applied in commercial, institutional as well as large residential buildings. The number of boreholes and the depth and cost of each borehole are highly dependent on the ground formation thermal properties. Hence, depending on the geographic location and the local drilling costs, the formation thermal properties strongly influence the initial cost to install a GSHP system.

The initial work to develop suitable methods to predict ground formation thermal conductivity was funded by the National Rural Electric Cooperative Association. Additional research activities were performed at the Oklahoma State University with the support of the DOE.

## PROJECT OBJECTIVES

The validation of the parameter estimation method must be based on high-quality input data in order to increase the confidence in the parameter estimation model. This is to be done using a medium-scale borehole apparatus that was constructed to allow testing of in-situ parameter estimation methods under closely controlled conditions.

Shortening the computational time for the objective function evaluation and the completion of the parameter estimation algorithm is highly desirable for a fast and accurate parameter prediction. Comparison of the current parameter estimation technique is necessary to other alternative techniques to assess the suitability and efficiency of various techniques for the objective function.

### *Technical Objectives*

- Further validate the parameter estimation procedure.
- Shorten the length of in situ tests.
- Shorten the overall analysis time by using on-line parameter estimation

### *Expected Outcomes*

- Increase the confidence placed in the in situ tests and the parameter estimation method for predicting the thermal conductivity of the ground formation. As more comparisons that utilize high-quality data can be made available, more confidence will be placed in the prediction model.

- Decrease in the in situ testing duration. As the length of time required to complete tests is reduced, so is the cost to contractors and their clients. Reducing costs will encourage further uptake of in-situ testing in the industry and will result in higher quality and more cost effective system designs.

## APPROACH

Further validation of the ground thermal conductivity parameter estimation technique has been attempted by using a medium-scale borehole apparatus and conducting a series of simulated in-situ tests. The apparatus consists of a box 4x4x48 feet with a 5” aluminum tube at its center representing the borehole. The box was filled with either dry or saturated silica sand of known thermal conductivity that represented the soil. The ‘U-tube’ heat exchanger pipe was inserted and grouted in the aluminum tube in the normal way and connected to the in-situ test equipment. An illustration of the apparatus is shown in Figure 1.

The main reason the two-parameter estimation procedure takes so long is that it takes time to resolve the differences between the effects of the ground thermal conductivity and the effects of the borehole resistance, or grout thermal conductivity. If a single-parameter estimation could be used, it should converge much more quickly. In order to make use of a single-parameter estimation, we would need the following:

1. Grout with known thermal conductivity.
2. Thermal characteristics of pipe well known.
3. Good estimate of the convection coefficient in the pipe.
4. Control of the U-tube placement in the hole.
5. Constant diameter borehole.
6. Highly accurate representation of the borehole geometry in the numerical model.

The first three items can reasonably be achieved. It is not at all clear whether items 4 and 5 are feasible to achieve in the field. The $6^{th}$ item, the numerical model has been developed here at OSU. The numerical model used in the original work used a polar grid system that required the pipe geometry to be approximated by a ‘pie sector’ in the grid (see Figure 2). An improved model has now been developed that uses a ‘boundary-fitted’ grid system that is much more flexible and can accurately represent the U-tube pipe geometry. Details of the grid around the borehole are shown in Figure 3. This makes the calculation of the heat fluxes and temperatures inside the borehole much more accurate. This is important for prediction of the borehole response near the beginning of the in-situ test and should lead to better parameter estimations.

Both the original numerical model and this improved numerical model have been used to estimate the soil conductivity from experimental data taken from the medium-scale borehole test facility. Estimations of the saturated sand conductivity have been made using different amounts of data up to 52.5 hours using the two-parameter method developed by Austin *et al.* and also with a one-parameter method. Estimating only one parameter assumes the grout conductivity, U-tube position and borehole size to be accurately known.

The results of these parameter estimations are shown in Figure 4 along with the results previously published by Smith for the line-source method. The results for the two-parameter method steadily increase as more data are used and approach a consistent value towards fifty hours of data. The results for the one-parameter method however, approach the independently measured value much more quickly, in a similar manner to the line-source method. It should be noted that, unlike the line-source method, the results of both the one and two-parameter methods do not rely on judgments by the user in selecting the data – the procedures are fully automatic.

It is encouraging that the one-parameter conductivity estimation method performs so well on test data of shorter duration. However, it should be emphasized that using this method requires the grout conductivity, U-tube position and borehole size to be accurately known. In practice, although the grout conductivity may be reasonably well defined, the position of the U-tube in the borehole cannot be controlled and the size of the borehole may vary along its depth depending on drilling conditions. Therefore, at present, we do not recommend its use in the field. The two-parameter conductivity estimation method we have previously recommended is able to compensate for variations in borehole size and U-tube position automatically by simultaneously estimating the *effective* grout thermal conductivity.

The parameter estimation method that has been developed previously has required two stages (1) collection of data in the field (2) off line data analysis. On-line parameter estimation would allow the data collected from the borehole to be analyzed as soon as it was available and a continually updated estimate of the ground thermal conductivity to be provided. It is also possible that feedback could be provided to the test operator and the test terminated at a shorter duration if a consistent prediction was being made. A number of methods of on-line parameter estimation have been attempted with some success using historical data (Jain 1999). These methods need further refinement and testing in the field before they can be deployed.

## RESEARCH RESULTS

- Further validation experiments using a medium scale borehole apparatus showed that the parameter estimation method can be used to estimate ground thermal conductivity to a high degree of accuracy (error < 0.23%) when conditions are well controlled.

- Using a boundary fitted numerical model it was possible to arrive at reasonable estimates of the ground thermal conductivity with test data of shorter duration by estimating only one parameter. However, this approach can only be successfully used when the borehole geometry is accurately known. For this reason it does not appear that this approach can currently be used in the field to reduce test duration.

- Initial development of an on-line parameter estimation method has shown some promise of reducing the overall test and analysis time. Further refinement and field-testing of this method is still required.

## FUTURE PLANS

No future plans.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Geothermal Design and Engineering, Oklahoma City, OK
Ewbank and Associates, Oklahoma City, OK

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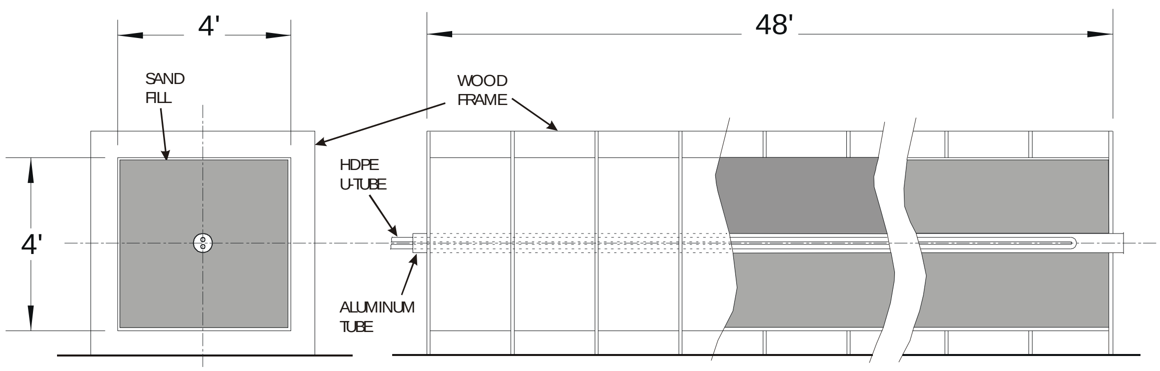


**Figure 1.** The medium scale borehole apparatus.

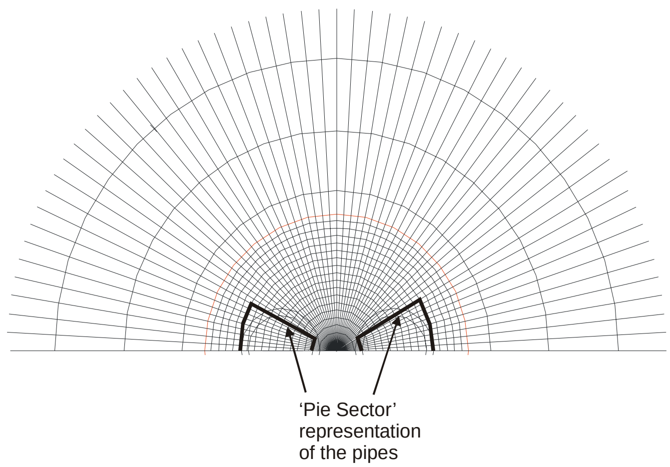


**Figure 2.** The numerical model polar grid with a 'pie sector' approximation of the U-tube pipe geometry.

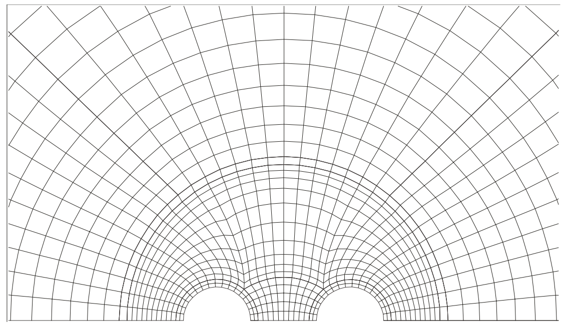

**Figure 3.** The numerical model boundary fitted grid showing the improved representation of the borehole and U-tube geometry.

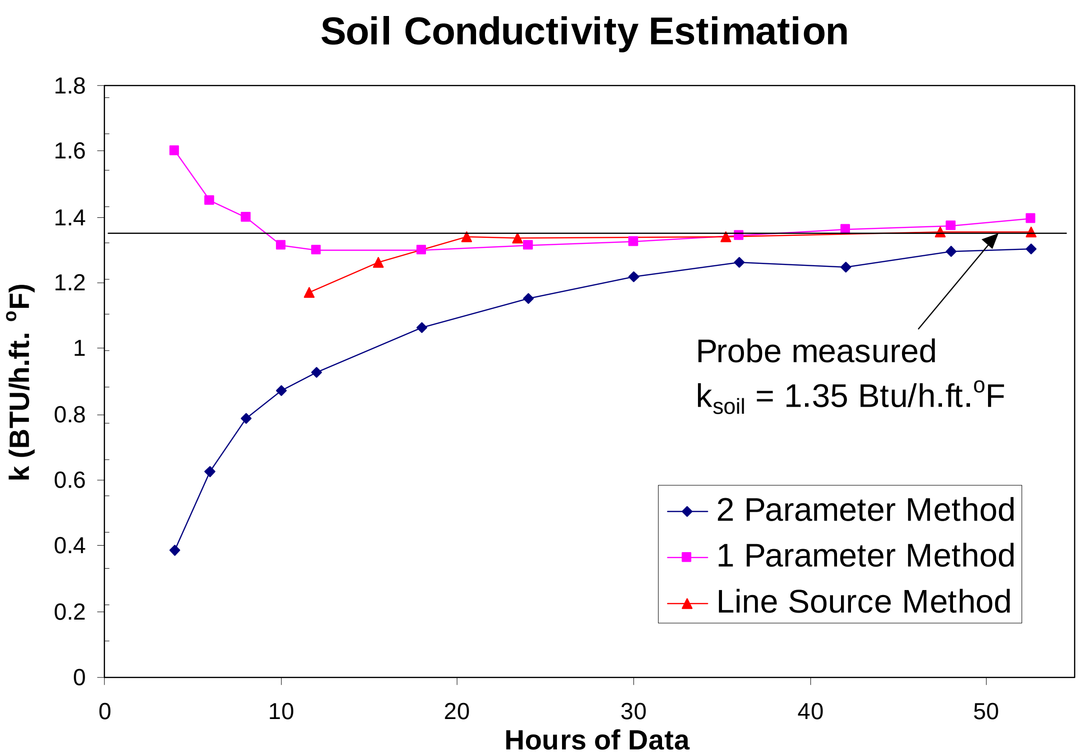


**Figure 4.** Results of soil thermal conductivity estimates using test data of different duration. Three sets of results are compared with the independently measured value, (a) the numerical two-parameter method (Austin 1998), (b) a one-parameter estimation method, and (c) the line-source method results (Smith 1999a).

