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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

OVERVIEW

Research and development (R&D) in Geothermal Energy has been conducted, on a national scale, since 1971 under the supervision of the Department of Energy (DOE) and its predecessors. To develop the technology needed to harness the Nation's vast geothermal resources, DOE's Geothermal Division oversees a network of national laboratories, industrial contractors, universities, and their subcontractors. The following mission and vision statements guide the overall activities of the Geothermal Division.

Mission

In partnership with industry and other stakeholders, plan and manage a balanced program of research, development, and demonstration that will stimulate an expanding use of geothermal energy for environmentally sound electric power generation and direct-use applications.

Vision

- ☐ *Achieve full competitive status for the geothermal industry in domestic markets.*
- ☐ *Maintain leadership for the U.S. geothermal industry in world markets.*
- ☐ *Gain recognition of geothermal energy as abundant, reliable, economic, and environmentally beneficial.*

This *Federal Geothermal Research Program Update* reviews the specific objectives, status, and accomplishments of DOE's Geothermal Research Program for Federal Fiscal Year (FY) 1994. The information contained in this *Research Program Update* illustrates how the mission and vision of the Geothermal Division is reflected in each R&D activity. The Geothermal Research 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 vision, the Geothermal Research Program is currently designed to serve two broad purposes: 1) to assist industry in overcoming near-term barriers by conducting cost-shared research that allows geothermal energy to compete in today's aggressive energy markets; and 2) to undertake fundamental research with potentially large commercial payoffs.

Since the inception of the Geothermal Program, the Federal Government and private industry have worked closely together — in promising new research directions, as well as 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 research program. This joint strategy serves to increase geothermal energy's role in the U.S. electric utility sector.

The five categories of work used to distinguish the research activities of the Geothermal Division reflect 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 Program 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. The 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. Cost-shared exploration will facilitate discovery of new geothermal fields in the Basin and Range Province. Deep drilling at Long Valley offers new insights into the nature of young silicic volcanic centers and also serves as a testing ground for new drilling and logging equipment.

Drilling Technology:

Drilling and completion of wells for exploration, production, and injection account for 35 to 50 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. The Drilling Technology projects focus 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 two 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 also being field tested. Advanced drilling bits are under development. Slimhole drilling, which might reduce exploration 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 measurements-while-drilling are also in progress. Technology for geothermal heat pump ground loops is being improved.

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. The 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 and hot dry rock reservoirs.

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 caused by different chemical reactions have improved markedly with the ongoing research in brine chemistry. Long-term flow testing of the Fenton Hill heat mining site has enabled data gathering that will facilitate commercialization of the technology. Efforts are also underway to minimize reservoir depletion at The Geysers and extend the resource lifetime.

Conversion Technology:

The three conversion technologies in current use for electricity generation are: 1) Dry steam conversion, such as that used at The Geysers geothermal reservoir in California since 1960; 2) Flash steam plants, favored for liquid-dominated or two-phase resources when the resource temperature is over 150°C

(360°F); and 3) Binary cycles, favored for moderate resource temperatures in the range of 100° to 150°C (200°F to 360°F). Dry steam and flash 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. The Conversion Technology research focuses on reducing costs and improving binary conversion cycle efficiency, to permit greater use of the more abundant moderate-temperature geothermal resource, and on the development of materials that will improve the operating characteristics of many types of geothermal energy equipment.

Increased output and improved performance of binary cycles will result from investigations in heat cycle research. High-temperature, scale-resistant, corrosion-resistant, and thermally-conductive liner materials are being developed for fluid transport systems, heat exchanger applications, and energy conversion processes. CO₂-resistant well cements able to withstand the aggressive chemistry of certain geothermal fluids are also under development. Biotechnology solutions for geothermal waste disposal problems are being developed. An ongoing assessment of U.S. low-temperature geothermal resources will facilitate increased use of these abundant resources for direct heating and heat pump applications.

Environment:

This category covers aspects of environmental, health, and safety research. During FY 94, the Heat Cycle Research Facility in the Imperial Valley, California, was decommissioned, and studies were made of possible commercial uses of the silica byproduct of some geothermal power plants.