## CONTACTS

Lew W. Pratsch
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
V:(202) 586-1512 Fax: (202) 586-8185
e-mail: LEW.PRATSCH@hq.doe.gov

Jeffrey D. Spitler, Ph.D., P.E.
Professor, School of Mechanical and Aerospace Engineering
Oklahoma State University
218 Engineering North
Stillwater, OK 74078
V:(405)744-5900 Fax:(405)744-7873
e-mail: spitler@okstate.edu

# EXTENSION OF EXISTING DESIGN AND SIMULATION MODELS

Jeffrey D. Spitler Ph.D., P.E., Andrew Chiasson, Cenk Yavuzturk
Oklahoma State University
School of Mechanical and Aerospace Engineering
Stillwater, OK

## KEY WORDS

design models, ground-source heat pump systems, heat transfer, HVAC, hybrid systems, pavement heating, cooling ponds, surface water-source heat pump systems

## PROJECT BACKGROUND AND STATUS

This project originated in 1996 with the aim to reduce the first costs of closed-loop ground-source heat pump (GSHP) systems by reducing the necessary size of the ground loop heat exchanger (GLHE). Commercial buildings are generally cooling-dominated, and therefore reject more heat than they extract over the annual cycle. For applications such as convenience stores and restaurants, auxiliary loads such as that from refrigeration systems and icemakers significantly add to the amount of heat rejected to the ground. In order to dissipate the heat, the required GLHE length may be as much as double the required length if the annual loads were balanced. Consequently, under these circumstances, GSHP systems are often eliminated from consideration during the feasibility study phase of the HVAC design process because of excessive first cost.

To effectively balance the ground loads and reduce the necessary size of the GLHE, supplemental components have been integrated into the system design. In applications where the excess heat that would otherwise build up in the ground is useful, domestic hot water heaters, car washes, and pavement heating systems can be used. In cases where the excess heat cannot be used beneficially, shallow ponds can provide a cost-effective means to balance the thermal loading to the ground and reduce GLHE length. GSHP systems that use a supplemental heat rejecter have become commonly referred to as “hybrid GSHP systems”.

Development and testing of design and simulation models were conducted during FY98. Several component models were developed for use with TRNSYS and HVACSim+, which are transient system simulation programs with a modular structure. A short-time step GLHE model (Yavuzturk and Spitler, 1999) and a simple water-to-air heat pump model are the core components in the simulated systems. Supplemental heat rejecter component models have been developed during FY98 and were validated during FY99 using field data collected from experimental setups at Oklahoma State University. These include a pavement heating model (Chiasson, et al., 2000a) and a pond model (Chiasson et al., 2000b). A detailed water-to-water heat pump model (Jin and Spitler, 2000) was also developed during FY99 and was validated using manufacturer’s catalog data. Additionally, a comparative study was conducted to investigate the impacts of various operating and control strategies for a hybrid GSHP application using a cooling tower (Yavuzturk and Spitler, 2000). The work of Yavuzturk and Spitler (2000) was extended by Ramamoorthy et al. (2000) to optimally size a hybrid GSHP that uses a cooling pond as a supplemental heat rejecter.

## PROJECT OBJECTIVES

The overall objective of this project was to develop and validate component models of supplemental heat rejecters and auxiliary equipment that may be connected to the GLHE, and to investigate the design of hybrid GSHP systems. There is a trade-off between the size of the ground loop heat exchanger, the size of the supplemental heat rejecter, and the control strategy used to operate the supplemental heat rejecter. Having this many degrees of freedom adds some difficulty to the design process.

***Technical Objectives***

- Validate the pond model and the pavement heating model with field-collected data.
- Develop a detailed water-water heat pump model based on laws of thermodynamics.
- Investigate the impact of various control and operating strategies of hybrid GSHPs to determine potential cost savings.

***Expected Outcomes***

- Availability of component models and simulation tools that can predict performance of hybrid GSHP systems, which have the potential to reduce the size of the GLHE significantly. These tools will facilitate the design and installation of such systems.

## APPROACH

### Validation of Existing Models

**Pavement Heating Model Validation:** Details of this model and the model validation results are described by Chiasson et al. (2000a). A concrete test slab was constructed at Oklahoma State University and was used for this study. The test slab is rectangular with a plan area of 40 ft by 4 ft and a thickness of 6 in. The slab is underlain by 6 in. of sand fill. Heat was rejected to the slab by circulating heated water through a "Slinky" heat exchanger coil installed near the concrete/sand interface. The slinky pipe is made of HDPE plastic and is 500 feet long with a nominal diameter of ¾ in. The pipe was coiled such that the resulting slinky heat exchanger is 40 ft long with a diameter of 3 ft and a 10-in. pitch. The temperature of the concrete surface was measured by two thermistors embedded in the concrete. Slinky supply and return water temperatures were measured by thermistors embedded in the slinky header. Weather data for this study were obtained from the Oklahoma Mesonet weather monitoring network at 15-minute intervals from the Stillwater monitoring station.

**Pond Model Validation:** Details of this model and the model validation results are described by Chiasson et al. (2000b). Two test ponds were constructed at the Oklahoma State University for this study. The ponds are rectangular with a plan area of 40 ft by 3 ft. Each pond was constructed with vertical sidewalls. One pond is 2 feet deep and the other is 3.5 ft deep. The walls and the bottom of each pond were constructed of reinforced concrete, approximately 8 in. thick. Heat was rejected to each pond by circulating heated water through a Slinky heat exchanger. Each Slinky pipe was of the same construction as described above. The Slinky was positioned horizontally in the 2-ft deep pond vertically in the 3.5-ft deep pond. The temperature of the pond water was measured by thermistors positioned within the pond. Slinky supply and return water temperatures were measured by thermistors embedded in the slinky header. Weather data were acquired as described above.

### Development and Validation of a Detailed Water-to-Water Heat Pump Model

Details of this model and the validation results can be found in Jin and Spitler (2000). The overall model approach is to employ deterministic models of each heat pump component part. Each of the fundamental equations describing the system components may have one or more parameters, which are estimated simultaneously using catalog data only; no other experimental data are required. The parameter estimation is done with a multi-variable optimization method. Once the parameters have been estimated, the heat pump model may be used as part of a multi-component system simulation.

This modeling approach has the advantage of not requiring experimental data beyond what is published in the manufacturer's catalog. Yet, its predictions are of similar or better accuracy than previously published deterministic models that required additional experimental data. Unlike the equation-fit models, the model domain may be extended beyond the catalog data without catastrophic failure in the prediction.

**Investigation of Control Strategies for Hybrid GSHP Systems**

A comparative study to investigate the impact of various operating and control strategies for hybrid GSHP systems that use a cooling tower as a supplemental heat rejecter was conducted through system simulations. Details of this work can be found in Yavuzturk and Spitler (2000). An actual small office building was used in the study and was modeled in two differing climatic regions. Twenty-year life cycle cost analyses were used to evaluate each operating and control strategy in order to determine the lowest cost alternative. The control strategies that were examined can be broadly characterized into three groups: (1) a set point control to operate a cooling tower when the fluid temperature exceeds a set value, (2) a differential control to operate a cooling tower when the difference between the heat pump fluid temperature and the ambient wet bulb temperature exceeds a set value, and (3) a scheduled control to decrease heat buildup in the ground by operating a cooling tower for a given period of time during the night.

A study to investigate the use of the system simulation approach to optimally design a hybrid GSHP system that uses a cooling pond as a supplemental heat rejecter was also conducted. Details of this work can be found in Ramamoorthy et al. (2000). The design challenge lies in finding the optimum size of both the GLHE and the supplemental heat rejecter, which directly depend upon the control strategy used to reject the excess heat. The same building was modeled as in the Yavuzturk and Spitler (2000) study. The design parameters to the component models were varied and the 20-year life-cycle costs of various designs were examined.

## RESEARCH RESULTS

The pond and pavement heating model performance were evaluated by comparing (1) the simulated to the observed heat exchange fluid return temperature and (2) the simulated cumulative heat rejected to the measured water heating element and pump power input. The simulated and observed fluid return temperatures are shown in Figure 1 for the 2-feet deep pond and for the concrete slab during the study periods. A review of Figure 1 shows that the model predicts the fluid return temperatures favorably. The average observed and modeled fluid return temperatures over the test period for the 2-feet deep pond were 70.5$^{o}$F and 70.2$^{o}$F, respectively and were 73.1$^{o}$F and 73.4$^{o}$F for the concrete slab, respectively. At the end of the respective test periods, the percent difference between the cumulative simulated heat rejected and the cumulative measured heat rejected was –2.95 % for the 2-feet deep pond and –5.01 % for the concrete slab. A description of the model, experimental uncertainty analysis, and additional details can be found at: http://www.mae.okstate.edu/Faculty/spitler/pdfs/chiasson_thesis.pdf

The water-to-water heat pump model was validated using catalog data for four heat pumps made by two different manufacturers. Units 1 and 2 were validated using the cooling mode data and units 3 and 4 were validated using the heating mode data. The heat pump capacities, number of operating points given in the manufacturer's catalog, and the root-mean-square (RMS) error for capacity and power are shown in Table 1. The results showed a relatively good agreement with generally acceptable accuracy.

The system simulation investigation of the impact of control strategies on hybrid GSHP system life-cycle cost (Yavuzturk and Spitler, 2000) showed that all of the operating strategies that were examined resulted in significant total cost savings as compared to conventional GSHP systems. The analyses suggest that the higher the building cooling loads relative to the heating loads, the more savings can be realized due to reduction in the GLHE size. The most beneficial control strategies were found to be those that operate the supplemental heat rejecter only when the weather conditions are favorable (control strategy 2 described above).

The system simulation approach to determine the optimal size of a hybrid GSHP that uses a cooling pond as a supplemental heat rejecter (Ramamoorthy et al., 2000) used the control strategy 2 (described above). The present values of the cases considered are plotted in Figure 2 versus the ratio of pond loop to total loop length. The cost savings are significant for both climatic regions examined. This study not only demonstrated the benefit of incorporating a supplemental heat rejecter into a GLHE system, but also demonstrated the value of system simulation in supporting the design process of a hybrid GSHP system.

## FUTURE PLANS

Funding for this project was terminated as of August 1999 and no future plans exist.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Air-O Heat and Air Conditioning | Use of shallow heat rejecters. |
| Phillips and Bacon (Consulting Eng.) | Reduction of ground loop heat exchanger size. |

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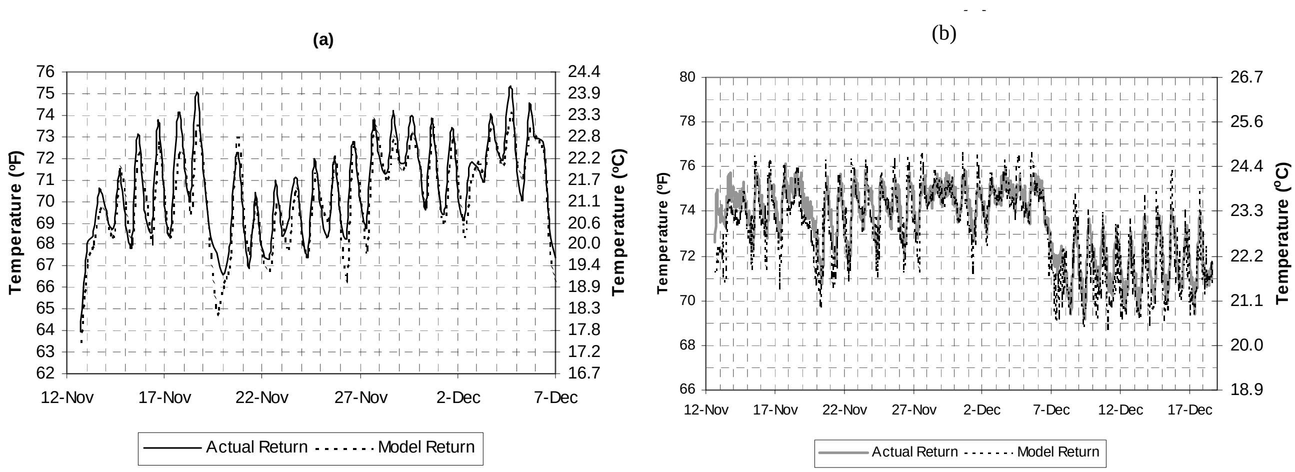


**Figure 1**. Comparison of observed and simulated heat exchange fluid return temperatures for (**a**) the 2-feet deep pond and (**b**) the concrete slab.

**Table 1.** RMS Errors of the Water-to-Water Heat Pump Simulations for 4 Sets of Catalog Data.

| No. | Nominal Capacity (Btu/hr) | Nominal Capacity (W) | Number of Points | RMS Capacity | RMS Power |
|---|---|---|---|---|---|
| 1 | 9352 – 30951 (cooling) | 2741– 9072 (cooling) | 81 | 4.57% | 4.77% |
| 2 | 57472 – 177978 (cooling) | 16845 – 52165 (cooling) | 81 | 4.71% | 5.44% |
| 3 | 12122 – 27918 (heating) | 3553 – 8183 (heating) | 81 | 2.66% | 1.70% |
| 4 | 174400 – 408500 (heating) | 51000-120000 (heating) | 234 | 3.08% | 5.76% |

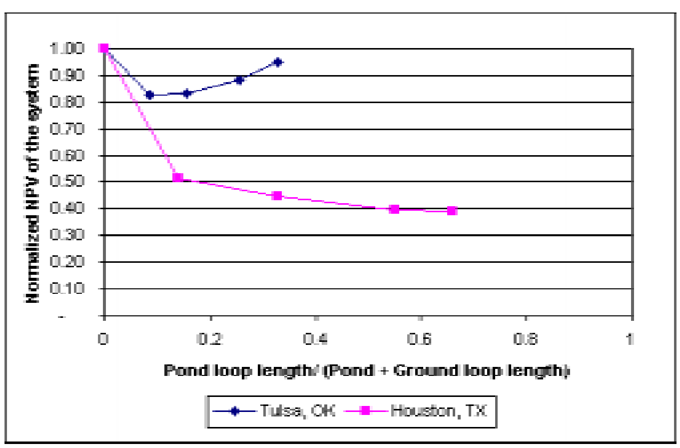


**Figure 2.** Normalized net present value of the system versus the ratio of pond loop length to total loop length for Houston, TX and Tulsa, OK climatic conditions.

## CONTACTS

Lew W. Pratsch
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
V:(202) 586-1512 Fax: (202) 586-8185
e-mail: LEW.PRATSCH@hq.doe.gov

Jeffrey D. Spitler, Ph.D., P.E.,
Professor
School of Mechanical and Aerospace Eng.
Oklahoma State University
218 Engineering North
Stillwater, OK 74078
V:(405)744-5900 Fax:(405)744-7873
e-mail: spitler@okstate.edu

# DEVELOPMENT OF SHALLOW GROUND HEAT EXCHANGER SYSTEMS

Marvin D. Smith, Ph.D., P.E., Randolf L. Perry, and William A. Holloway
Oklahoma State University
Division of Engineering Technology/IGSHPA
Stillwater, Oklahoma

## KEY WORDS

heat pump systems, ground heat exchangers, heat dissipation, pond loops

## PROJECT BACKGROUND AND STATUS

Vertical wellbore ground heat exchanger systems build up temperature over long periods of time for most commercial systems. To counter this effect, the depths of the boreholes are increased. These depths could be reduced if some of the heat was dissipated through a lower-cost alternate method. Horizontal systems have the potential to reduce the costs of drilling deeper boreholes by dissipating sufficient heat to augment a vertical system.

One such system uses a Slinky® heat exchanger, that is a continuous pipe length coiled into circles that overlap each other. When viewed along the axis of the heat exchanger, the distance between the apex of each loop is called the “pitch.” In this project, the Slinkys used have a pitch of 10 inches and a length along the axis of 40 feet.

Experience with Slinky heat exchangers began with applications to residential ground source heat pump systems. A new application was conceived after the design loop in a ground source system installed in a convenience store proved to be insufficient. A cooling tower was added to dissipate some of the accumulated heat. The idea was to replace the cooling tower with Slinky heat exchangers under the convenience store drive and the car wash drive. This application allowed controlled dissipation of heat, with the added benefit of ice removal during winter months. From this success, a concept was formed to reduce the cost of heat exchanger fields by adding surface heat exchangers to augment the performance of the vertical loops.

This project was designed to determine costs and performance of 5 different shallow heat exchanger systems. Water, saturated sand, soil and concrete are the media used to transfer heat in the five different heat exchanger systems. All systems have 40-ft long Slinky heat exchangers, that are made from 500 feet of 3/4 inch HDPE pipe. All of the Slinkys have the same inside dimensions of 4 feet wide and 40 feet long. One of the water (shallow pond loop) systems has a depth of 3.5 feet. The Slinky is installed vertically, and the system is built to hold one to three heat exchangers. The second water system is the same as the first, except that it is 2.5 feet deep and the Slinky is installed flat (horizontally). A third system involving water uses saturated sand and a float system to maintain the system’s water level. The Slinky is in an HDPE liner and is covered with 6 inches of saturated sand. The soil version has 6 inches of sod over the Slinky with no method of controlling moisture content. The fifth system covers the Slinky with a 6 inch slab of concrete, simulating a driveway.

Thermistors are embedded below the Slinky and above it to monitor the transfer of heat. Supply and return temperatures are measured at the Slinky header to determine the heat transfer dissipated to the surrounding media. A flow meter is installed in each system and a heating element is also in the line to heat the water circulating through the loop. A kWh meter is used to measure the energy used by the circulating pump and the heating element. The data acquisition system records all sensor information in

6 minute intervals on a 24 hour basis. Data have been taken in the summer, fall and some of the winter months. Air and ground temperatures affect the relative and absolute performance of the five systems.

Data have been provided to one modeler, and a preliminary design of a commercial building shows the concept of augmenting vertical boreholes with shallow heat exchangers to very viable.

## PROJECT OBJECTIVES

Since first cost of geothermal heat pump installations has been a deterrent to many customers, the focus of this project is to develop shallow ground heat exchanger systems that will reduce the cost of heat exchanger fields by reducing the depths and/or numbers of vertical boreholes required for a given system. Data will be obtained to determine the relative cost and performance of the various shallow heat exchanger systems and to verify models for designing shallow ground systems.

### *Technical Objectives*

- Develop and construct 5 shallow ground heat exchanger systems.
- Test shallow ground heat exchanger systems to obtain performance data to validate models for these systems.
- Determine relative costs and performance of the systems with respect to the cost and performance of vertical boreholes.

### *Expected Outcomes*

- Reduce vertical borehole costs by 30%
- Concrete and soil systems to have performance levels not less than 50% of the deeper (3.5-ft) pond system, with incremental cost of the concrete system being less than 10% of the pond system.

## APPROACH

Design of the five systems was accomplished using CAD systems, and the drawings were reviewed and modified several times. The instrumentation and data acquisition system were designed and tested. A control system strategy was developed, and the control system was designed to implement the strategy. Thermistors and flow meters were calibrated and tested for accuracy. Thermistors were treated to make them waterproof at the connections. The five systems were constructed, and loops and instrument lines were run to each. Sensors were placed during construction, since the majority of the sensors are buried. A building was modified to accommodate the electrical system, water heater loops, flow system controls, and the data acquisition and control systems.

The main header in a heat pump system for commercial use is simulated for this study. When the water in the header reaches a set temperature, the dissipation system is activated. In the test system, the flow is maintained at the set temperature with a resistance heater, and the electrical power output is measured to determine how much heat is dissipated at the set temperature. Since the temperatures of loop systems in an actual vertical heat pump installation will vary — especially with weather-dependent systems — the set temperatures of the test system are changed from 90°F in the summer to 70°F in the winter. All of the heat exchangers are independent of each other and operate when the set temperature is reached. The data acquisition system displays all the data and records every 6 minutes the values and status of switches and controls. A Zip disk is used to transfer files from the data acquisition computer to the data reduction computers. Files are reviewed, evaluated, and prepared for transfer to model developers.

Modifications are made to the system when situations reveal problems or potential problems. For example, when one of the circulating pumps failed, the electrical heater overheated the non-circulating water, creating sufficient pressure to blow the top out of one of the systems. Following this incident, a control was installed that shuts the system down if the flow rate drops below 2 gpm.

## RESEARCH RESULTS

A view of the 5 systems is seen in Figure 1. The concrete slab (driveway, sidewalk, or parking) is the closest one in the photo, and the farthest is the 3.5-ft deep concrete pond.

As seen in Figures 2, 3, and 4, the surface heat exchangers perform much differently in a hot, warm, and cold temperatures, and their performance varies from day to night. Figure 2 shows the August 100°F temperature effect and how the 2.5-ft pond system has the greatest extreme in performance variation. For the period of time shown on the figure, the average heat dissipation for the 3.5 ft pond system is 4394 Btu/hr, while the 2.5-ft pond system is 3772 Btu/hr, and the saturated sand system is 3558 Btu/hr. Then a large decrease occurs in the other two, with the soil dissipating 935 Btu/hr and the concrete dissipating 568 Btu/hr.

On the warm day in October, with the temperature in the 60’s and 70’s, the performance variations were not so large, and the difference between the systems was less. The lowest average performer, the soil, performed at 81% of the best performer, the 3.5-ft pond system. The average performance of the 3.5-ft pond, 2.5-ft pond, saturated sand, soil, and concrete systems are 7130, 6694, 6749, 5792, and 6517 Btu/hr, respectively, for the period of time shown on Figure 3.

During the months of September 1999 through February 2000, the system was operating at a set temperature of 90°F, which is in the range of temperatures that could be dissipated from a commercial building. Figure 4 shows the relative performance of the five different configurations. In addition to the set point, another difference between the 1998 data and this set of data is that the Slinky was mounted in the horizontal position in the 3.5 ft water tank.

Fewer performance variations occurred during the day for the cold temperature day in December shown in Figure 4, but a more consistent spread between the types of systems occurred. The 3.5-ft and 2.5-ft pond systems dissipated heat at the rate of 16,423 and 15,714 Btu/hr on average; the sand and concrete systems dissipated 11,804 and 11,591 Btu/hr. The lowest performer was the soil, dissipating 7090 Btu/hr for the time period shown.

These results are for areas of 160 $ft^2$ for each of the systems. If the areas were enlarged, the edge effects would need to be determined, but these heat exchangers have demonstrated that a large potential exists for reducing built-up heat in normal vertical loads through the use of surface systems.

All of the data in Figure 5 are based on unit performance; that is, the $Btu/hr/ft^2$ rate is for the respective unit surface area, which covers 120 $ft^2$ for the water systems and 160 $ft^2$ of area for the sand, sod, and concrete. The tests are controlled to maintain a set water temperature by heating the water if the temperature falls below a set point. There are four set points in this data: 35°F, 75°F, 80°F, and 90°F. The 75°F set point is for the coolest period of the year, 80°F for the transition period, and 90°F for the hot season. The 35°F set point is to keep the system running without applying heat to the circulating water.

Figure 5 shows the trend of heat transfer rates from September 1998 through August 1999 for the five systems. The most notable difference is that for any month of the year, the two water systems out-perform the saturated sand and dry systems. The systems are also very responsive to the weather, with many variations occurring during relatively short periods. On hot days, the concrete slab is the lowest performer, and the saturated sand is markedly better, but in cooler weather, the two perform relatively the same. Also note that the sod system has a lower heat transfer rate than the concrete system during cooler periods, but it has slightly better performance than the concrete during the very hot periods. Even with the observed variations in performance of the systems, any of them could be used effectively to reduce vertical loop lengths.

Performance of the water systems during the winter months can be about 3 times higher than the other systems, which do not have convective currents across the coils. If shallow water is available in relatively small areas for heat dissipation, the potential for borehole field size reduction is significant.

A system for a local restaurant has been designed using the data as a guide for the loop requirements in the pavement. The building is still under construction and will be tested beginning about April 2000.