MAJOR RESEARCH ACCOMPLISHMENTS IN FY 1994**Exploration Technology:**

- Steady progress was made in improvements of magnetotelluric and electrical methods for geothermal exploration. Magnetotelluric surveys appear to be more valuable for specific structural studies late in the exploration process than for mapping deep regional conductors during early prospecting for geothermal districts. Interpretation software for two-dimensional resistivity surveys was improved. A significant field test was conducted of the cross-borehole resistivity method. All of these methods seek to improve the ability of geothermal explorers to understand variations in the underground characteristics of geothermal prospect areas.
- A project was initiated to assess the value of integrating remote sensing data from the Thematic Mapper satellite with ground data from geochemical and geobotanical anomalies, with respect to the detection of hidden geothermal reservoirs. Another project is evaluating the application of similar methods specifically in southeastern Oregon.
- A project was begun to relate what is known about the Coso, California, geothermal reservoir to detailed knowledge of the Mesozoic and Cenozoic structural and lithologic features of the area surrounding the reservoir. This case study will contribute to the improvement of generalized geothermal resource assessment methods.
- Seven of the ten western state teams participating in the Low-Temperature Geothermal Resources Assessment completed their inventory, database listings, and resource-occurrence maps. An

important aspect of the assessment is to identify more geothermal resources located near populated centers that could use the energy.

- In exploration and reservoir analysis studies, improved integration of a variety of geochemical measurements now enables engineers to distinguish regions of a reservoir that are still heating up from regions that are cooling down. This will help improve where geothermal production and injection wells are sited.

Drilling Technology - General:

- Comparison of data from a slimhole and a nearby production well at the Steamboat Hills, Nevada, geothermal reservoir confirmed that data from the slimhole were adequate to predict the performance of the production well at this reservoir. If this correlation can be extended to pairs of wells at other reservoirs, then the use of slimholes could substantially reduce the cost of geothermal exploratory drilling.
- Steady progress continued in projects to develop advanced synthetic diamond bits for hard-rock drilling. Work is being pursued on the design of polycrystalline diamond cutters and bits, impregnated diamond bits, and thermally stable polycrystalline bits. The expectation is that technology advances made here could double penetration rate and bit life, resulting in a 15 percent reduction in the overall cost for geothermal wells. Many of the advances expected here will be applicable to oil and gas drilling as well.
- Research to improve the detection of loss-of-circulation events continued to focus on measuring both the inflow and outflow of drilling fluids from wells. Reduction of noise originating from rig vibrations has emerged as an important research goal. This research seeks to reduce the cost of lost-circulation episodes by detecting the episodes very soon after they start.
- Development of methods to treat zones of lost circulation continued. The development of a laboratory-prototype drillable straddle packer was completed. The Packer Demonstration Facility needed for the next phase of testing and development was nearly completed at the end of FY 94. Planning began for field testing of cementitious muds (developed by Brookhaven National Laboratory and Halliburton Services) in cooperation with California Energy Company, Inc., and Halliburton Services.
- Development of memory-based tools for downhole measurements progressed rapidly. Extensive field tests were conducted using a pressure/temperature tool. A spectral gamma tool was run for the first time and detected fracture zones mineralogically altered by the deposition of water-soluble minerals. Detailed requirements were defined for a tool that will collect specimens of liquids and gases.
- Research on acoustic data telemetry concentrated on equipment development and continuing field tests. The length of the surface simulation facility was increased to 1400 feet. A mobile laboratory was acquired, outfitted, and used in a series of field tests of the acoustic transmission characteristics of production tubing. Researchers completed the initial layout of a new downhole transmitter design. The objective of this research is to markedly increase the data rates of measurement-while-drilling tools.

- The Geothermal Drilling Organization (GDO), cost-shared by the Department of Energy and industry partners, continued work on: improved positive displacement downhole motors for air drilling, new cement formulations for better casing protection in corrosive geothermal environments, adaptation of a retrievable whipstock to geothermal well conditions, development of rotating drilling head rubbers, and testing of cementitious muds for lost circulation control.

Drilling Technology - Geothermal Heat Pumps:

- Research continued to reduce the cost of the ground loop portion of geothermal heat pump (GHP) space-conditioning systems. A detailed survey of GHP vertical heat exchanger drilling techniques now in use around the country identified a number of practices that can be improved. This and other assessments will help to accelerate the use of GHPs nationwide.