## FUTURE PLANS

- Contract ended.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Oak Ridge National Laboratories | Use data for model development |
| OSU, School of Mechanical Engineering | Use data for model development |
| ASHRAE | Dissemination of information to industry |
| GHPC | Dissemination of information to industry |
| IGSHPA | Dissemination of information to industry |

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## CONTACTS

Lew W. Pratsch
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
V: (202) 586-1512 Fax: (202) 586-8185
e-mail: LEW.PRATSCH@hq.doe.gov

Marvin D. Smith, Ph.D., P.E.
Professor and Director of GHP Research
Division of Engineering Technology
Oklahoma State University
499 Cordell South
Stillwater, OK 74078
V: (405) 744-9370 Fax: (405) 744-5283
e-mail: smarvin@ceat.okstate.edu

## FIGURES, PHOTOS AND TABLES

**Figure 1.** Five Shallow Heat Exchanger Systems.

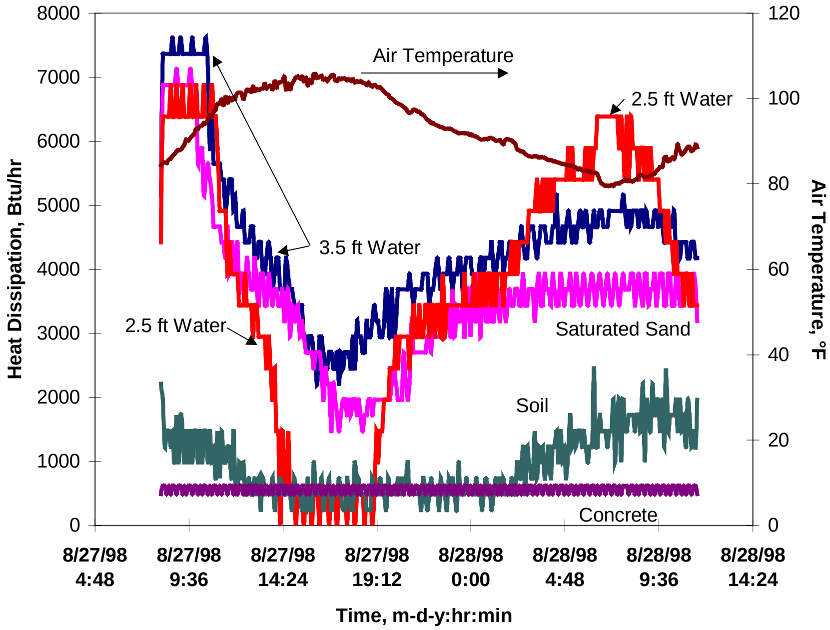


**Figure 2.** Heat Dissipation During Hot Weather.

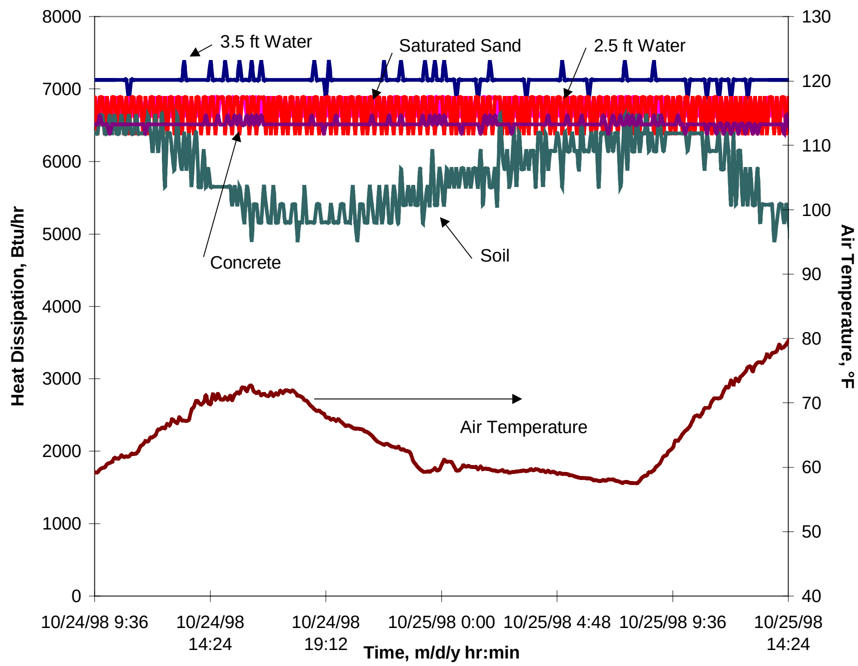


**Figure 3.** Heat Dissipation on a Warm Day.

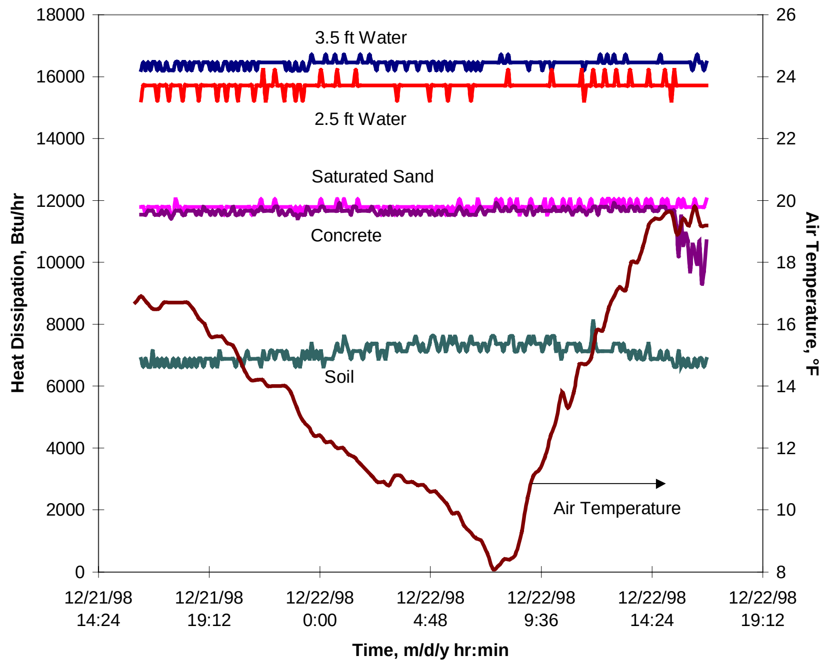


**Figure 4.** Heat Dissipation During Winter Weather.

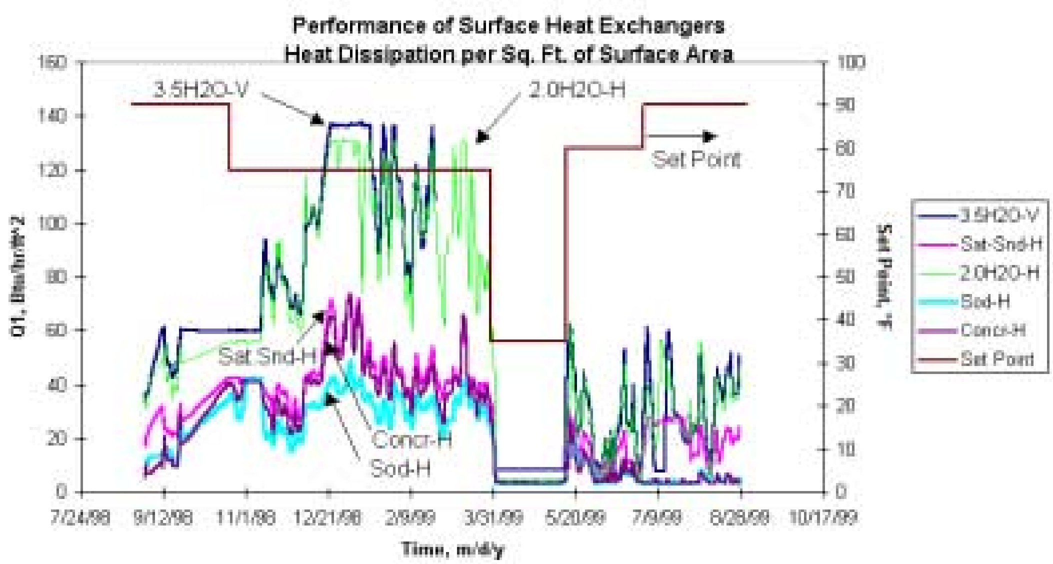


**Figure 5.** Heat Dissipation per Square Foot.

# OPERATION AND MAINTENANCE (O&M) COSTS STUDY FOR THREE GROUND SOURCE HEAT PUMP SYSTEMS

Marvin D. Smith, Ph.D., P.E., and Phil Albertson, P.E.
Oklahoma State University
Division of Engineering Technology/IGSHPA
Stillwater, Oklahoma

## KEY WORDS

life cycle cost, operation costs, maintenance costs, geothermal heat pumps

## PROJECT BACKGROUND AND STATUS

Geothermal heat pump systems have been perceived by some to be more expensive to operate than alternate HVAC methods. This operation and maintenance (O&M) costs study is to improve the dearth of data available for application in life cycle cost (LCC) analysis.

Contents of the "Survey and Analysis of Maintenance and Service Costs in Commercial Building Geothermal Systems" by Caneta Research, Inc. (sponsored by the GHPC under a contract with the DOE) were compared with a 1983 ASHRAE sample of HVAC systems. The more recent Caneta maintenance costs were shown statistically to be **significantly lower** than those of the ASHRAE report. For example, the more recent survey shows median costs ranging from $5.63 to $8.37 per 100 square feet for ground source heat pumps, while the earlier ASHRAE report showed $20.80 per 100 square feet for a water source heat pump. ASHRAE is updating their survey, but the use of their data for LCC analysis leaves the geothermal heat pump system at a disadvantage.

Geothermal systems in the following three facilities were chosen for evaluation of maintenance frequency:

- Oklahoma State Capitol, Oklahoma City, OK
- Park Chase Apartment complex, Tulsa, OK
- Langston University's White House, Langston, OK

The State Capitol has 378,000 square feet of space conditioned by 460 heat pump units. The system has two pumps to circulate the heat exchange fluid through 94,720 feet of borehole. The loop system is augmented by a cooling tower. When the loop temperature reaches 85° F, the cooling tower operates to bring the loop temperature back down to 65° F.

The Park Chase Apartment complex has 293,000 square feet of space conditioned by 416 heat pump units, without additional systems. Park Chase uses 95,000 feet of borehole. Each of the 416 heat pumps has its own dedicated heat exchanger and pumps, which operate only when needed.

The Langston University's White House is the former university president's house. It has a GHP system that was installed in 1990, when the house was being remodeled into a hotel with a cafeteria and a bar. It is a three story building with 12,275 square feet conditioned by fifteen heat pumps totaling 65 tons, connected to sixty-three 200-ft vertical loops under an adjacent parking lot, for a total of 12,600 feet of borehole. Each heat pump has its own small circulating pump that runs only when the heat pump runs. During the remodeling, large number of glass windows and doors were incorporated into the dining area.

Information has been gathered on the Park Chase and State Capitol systems, but the White House does not keep maintenance records. This information shows that the type of system and the maintenance contract result in considerably different maintenance costs. The maintenance costs for the Oklahoma State Capitol are, on average, over 6.3 times higher than the Park Chase system. Additional studies are being done with the data to determine ways to assist in guiding designs and maintenance to decrease the life cycle cost of the geothermal heat pump system even more.

## PROJECT OBJECTIVES

The life cycle cost (LCC) analysis is a salient comparative method for determining the relative economic merits of one HVAC system over another. More detailed studies on operation and maintenance costs for geothermal heat pump systems are needed to give credence to claims of lower costs compared to other HVAC systems. This study is to improve the dearth of data available for application in LCC analysis. Low maintenance cost records of ground source heat pump systems will help give these systems a competitive edge over more traditional alternatives.

An additional objective is to evaluate the data and present it in a form that will provide direction for improving the operation and maintenance costs for a specific type of system and to select the design features that will yield the most favorable costs.

### *Technical Objectives*

- Produce details on operation and maintenance costs for commercial systems that have been operating multiple years for use in LCC analysis.
- Present data to assist designers in determining geothermal heat pump system alternatives that will minimize operation and maintenance costs.
- Use the experience from these cases to provide valuable guidelines for identifying techniques and products to be developed to improve GHP designs and installations.

### *Expected Outcomes*

- Increase decisions to use environmentally friendly geothermal heat pump systems based on life cycle cost competitiveness.
- Increase the number of geothermal designs that use alternatives leading to lower operation and maintenance costs.

## APPROACH

Three operating systems were selected that were within close proximity (65 mile radius) to each other and had been in operation several years. The systems chosen were:

- Oklahoma State Capitol, Oklahoma City, OK
- Park Chase Apartment complex, Tulsa, OK
- Langston University’s White House, Langston, OK

Maintenance and operation information was acquired from other sources and reviewed. Visits were made to the three sites and data gathering began. Some of the information required on-site gathering and duplicating; other information was made available by concerned parties. The personnel in charge of the facilities and their staff were interviewed, as were maintenance staff. A great deal of time was spent reviewing the data, compiling it and putting it into a format useful for evaluation purposes. Each type of maintenance request was tabulated for each applicable system, and ratios of system characteristics were made to determine relationships of systems.

## RESEARCH RESULTS

There were 45 categories of service, maintenance, and repairs considered in the study. The Oklahoma State Capitol's EMS system required the most attention, accounting for over 20% of the total maintenance calls. This was followed by the Condensate system category, which had a little over 60% of that recorded for the EMS. The next two were the Adjustments/Miscellaneous and the Reversing Valve categories, which were slightly over 1/3 of the EMS frequencies. The Temperature Controls and T-slats categories were slightly under 1/3 of the EMS frequencies. These six categories accounted for over 60% of all the maintenance calls in all categories.

The Park Chase Apartments had the highest frequency of calls in the category of Refrigerant Leak, which was twice as high as the next three categories of Adjustments/Miscellaneous, Condensation systems, and Expansion Valves. The other two significant categories were Relay and Compressor, with frequencies of less than 1/3 of the Refrigerant Leak category.

After continued effort to obtain data from the Langston University's White House it was finally discovered they did not have records on system maintenance, and they were making estimates of what had occurred. Their biggest maintenance complaint was their system was not operating properly in the summer, and they had to put make up water through the system during hot weather. During construction, the borehole field was completed in an area that later became the parking lot. Excavation for the parking lot removed several feet of soil from above the boreholes and header system. As a result, it is believed the asphalt area influences the temperature of the loop, which requires them to put makeup water into the units after the outside temperature rises above 90° F.

The Capitol installation uses large diameter header pipes, buried outside and connected to two large variable pumps in the equipment room. They in turn pump the water through large header pipes in the building that decrease in diameter as they approach the individual 460 GHP units ranging in size from 1/3 ton to 30 tons. In contrast, the Park Chase installation has the vertical loops located around the periphery of the buildings, each with short, much less expensive, small diameter headers connecting to each of the 416 nearby 1-2 ton GHP units. Table 1 shows a comparison of the characteristics of the two systems and reveals that even though the ratio of the number of heat pumps for the Capitol and Park Chase is 1.1 (460/416), the maintenance report frequency per year for the two facilities is 5.89 (536/91). This implies the smaller heat pump system with pumps that activate only when the room thermostats call for operation is a more efficient system.

Table 2 has data to show the comparison of the annual maintenance cost per year for the Capitol versus Park Chase. It is evident that the Capitol maintenance costs, at $\$28.90/100\ ft^2$, are higher than the 1983 ASHRAE report value of $\$20.80/100\ ft^2$, and the Park Chase costs, at $\$4.54/100\ ft^2$ are less than GHPC report. It should be noted that even though the cost of the Oklahoma State Capitol is high for the GHP/Cooling tower system, it is much lower than the previous system which was $\$97.90/100\ ft^2$. It is believed that design and maintenance philosophies have a strong impact on maintenance cost per square foot, and data such as these should be expanded to guide design and maintenance procedures.

## FUTURE PLANS

- Doe contract ended.
- Make the full report available on www.igshpa.okstate.edu

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| ASHRAE | Dissemination of information to industry |
| FEMP | Dissemination of information to industry |
| GHPC | Dissemination of information to industry |
| IGSHPA | Dissemination of information to industry |

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## CONTACTS

Lew W. Pratsch
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
V:(202) 586-1512 Fax: (202) 586-8185
e-mail: LEW.PRATSCH@hq.doe.gov

Marvin D. Smith, Ph.D., P.E.
Professor and Director of GHP Research
Division of Engineering Technology
Oklahoma State University
499 Cordell South
Stillwater, OK 74078
V: (405) 744-9370 Fax: (405) 744-5283
e-mail: smarvin@master.ceat.okstate.edu

## FIGURES, PHOTOS, AND TABLES

**Table 1.** Comparison of GHP Systems for Park Chase Apartments and the State Capitol.

| | Oklahoma State Capitol | Park Chase Apartments | Ratio Capitol/Park Chase |
|---|---|---|---|
| **Conditioned Space (ft$^2$)** | 378,000 | 293,000 | 1.3 |
| **Total Borehole (ft)** | 94,720 | 95,000 | 0.99 |
| **Number of GHPs (size range)** | 460 (⅓ - 30T) | 416 (1 -2T) | 1.1 |
| **Cooling Tower Tons (temp range)** | 607(85°F - 65°F) | N/A | — |
| **GHP Capacity (tons)** | 883 | 543 | 1.63 |
| **Total Capacity (tons)** | 1490 | 543 | 2.74 |
| **GHP Capacity / 1000 ft$^2$** | 2.2 | 1.9 | 1.16 |
| **Total Capacity / 1000 ft$^2$** | 5.1 | 1.9 | 2.68 |
| **Total System Costs (US$)** | $4,792,445 | $1,700,000 | 2.8 |
| **Yearly Energy Savings (US$)** | $69,767 | $60,804 | 1.15 |
| **Maintenance Request Frequency** | | | |
| **Number/period** | 1608 / 3 years | 414 / 4.5 years | — |
| **Number/year** | 536 | 91 | 5.89 |
| **Number/week** | 10 | 2 | — |
| **Hourly Rate for Maintenance** | $29.70 | $49.00 | 0.61 |

**Table 2.** Maintenance and Maintenance Cost for Park Chase Apartments and the State Capitol.

| | US$ per 100 square feet, or cents per square foot | | | | | |
|---|---|---|---|---|---|---|
| **Comparative Annual Maintenance for Year:** | **1994** | **1995** | **1996** | **1997** | **1998** | **Avg.** |
| **Capitol Building (387,000 ft$^2$)** | | | 21.7 | 39.2 | 35.7 | 28.9 |
| **Park Chase Apartments (293,000 ft$^2$)** | 3.4 | 4.8 | 3.1 | 2.9 | 8.4* | 4.54 |
| **Annual Maintenance Costs** | **x $1000** | | | | | |
| **Capitol Building** | | | 75 | 108 | 124 | 102 |
| **Park Chase Apartments** | 10.2 | 1431 | 9.0 | 8.6 | 14.3† | 11.2 |

**Notes:**
* New contract through June
† Replaced by previous contract

# DEVELOPMENT OF A SYSTEM FOR VERIFICATION OF TRANSIENT IN-SITU TESTING MODELS AND DEVELOPMENT OF A TESTING STANDARD

Marvin D. Smith, Ph.D., P.E., Randolf L. Perry, and William A. Holloway
Oklahoma State University
Division of Engineering Technology/IGSHPA
Stillwater, Oklahoma

## KEY WORDS

heat pump systems, grout, enhanced grout, in-situ thermal conductivity test

## PROJECT BACKGROUND AND STATUS

In-situ thermal conductivity models can provide good agreement with homogeneous material if test times are long and power is constant. This constraint increases the cost of the test and is a deterrent to conducting in-situ testing, even though the data could provide a significant savings in the construction of the loop field. Thus, a system is needed to assist in the refining of models for obtaining valid thermal conductivity values in the shortest time possible. The shortest time possible is a function of the grout and formation properties.

Also, to maintain consistency and valid data within the industry, it is recommended that a governing board set a standard for thermal conductivity testing. Many design problems could be reduced by having commercial systems tested in a known environment that produces results that are within the acceptable limits set by the standard.

Currently, the most complete verification data were obtained with the Ewbank/DOE/OSU joint project in building a simulated borehole in-situ testing system and testing a 48-ft long loop in a 4-ft by 4-ft cross-section sand formation. This was done with both dry and wet sand. This work has contributed to our understanding of temperature distributions in the formation, and relatively good agreement was demonstrated between average thermal conductivity from probe tests and three in-situ test models. However, the long-term portion of the test was skewed because the enclosure was too small for long-term tests and because leaks in the system resulted in stratified moisture content in the sand. Therefore, the system needs to be increased in size to 6-ft by 6-ft by 60-ft so that heat transfer interference with the walls will not be an issue. The system will be sealed and have structural integrity to withstand the load of the saturated sand. Thermistors will be embedded in the sand to obtain radial transient temperature profiles at three stations. The system will be placed in a controlled environment to simulate far field temperature stability. It will have the capability of having the grout, pipe and pipe spacing changed in the borehole.

Results of the Ewbank/DOE/OSU simulated borehole system provided a good start in producing data which gave model developers a way to verify their results. Models were refined and better results were obtained. As more complete data become available, the issue of the length of time needed to predict thermal conductivity will be addressed with greater success.

## PROJECT OBJECTIVES

A system is needed to provide information to assist in the refining of the models to obtain valid thermal conductivity values in the shortest time possible, which is a function of grout type, formation properties, pipe, and pipe configuration. A series of tests is to be made that will simulate the effects of the grout, pipe, and formation variations on thermal conductivity, so future thermal conductivity models can take into account potential variations in the field.

Another objective is to maintain consistency and valid data in the GHP industry, so it is recommended that a governing board set a standard to be followed and a location to test the model against the standard.

***Technical Objectives***

- Develop a permanent simulated wellbore heat exchanger system (sandbox test), which will have known thermal properties of the materials around the wellbore.
- Provide a system where users can verify their equipment and their models against a set standard.
- Increase understanding of the heat transfer process through the heat exchanger system and out into the surrounding formation.

***Expected Outcomes***

- Improve accuracy of in-situ borehole thermal conductivity test models and reduce testing time to 8-14 hours.
- Improve consistency in model predictions industry-wide.
- Increase the confidence of engineers in specifying in-situ testing and using those values in geothermal heat pump system designs.

## APPROACH

Valuable experience was gained earlier in the year with the Ewbank/DOE/OSU simulated system. This system was constructed and tested with both dry and wet sand. Some problems and limitations were encountered. The design of Version 2 utilized that experience and knowledge. A design was made on CAD, and alternatives were discussed in arriving at the model that was constructed. Only a limited amount of space was available because of another indoor experimental test system. A large amount of preparation for the simulated system was required, including moving and wall and storage space construction.

The system was constructed with 2 × 12 lumber and 1 1/8-inch plywood for structural and heat transfer purposes. Specific attention was given to sealing the system with both a liquid sealer and a carefully placed thick plastic liner inside the structure. A drip system was placed on the liner in the bottom of the box to provide controlled water supply to the sand when it is time to saturate the sand. Once this stage was completed, a borehole made of 5 inch aluminum pipe was placed down the center axis of the structure. Specially graded dry sand was placed carefully in the box and instruments were strategically placed in the sand at previously selected locations. All sensors were previously calibrated and waterproofed.

Figure 1 shows the structure filled with sand, as viewed from the top. Data acquisition will be done with two systems, one dedicated to the internal and external sand system temperatures, water flow to the system and environmental control. The other will be done with an in-situ test system similar to that which is currently being used in industry. These systems are still under construction.

The pipe and tremie tube are inserted into the borehole, and the heat exchanger is grouted. The thermistors are then monitored until the entire system comes into thermal equilibrium and testing can begin. The in-situ test is operated for 50 or more hours. A 6-inch thermal conductivity probe is used to determine the TC value for the sand at multiple locations in the system. An average of these tests produces the comparison value used in model validations. Data from these sources are compiled, evaluated and made available to model developers.

## RESEARCH RESULTS

Results from the first simulated system are shown in Figures 2 and 3. The first figure shows the characteristics of the data when dry sand surrounds the borehole of a bentonite-grouted system with a 1-inch HDPE U-bend loop. The second is the same test configuration, but with saturated sand. Probe readings were taken from 5 stations in the box and at different levels. Tests on the dry sand resulted in an average value of k= 0.149 Btu/hr-ft-°F. Probe tests on the wet sand yielded an average value of k=1.353 Btu/hr-ft-°F. As noted in Figure 2, the value obtained with the linear line source model is 0.156 Btu/hr-ft-°F. After refining their model, Austin, et. al., reported obtaining a value of 0.152 Btu/hr-ft-°F for dry sand. This was done using 50 hours of test data. Figure 3 shows a value of k=1.356 Btu/hr-ft-°F when using the line source model with data from 12.7 to 52.5 hrs of the test. With the Austin, et. al., model the value predicted was 1.336 Btu/hr-ft-°F using 50 hours of test data. Present models do a good job of predicting the test value of thermal conductivity, but a reduction in the time required to predict those values it is a key feature of this project.

A look at the test data in Figure 2 shows that the loop temperature minus the grout/sand interface temperature was not constant during the test time. This implies that the grout was not in equilibrium, and a truly transient model is required to predict the value accurately. In the case of the wet sand shown in Figure 3, the $\Delta T$ is relatively constant shortly after 12 hours into the test. As a result of this condition, the influence of the grout is minimized after that time and less truly transient models can be used very successfully.

The thermal conductivity of the grout used in this project had a value of 0.43 Btu/hr-ft-°F which is higher than the dry sand and lower than the wet sand. The effect of this difference can be seen in the two figures. In Figure 2, the slope of the loop temperature is initially low, then becoming higher, which implies heat transfer from the higher thermal conductivity grout to the dry sand’s lower thermal conductivity. The opposite is the case in Figure 3, where the slope of the loop temperature curve is initially steep, becoming more flat as the influence of the lower thermal conductivity grout in the beginning portions of the curve yields to the saturated sand’s higher thermal conductivity.

As more is learned about the effects of the borehole on the system, time requirements for in-situ testing will be reduced.

The total system, including controls was completed and one test was run. It was determined that the heat pumps were not operating properly. This was corrected, and the system was operated and monitored over an extended time. The system was successful in holding a temperature band that would provide a 2 to 3°F variation along the centerline of the sand system. A modification to the control system will improve the temperature control since the current system operates on the premise that all three heat pumps are equal and are turned on and off simultaneously. By controlling each heat pump separately to maintain the set point temperature, a better overall temperature band can be maintained.