Reservoir Technology - General:

- Significant fundamental data were collected in the domains of geochemistry and rock mechanics. Chemistry measurements focussed on the geochemistry of aluminum in high-temperature brines, salt effects on stable isotope partitioning, and behavior of aqueous fluids associated with granite melts. These data will be used to improve computer-simulation models of geothermal fluid chemistry. Basic measurements of the mechanical properties of rocks in The Geysers, California, reservoir will be used to improve signal processing in passive and active seismic surveys.
- The suite of user-friendly computer-simulation models of geothermal fluid chemistry, developed at the University of California, San Diego, were improved through enhanced simulations of: a broader range of temperatures and pressures for the H_2O - CO_2 - $NaCl$ system; H_2S solubility; enthalpy values; silica geothermometers; liquid-density brines to $250^\circ C$; and ammonia-water mixtures. These models are increasingly used by industry to solve problems related to scale deposition and reservoir behavior.
- Heat and mass transfer in hyper-saline geothermal systems continue to be studied using reservoir-simulation codes that include certain brine chemistry calculations. Current work focuses on understanding the relationship between chemical fronts and temperature fronts in the Salton Sea, California, reservoir.
- Researchers continued to devote substantial effort toward improving some of the fundamental relationships expressed within reservoir simulation models. Work in FY 94 included: measurements to improve the characterization of fracture-controlled porosity in active geothermal system; improving the equations in dual-porosity simulation models; measuring and modeling the effects of adsorption of water on rock; and coupling a wellbore simulator to a reservoir simulator to improve modeling of well-reservoir interactions. The Lawrence Berkeley Laboratory TOUGH2 simulation code was transported to personal computer platforms, to improve industry access to the TOUGH2 simulator.
- A case study of the Roosevelt Hot Springs geothermal reservoir was initiated in FY 94 with the cooperation and support of California Energy Company, Inc. (CECI), the operator of the field. CECI has made available almost 20 years of high quality data, including preproduction testing, the complete production history, and a calibrated numerical reservoir simulation model. This study

will contribute to a growing body of evaluations of the usefulness of various kinds of data and techniques for geothermal exploration, resource assessment, and reservoir management.

- A similar case study of a high-temperature geothermal resource in a fractured volcanic formation at Sumikawa, Japan, has been in progress since FY 1993. This case study emphasizes integration of multiple forms of data using a geothermal reservoir data management system and the correlation of flow data between slimholes and nearby production wells.

Reservoir Technology - The Geysers Reservoir:

- Analysis of the nature of controlling factors in the deep steam reservoir at The Geysers was about 80 percent complete at the end of FY 94. The "felsite" rock body is clearly the heat source for a vast high-temperature, liquid-dominated reservoir from which the modern steam reservoir evolved in recent times. More than 1000 samples of cuttings have been logged in detail and analyzed by various means to construct a database of maps for comparison with field-wide steam production characteristics. Results of the study will promote more efficient exploitation of steam reserves, and likely target new reserves for future drilling.
- The Geysers Coring Project in August and September 1994 collected 251 m of continuous core from the transition from the reservoir caprock into the steam reservoir. This nearly quadruples the amount of Geysers core available for study. Extensive analysis of core mineralogy and fluid contents will be conducted to learn more about the controlling factors in the reservoir.
- A number of projects continued to advance significant understanding of geochemical characteristics of The Geysers reservoir. These include: analysis of the temperature of formation and the gas contents of fluid inclusions to attain significant insights about the historical evolution of the reservoir; use of phase and reaction equilibrium analyses of noncondensable gases to explain and predict changes in the characteristics of produced steam; relate current distribution of noncondensable gases to the distribution of magmatic rocks in the high-temperature reservoir; and analysis of the volatility of HCl during brine dryout. All of these projects are expected to enhance industry's ability to produce steam and gain greater control of its chemical constituents.
- Evaluation and selection of new chemicals for use as vapor phase tracers at The Geysers continued, with an extensive tracer test at an injection well in the Southeast Geysers. The use of three tracers in the same test afforded improved insight into how injected liquid boils within the reservoir.
- Sophisticated mathematical analyses of seismic signals from microearthquakes in the Northwest and Southeast Geysers were conducted by two national laboratories in FY 94. Results to date indicate that such analyses can elucidate: the paths that injected fluids follow into the reservoir; the varying principal stress axes in the reservoir rocks; and the degree of steam saturation at various places in the reservoir. These studies are expected to be of great value to geothermal operators at The Geysers and other reservoirs, since they begin to reveal conditions within the reservoir from data collected entirely at the surface.
- Detailed analysis and modelling was performed of production history and injection tracer test data for the part of the Southeast Geysers reservoir that supports the Pacific Gas & Electric Unit 13 power plant. This included detailed tracking and determination of injection-derived steam issuing from each production well. Injection-derived steam is strongly influenced by reservoir shape and

structure. A similar study, using different methods, was conducted in the vicinity of Unit 18. The results will help industry select sites for future injection wells.