The in-situ test unit developed in conjunction with the simulated borehole system was tested on over 8 different boreholes. Results of the tests have shown that the ambient temperature in the box affects the results of the tests. The magnitude of the effect depends on the difference between the test water temperature and the ambient temperature.

As more is learned about the effects of the borehole and ambient conditions on the system, time requirements for in-situ testing will be reduced, and accuracy will be improved.

## FUTURE PLANS

- DOE contract ended.
- This system is to be used for a DOT contract to evaluate heat exchanger performance to provide a basis for improving heat exchanger design.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Oak Ridge National Laboratories | Use data for model development |
| OSU, School of Mechanical Engineering | Use data for model development |
| Ewbank & Associates | Apply data to industrial applications |
| ASHRAE | Dissemination of information to industry |
| GHPC | Dissemination of information to industry |
| IGSHPA | Dissemination of information to industry |

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## CONTACTS

Lew W. Pratsch
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
V:(202) 586-1512 Fax: (202) 586-8185
e-mail: LEW.PRATSCH@hq.doe.gov

Marvin D. Smith, Ph.D., P.E.
Professor and Director of GHP Research
Division of Engineering Technology
Oklahoma State University
499 Cordell South
Stillwater, OK 74078
V: (405) 744-9370 Fax: (405) 744-5283
e-mail: smarvin@master.ceat.okstate.edu

## FIGURES, PHOTOS AND TABLES

**Figure 1.** View from above of the new in-situ test apparatus.

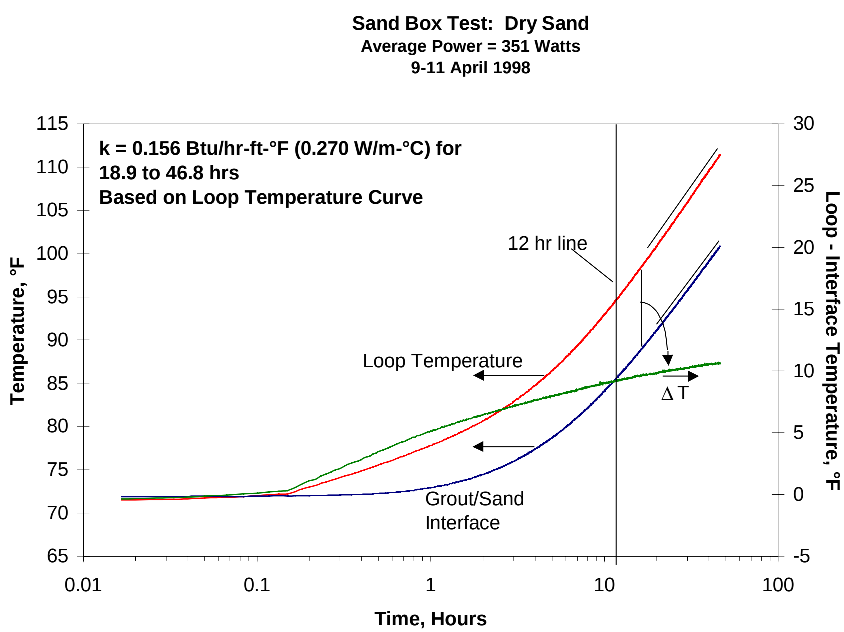


**Figure 2.** Sandbox test with dry sand.

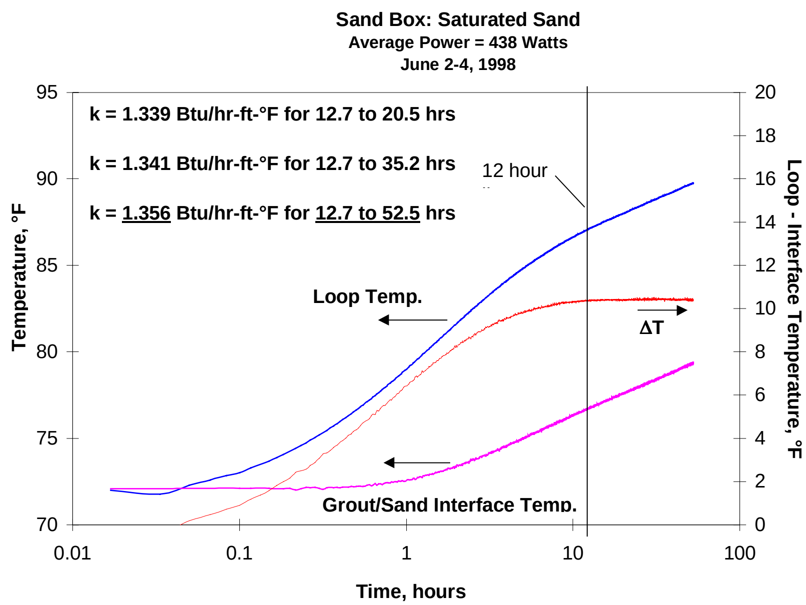


**Figure 3.** Sandbox test with saturated sand.

# FIELD EVALUATION OF CEMENTITIOUS GROUT COMPLETIONS IN COLLABORATION WITH BROOKHAVEN NATIONAL LABORATORY (BNL) AND DEVELOPING A DATABASE FOR LONG-TERM GROUT PERFORMANCE FOR THREE GROUT TYPES

Marvin D. Smith, Ph.D., P.E., Randolf L. Perry, and William A. Holloway
Oklahoma State University
Division of Engineering Technology/IGSHPA
Stillwater, Oklahoma

## KEY WORDS

geothermal heat pump, grout, ground source heat exchangers, high solids grout, enhanced grout, cementitious grout

## PROJECT BACKGROUND AND STATUS

Interest in the industry has grown with respect to grout performance and its effect on ground source heat exchanger lengths to reduce first costs and operating costs for geothermal heat pump systems. Dr. Charles Remund of South Dakota State University developed a thermally enhanced grout (TG 85) — with the basic components of bentonite, sand, and water — which was field tested at Oklahoma State University in 1996 in conjunction with various standard bentonite grouts (BH 30, EZ-Mud, and Grout-Well). In 1997, Dr. Marita Allan of Brookhaven National Laboratories developed a cementitious grout (CG 111), which has application for dry soil/rock formations surrounding the borehole. The current project was developed to compare the field tests of three grouts under heat pump load conditions and to provide data for model developers of borehole heat transfer designs.

There are six boreholes in close proximity with three different grouts (BH 30, TG 85, and CG 111) and three different borehole diameters (3.6, 4.5, and 4.9 inches). Depths of boreholes range from 244 feet to 252 feet, and all have 3/4-inch HDPE U-bend loops for heat exchangers. Pairs of grouted boreholes are connected by water-to-water heat pumps with the source side connected to the 3.6 inch boreholes and the load side to the larger boreholes. Construction of the system has been completed and preliminary testing of boreholes with in-situ test units has been accomplished. Heat pump cycling loads are scheduled to start as soon as the instrumentation has been verified.

Preliminary results show that the performance of the grouts is proportional to the percentage of solids by weight and inversely proportional to the diameter of the borehole. Down-hole sensors have shown that the borehole resistance is effectively constant for the CG 111 grout after about 8 hours of constant heating of the loop water.

## PROJECT OBJECTIVES

The immediate objectives of the project are: 1) to provide the industry with operational characteristics of grouts having wide range of physical properties; and 2) to provide performance data for use in validating loop design models and refining in-situ borehole thermal conductivity testing.

Long-range objectives include: 1) reduced first costs and operating costs of ground source systems through improved grout selection for a given formation; 2) refined thermal conductivity (TC) determination; and 3) validated design models.

***Technical Objectives***

- Determine characteristics of grouts in heating and cooling modes of operation
- Improve knowledge base for selecting grouts considering operation characteristics
- Produce high quality data to assist in refining and validation of in-situ TC models
- Produce high quality data for validating loop design models

***Expected Outcomes***

- Reduce range for in-situ thermal conductivity test times from 48-50 hours to 8-14 hours
- Reduce costs of boreholes by 15-25% through proper selection of grout for a given job
- Reduce combined first costs and operating costs by 20-30% with proper design tools

## APPROACH

The first task of the project was to design the total system including the data acquisition building, borehole locations and connections, instrumentation, software and test procedure. Subsequent to the design phase, the materials, parts, and equipment were ordered, and construction began. Of the six boreholes for the system, four had been completed in prior projects but not connected to any system. A method was developed to place thermistors down-hole at four different locations, so they would sense the temperature of the borehole wall. Figure 1 shows this system being run into the cored borehole. Temperature and flow rate sensors were calibrated. Preparations for coring one borehole and drilling another were made, and the process was completed in August 1998. Dr. Marita Allan was on site to supervise the mixing of the CG 111 grout. Initial attempts to grout the boreholes with CG 111 were not successful with the equipment available on site. An alternate method was developed that involved building an overhead structure between the two boreholes to allow continuous pumping of the grout.

Trenching was done from each borehole to the newly constructed building in a path that maintained the same header length for all 6 boreholes. Manholes were placed at each of the 6 boreholes, and fittings and valves were fused to the U-bend heat exchangers. These valves were used to control the flow to the heat pumps and to provide a quick connection method for intermediary in-situ borehole thermal conductivity tests. Temperature sensors were placed at the borehole, and flow meters were placed at the heat pump location, along with sensor ports to measure temperature and pressure. This approach provides a method for obtaining the contribution of heat transfer from the borehole apart from the heat transfer from the headers between the borehole and heat pump.

A view of some of the borehole sites is shown in Figure 2. The manhole covers give us access to the headers so that we can do in-situ tests or set the valves to allow the system to operate from heat pumps. Pairs of boreholes with the same grout are connected to a water-to-water heat pump so that one heat exchanger is absorbing heat, while the other is dissipating heat. Figure 3 shows the inside of the heat pump building with the units and the data acquisition system.

A transformer was set up at the building, and electricity was supplied to it. A ground source heat pump was installed to meet the conditioning needs of the building. Each water-to-water heat pump will be monitored with 3 kWh meters to determine compressor load, source side load and load side electrical load. A data acquisition system will save data to a disk every 6 minutes and control the on-off time of the water-to-water heat pumps. The screen display shows each of the 3 systems separately, with a schematic of the system and measured output displayed in real time. A Zip drive will be used to transfer data from the data acquisition system to another computer for evaluation and preparation for distribution to those who model this type of system.

## RESEARCH RESULTS

Under extremely hot weather conditions, it was demonstrated that the CG 111 grout could be successfully placed in the borehole by continually pumping the grout into the tremie pipe. This requires mixing the grout in one mixer while a batch from another mixer is being placed in the hopper to be pumped down-hole. (Note that a month later at Sandia National Laboratories, Dr. Marita Allan modified the grout mix slightly and successfully pumped the new grout using only one mixer.) The down-hole sensors were successfully placed and working properly in the cored borehole. The drilled borehole was too small to install down-hole sensors.

The density of the CG 111 is sufficiently high that collapse pressure in the loops is possible. For our 250 ft loop, with water in the loop and grout in the annulus, the differential pressure would have been about 134 psi, whereas the collapse pressure of the pipe is about 78 psi. We applied air pressure of 85 psi to the loop to offset the differential pressure.

Operation considerations when pumping a very high solids grout are: 1) always keep the grout flowing in the tremie pipe; 2) match mixing time with pumping time through carefully sized batches; 3) pull the tremie pipe at a rate that maintains the end just below the grout level in the borehole; 4) do not cut a side passage in the tremie at the bottom, but allow the grout to flow out of the tremie pipe's open end.

Figure 4 is a graph of the measured pseudo-thermal resistance for the BH 30, TG 85, and CG 111 grouts. This is plotted against the cumulative power per depth of the borehole to provide a consistent scale of comparison. As heat is applied to the borehole through the U-bend loop, the temperature in the loop increases. Thermal resistance is based on the difference between the loop temperature and the far field formation temperature, divided by the heat transfer per foot going into the loop. A high thermal resistance indicates a low performing grout, since all the boreholes are in the same formation and have the same pipe size. The figure legend shows the borehole diameter, the percent solids by weight of each grout, and the grout identification. According to Figure 4, the higher-solids grouts have better thermal performance; also, for the same percent solids grout, a smaller diameter borehole performs better.

With borehole wall temperature data, it is possible to determine the pseudo-thermal resistance for the borehole, which includes the pipe and the grout. In Figure 4, the thermal resistance included the pipe, the grout, and the distance heat had propagated into the formation. Figure 5 shows the trend of U, R, and Rtb as a function of time for the CG 111 mix in the cored borehole, which is designated borehole #6a. R is the pseudo-thermal resistance discussed in the previous paragraph, and U is the reciprocal of R. Rtb represents the pseudo-thermal resistance for the total borehole, and the temperature difference is the loop temperature minus the average of the borehole wall temperatures. From Figure 5 curves, it appears that U is approaching an asymptotic value, but by comparing it to the R curve, it becomes apparent that equilibrium has not been attained. After about 8 hours of operation, the thermal resistance of the grout (Rtb) is essentially constant, which implies that changes in the loop temperature are influenced strongly by the formation properties. This information has significance with respect to the minimum test duration for in-situ borehole thermal conductivity tests.

One of the objectives of the project is to determine the characteristics of grouted heat exchanger systems in the heat absorbing mode from the surrounding grout and formation soils. Figure 6 shows two periods of data when heat exchangers in wells #1, #3 and #5 were absorbing heat. From the last of September to the first part of December, the heat pumps and circulators were turned off to allow the boreholes to approach equilibrium. Electrical outages resulted in brief downtimes and spikes in the data.

After rejecting heat to the grout and formation, the heat exchangers were reversed during August and September so that they were extracting heat from the same formation. It is evident from the curves that the overall resistance during this time period is smaller than the resistance after the quiescent period. This shows the effects of seasonal transitions. (Note: the lines in the graph in the quiescent period have no meaning other than connecting the two periods of time.)

When comparing the data, remember that the lower the resistance, the better the grout performance. The resistance shown in Figure 6 is overall resistance, but the same formation surrounds each. Therefore, we can deduce the relative performance of each grout. With the higher formation temperature in the August and September time period, there was a demarcation among the three grouts, with the cementitious being the best performer. In the December to February period the bentonite grout was distinctly higher than the other two, and the enhanced bentonite and the cementitious grouts were essentially the same.

A test facility has been constructed that will produce data to help further our understanding of the characteristics of grout and borehole diameter in the design of heat exchanger fields for geothermal heat pump applications. Tests have been conducted in heating and cooling modes under heat pump load cycles.

## FUTURE PLANS

- DOE contract ended.
- The facility is now being used to evaluate the grouts for modeling cycling loading under a DOT contract for use in bridge deck heating.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

| Organization | Type and Extent of Interest |
|---|---|
| Brookhaven National Laboratories | Use of data for grout refinement |
| Oak Ridge National Laboratories | Use data for model development |
| OSU, School of Mechanical Engineering | Use data for model development |
| Ewbank & Associates | Apply data to industrial applications |
| GeoPro, Inc. | Apply data to industrial applications |
| Ochsner Heat Pumps, Germany | Requested information |
| ASHRAE | Dissemination of information to industry |
| GHPC | Dissemination of information to industry |
| IGSHPA | Dissemination of information to industry |

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## CONTACTS

Lew W. Pratsch
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, DC 20585
V:(202) 586-1512 Fax: (202) 586-8185
e-mail: LEW.PRATSCH@hq.doe.gov

Marvin D. Smith, Ph.D., P.E.
Professor and Director of GHP Research
Division of Engineering Technology
Oklahoma State University
499 Cordell South
Stillwater, OK 74078
V: (405) 744-9370 Fax: (405) 744-5283
e-mail: smarvin@ceat.okstate.edu

**FIGURES AND PHOTOS**

**Figure 1a.** Thermistor system during installation.

**Figure 1b.** Thermistor system detail.

**Figure 2.** Grout performance well site.

**Figure 3.** Interior of data acquisition shelter — grout performance comparison.

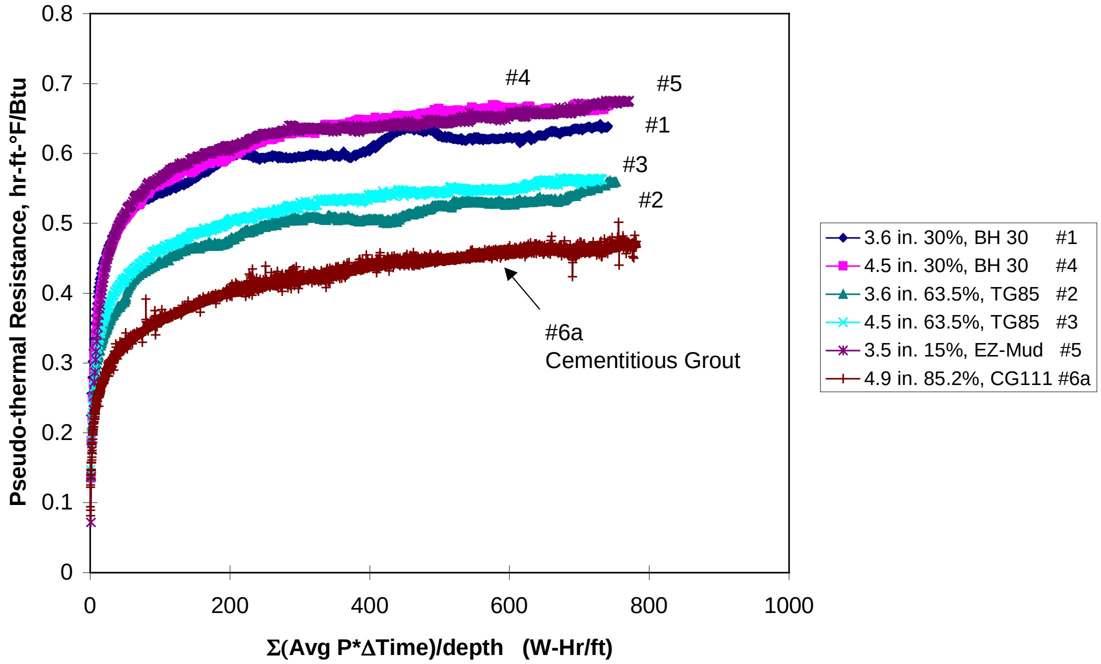


**Figure 4.** Measured pseudo-thermal resistance vs. power per depth of loop.

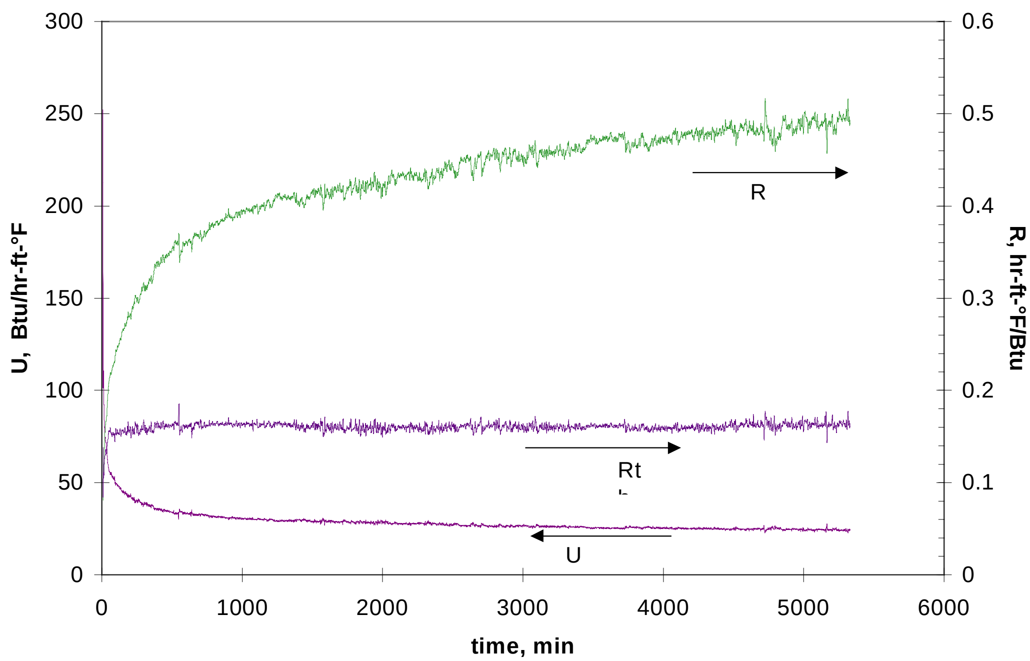


**Figure 5.** Pseudo-thermal resistance trends for CG 111 grout.

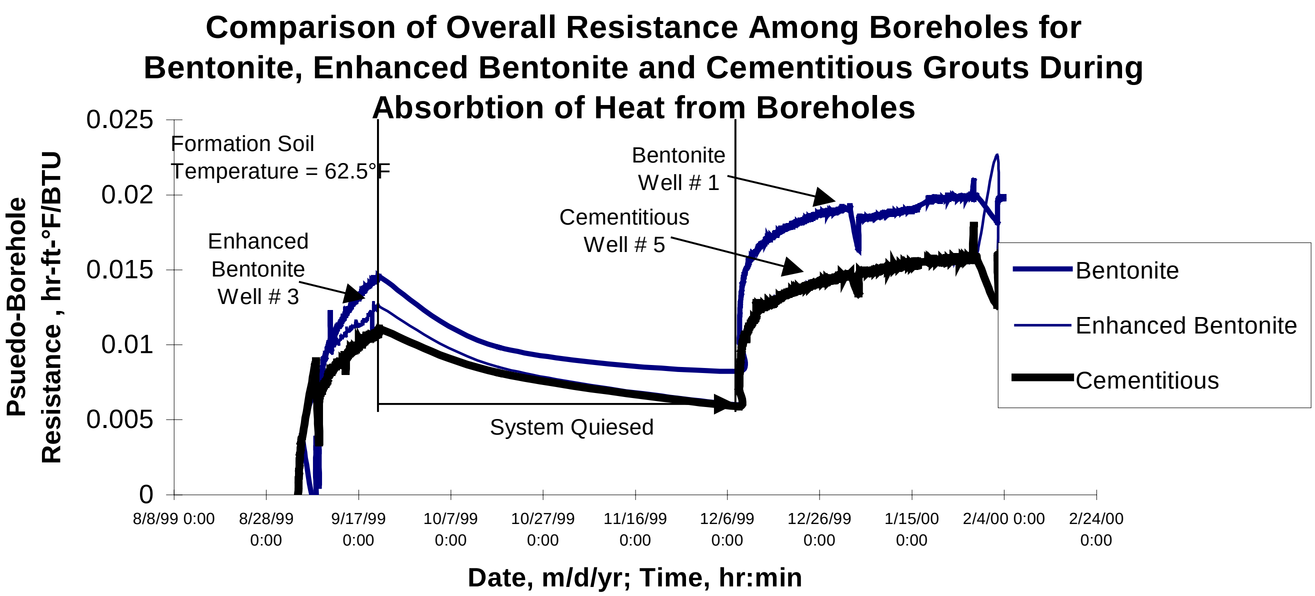


**Figure 6.** Comparison of Overall Resistance.

# GEOTHERMAL HEAT PUMP PROGRAM

Patrick J. Hughes, John A. Shonder
Oak Ridge National Laboratory

## KEY WORDS

geothermal (ground source) heat pumps; energy, demand and maintenance savings of Geo-Exchange systems; borehole heat exchanger design; soil/rock formation thermal properties measurements; building energy analysis

## PROJECT BACKGROUND AND STATUS

The U.S. Department of Energy (DOE) and other Federal agencies have long recognized the potential of geothermal heat pumps (GHP) to reduce energy use and pollutant emissions associated with building space conditioning. The Energy Policy Act of 1992 acknowledged this, citing the technology in seven different sections (3013(1), 2102(3A), 103(a), 106(c), 112(a), 114(2) and 1202(H)). A 1993 report by the U.S. Environmental Protection Agency (EPA) comparing 11 emerging technologies found that GHPs, in all areas of the country, have the lowest annual operating costs (including annualized capital costs), the lowest energy use and the lowest emissions, when compared to established space conditioning technologies. Despite these benefits, however, barriers still exist to the wider application of GHPs in the U.S. One has been a lack of hard data from unbiased third party organizations documenting the energy, demand, load factor, maintenance and financial benefits of GHP systems. Another has been the lack of accurate representations of GHPs and their energy use characteristics in standard building energy analysis tools, both at the feasibility level, and at the level of design. Finally, the tools available to design GHP systems are not at the same level of development as the tools used to design other space conditioning systems. Research being carried out at the Oak Ridge National Laboratory (ORNL) seeks to reduce or eliminate these barriers.

## PROJECT OBJECTIVES

### *Technical Objectives*

- Collect and disseminate statistically-valid data establishing the energy, demand, maintenance, and financial benefits of GHPs in federal buildings, schools and other common applications.
- Develop improved representations of the energy-use characteristics of GHPs and associated equipment in standard building energy analysis software such as DOE-2.
- Develop improved software tools for the design of borehole heat exchangers (BHEx).
- Identify reliable methods of determining soil/rock formation thermal properties from short-term in-situ tests.

### *Expected Outcomes*

- Energy savings, cost savings and reduction of pollutant emissions through more widespread use of GHPs.
- More reliable and cost effective GHP designs due to improvements in design tools.

- More accurate in-situ determination of soil/rock thermal properties, leading to GHP designs that are more reliable and more cost-effective.

## APPROACH

ORNL's general approach has been to identify technical issues important to the GHP industry, and to rationally select field sites with existing or planned GHP systems for use as data sources to address these issues. The data is used both to document the benefits of GHP systems at the site and to perform engineering analysis to address the issues identified. The initial site was Fort Polk, Louisiana, where GHPs were installed in 4,003 residences under an energy savings performance contract (ESPC). Data from an additional residential site in Madison, Wisconsin was also obtained. To address technical issues associated with larger commercial sites, data was obtained from four identical elementary schools in Lincoln, Nebraska that are heated and cooled by GHPs. The Lincoln schools, and another school in Tennessee, are the focus of a major effort to document the cost, energy and maintenance benefits of GHPs in K-12 schools.

## RESEARCH RESULTS

**Evaluation of the Fort Polk Retrofits.** The GHP industry recognizes that its growth has been limited by the lack of sufficient hard data from unbiased third party organizations documenting the benefits of GHP systems. The evaluation of the Fort Polk project, in which 4,003 residences were retrofit with GHPs and other energy conservation measures, has provided the industry with a wealth of information on the largest GHP project in the world. The key results of the evaluation include statistically-valid documentation of the energy and demand baseline and savings, verification of the maintenance baseline and savings, and verification of the financial value of the project. These findings have been widely disseminated in reports, technical papers, brochures, and presentations at industry conferences and meetings of professional societies. The credibility of the evaluation was a major factor in the implementation of FEMP's GHP-specific Super ESPC, which will enable ESCOs to finance $500 million worth of GHP projects at Federal sites.

**Determination of soil formation thermal properties.** BHEx-based GHPs depend on heat transfer to the soil/rock formation for efficient operation. In general, the rate of heat transfer depends on the thermal properties (thermal conductivity, density and specific heat) of the formation at the site. The GHP industry sees the lack of accurate localized information on formation thermal properties as one handicap in its competition with less-efficient conventional HVAC systems that exchange heat with outdoor air. To overcome this problem, the GHP industry has developed commercial services to perform short-term in-situ tests during project design to determine local soil/rock formation and bore backfill thermal properties. The Fort Polk evaluation determined that commercial services available when that project was designed were not reliable, and there is a continuing lack of consensus in the industry as to the methods used for collection and analysis of short-term test data. At the urging of the GHP industry, ORNL established a program to identify reliable, statistically-valid data collection and analysis protocols. Active ORNL participation in ASHRAE committees has resulted in significant leveraging of DOE funds in this area, as ASHRAE will shortly be funding a project to develop a standard for in-situ measurement of soil/rock formation thermal properties.

Also at industry request, ORNL has established a program to test commercial services against known benchmarks so that the GHP industry, design engineers, and customers can have confidence in their results. In this program the benchmarks are developed from data from operating GHP systems and from the laboratory-based box tests conducted by IGSHPA using known soil/rock formation and bore backfill materials.

ORNL has also developed a new method of analyzing data from short-term field tests. Using statistical techniques, the method not only provides estimates of the properties, but also gives confidence intervals for the property estimates. This is important because one of the areas of disagreement in the GHP industry has been the required duration of an in-situ thermal properties test. The method developed by ORNL shows that, as expected, the required duration depends strongly on the level of accuracy desired.

**Benchmarking of BHEx design methods.** The GHP industry believes that another handicap in their competition with less efficient conventional HVAC systems that exchange heat with outdoor air is that design engineers have better vendor support for sizing of conventional HVAC system components than they have for sizing the BHEx. To overcome this problem, the GHP industry has been encouraging the development of better BHEx design methods for years. Using the data from the Fort Polk evaluation, ORNL developed a calibrated, research-grade engineering model of a residence, a GHP and the associated vertical borehole ground heat exchanger. The model was used to compare five commercially-available BHEx design methods. The results were unsettling: even with consistent inputs from the calibrated model, there was a large variation in the heat exchanger lengths recommended by the programs – as much as 87% between the shortest and the longest design. As a result of this comparison, improvements were made in a number of the design methods by the developers, and a new comparison was performed by ORNL using the updated programs. Figure 1 shows the dramatic improvement in these design methods since the original comparison. Additional comparisons have also been carried out for the Lincoln schools, the Virginia Beach Navy buildings, and the Madison, Wisconsin residence.

**Benchmark of mainstream building energy analysis (BEA) methods:** The GHP industry has also stated that they are handicapped in their competition with less efficient conventional HVAC systems that exchange heat with outdoor air, because mainstream building energy analysis methods such as Trane Trace 700/System Analyzer, Carrier E-20, DOE-2/PowerDOE, and BLAST either lack representations of GHP systems or the representations are inadequate. Since these widely used software programs are controlled by equipment manufacturers that derive nearly all of their revenue from the sale of conventional HVAC equipment, or by Government agencies, the GHP industry has been unable to address the problem. At industry urging, ORNL established a program to represent GHP systems in the public domain TRNSYS program, and then to calibrate TRNSYS with data from monitored sites. TRNSYS is then available to serve as a comparative benchmark for the other methods. The initial focus has been on DOE-2. A detailed analysis of DOE-2's GHP model has been carried out using the data from one of the Lincoln schools. ORNL is working with the software publisher to correct the deficiencies identified in both the BHEx and the GHP models in DOE-2 and its derivative, PowerDOE.

**Evaluation of GHPs in K-12 Schools.** Both the GHP industry and the Department of Energy have identified K-12 schools as an important potential market for GHPs. Consequently, ORNL initiated a cooperative agreement with the school district of Lincoln, Nebraska to determine the energy, demand, maintenance and financial benefits associated with GHPs as compared to conventional HVAC equipment. The school district has provided a wealth of data on energy use, repair, service, and maintenance requests, both for four new, identical elementary schools served by GHPs, and for 20 other schools in the district served by a variety of other HVAC equipment. ORNL began its evaluation of GHPs in schools in early FY98 and with FY99 funds will complete the report(s) documenting the effort. The report(s) will address energy, demand, load factor, maintenance, financial, and comfort benefits to school districts of owning and operating GHP schools, based on a detailed evaluation of 4 GHP schools and significant evaluation of about 50 conventional schools in Lincoln NE. Also included in the report(s) will be more general comparisons of energy use in GHP K-12 schools versus conventional schools in several other areas of the country where data exists.

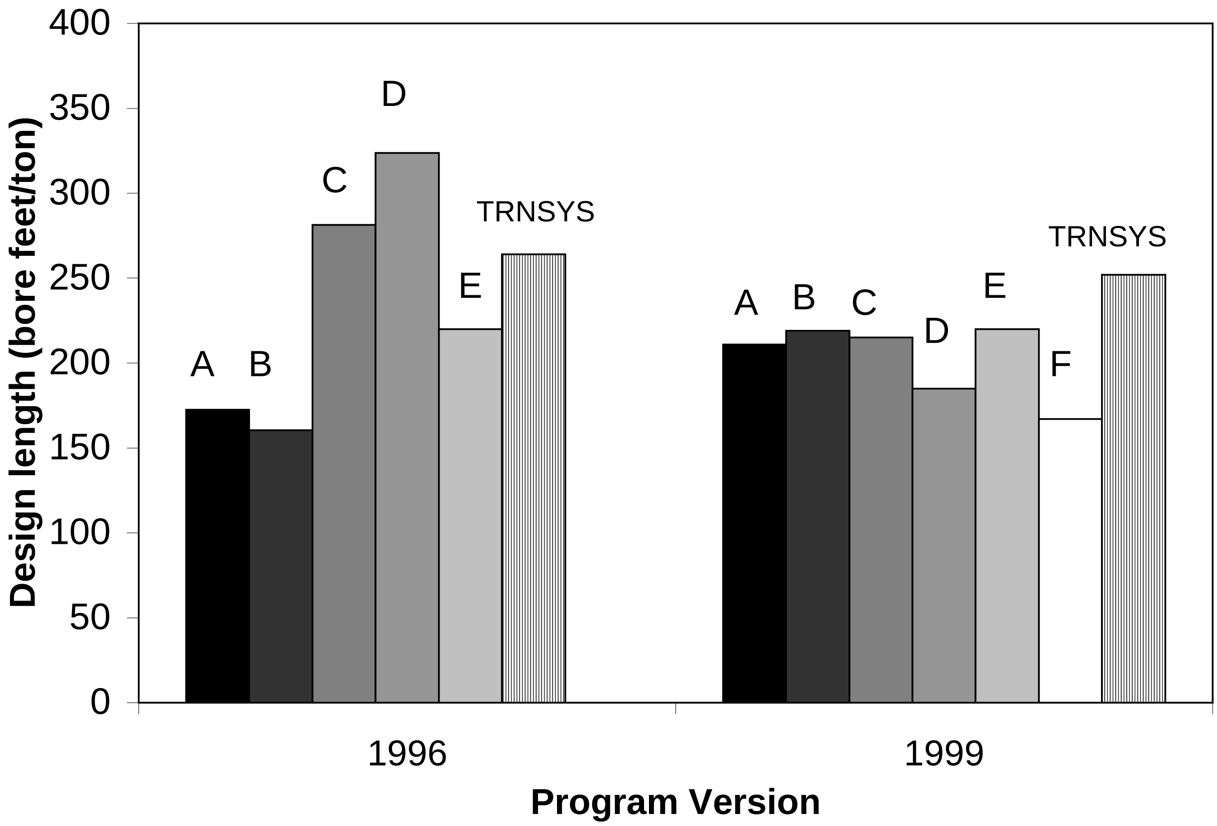


**Figure 1.** Comparison of recommended heat exchanger lengths from 1996 and 1999 versions of five commercially-available design programs, and benchmark.

## FUTURE PLANS

ORNL will continue to work closely with the GHP industry to identify research topics which meet the industry's needs. These may include, but are not limited to, areas such as the evaluation of design tools for hybrid GHP systems, surface water loops, and standing column wells; and improving the representation of GHPs in other building energy analysis software packages such as Trane Trace 700/System Analyzer, Carrier E-20 and BLAST. A major collaborative effort is also planned between this program and the FEMP GHP-centered Super ESPC. Possible outcomes include statistically-valid guides to installation and maintenance cost estimating, a survey guide for educating energy auditors so that GHPs are considered when appropriate, a feasibility study guide to educate engineers so that GHPs are selected when appropriate, generic preventative maintenance plans, generic guide to system commissioning, and a set of generic guide specifications covering a broad range of GHP systems and applications.

## INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

**FEMP and Federal Agencies: Fort Polk Evaluation.** Super ESPCs are contracting vehicles that allow Federal agencies to tap private expertise and financing from energy service companies (ESCOs) to make energy efficiency improvements in their buildings. The Fort Polk evaluation provided such convincing proof of the benefits of GHPs to Federal agencies that FEMP has awarded GHP-specific Super ESPCs that will enable agencies to implement $500 million worth of GHP projects.

**ASHRAE, IGSHPA, GHPC, GHP Manufacturers – Fort Polk and Lincoln Schools Evaluations, Borehole Heat Exchanger Design Method Benchmarking, In-Situ Test Method Benchmarking, Building Energy Analysis Method Benchmarking** Over two dozen presentations of ORNL results have occurred at industry conferences. There have been 17 peer reviewed technical publications. ASHRAE has spent, or is committed to spending, over $400,000 on GHP research defined or managed in part by ORNL staff.

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## CONTACTS

Raymond Fortuna
(Raymond.Fortuna@ee.doe.gov)
U.S. Department of Energy
Office of Geothermal and Wind Technologies
Forrestal Building
1000 Independence Avenue, S.W.,
Washington, DC 20585
Telephone: 202-586-1711
Fax: 202-586-8185

Patrick J. Hughes
(hughespj1@ornl.gov)
Oak Ridge National Laboratory
P.O. Box 2008
Bldg. 3147, MS-6070
Oak Ridge, TN 37831-6070
Telephone: (423) 574-9337
Fax: (423) 574-9329

John A. Shonder
(shonderja@ornl.gov)
Oak Ridge National Laboratory
P.O. Box 2008
Bldg. 3147, MS-6070
Oak Ridge, TN 37831-6070
Telephone: (423) 574-2015
Fax: (423) 574-9329

Michaela Martin
(martinma@ornl.gov)
Oak Ridge National Laboratory
P.O. Box 2008
Bldg. 3147, MS-6070
Oak Ridge, TN 37831-6070
Telephone: (423) 574-8668
Fax: (423) 574-9338

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