- Two projects continued to improve reservoir numerical-simulation codes for analysis of steam-dominated reservoirs. One project concentrates on simulating the effects of water injection. The other is modelling the formation of the "high-temperature reservoir" at The Geysers. Both projects will contribute to industry's understanding of where to inject fluids to better sustain long-term production.

Reservoir Technology - Other:

- Heat Mining research continued. The Fenton Hill test facility was maintained on standby status while results from the Long-Term Flow Test of 1993-1993 were further elucidated through refined analytical modeling. The Geothermal Division instituted efforts to find private-sector partners for an industry-led, Government cost-shared, commercial Heat Mining project.
- The Geothermal Technology Organization (GTO) continued to coordinate several of the projects described in this *Update*.
- International cooperation on reservoir analysis issues continued through the long-standing cooperative agreements with Mexico and Italy. In addition, DOE sponsored trade missions and technical contacts with international geothermal developers, especially in Central and South America and the Far East. In particular, an industry/DOE trade mission to Costa Rica arranged by the Deputy Secretary of Energy took place in June 1994.

Conversion Technology - Electricity Conversion Systems:

- Operation of an axial-flow impulse turbine and a radial-flow reaction turbine at the Heat Cycle Research Facility, Imperial Valley, California, confirmed that dry expansions, supersaturated expansions, and wet expansions of hydrocarbon vapor through the turbines are all feasible. The results are sufficiently encouraging that arrangements are being made for the extended operation of a turbine at a commercial plant at inlet conditions that will produce a supersaturated vapor during the expansion process.
- Operation of the Heat Cycle Research Facility concluded in the summer of 1994, and the facility was decommissioned.
- An analysis of engineering and costs of "Next Generation Geothermal Power Plants" was initiated in partnership with the Electric Power Research Institute (EPRI). Conditions under which dual flash plants, hydrocarbon-fluid binary plants, ammonia-water mixture binary plants, rotary separator turbines, and combustion turbine/binary hybrid plants are the optimal selection have been evaluated. The study performer, The Ben Holt Company, will release the final report in early 1995.
- A Cooperative Agreement between DOE and Exergy, Inc., to demonstrate an advanced binary geothermal power plant utilizing the Kalina cycle was signed near the end of FY 94. The Kalina cycle uses an ammonia-water mixture as the working fluid and takes advantage of regenerative

heating. The cycle is estimated to be up to 40 percent more efficient than existing binary geothermal power plants.

- A subscale rotary separator turbine was installed and operated on a slip stream of a production well at Coso Hot Springs, California. About 750 hours of testing were completed, measuring efficiencies of the turbine at various inlet fractions of steam. A hydro-blast descaling system was added to the system to solve silica-scaling problems that appeared late in the test series. Douglas Engineering is incorporating the results into its design of the full size rotary separator turbine that will be tested in the third year of this project. Rotary separator turbines are expected to increase the amount of energy that can be extracted from high-temperature geothermal fluids.
- Researchers began to develop a computer model to evaluate the technical performance and system cost impacts of various cooling and mixed-working-fluid options for binary geothermal power plants. The results will help industry attain better flexibility in the design and operation of cooling systems at geothermal sites where limited supplies of cooling water are available.
- Under a Cooperative Research and Development Agreement (CRADA) between Pacific Gas & Electric and the National Renewable Energy Laboratory, initial evaluation studies were conducted on the feasibility of retrofitting advanced direct contact condensers to one or more PG&E plants at The Geysers. A computer code for modeling direct-contact condensers, including chemical reactions, was developed and exercised to evaluate the operation of PG&E Geysers Unit 11.
- The Geothermal Power Organization (GPO) was organized in FY 94, and developed lists of prioritized research areas and high priority research goals important to the industry.

Conversion Technology - Materials Development:

- Field tests continued of polymer cement linings to prevent corrosion in steam production wellheads and steam transmission lines at The Geysers. Prototype sections of polymer coated finned-tube heat exchanger tubing for potential dry cooling tower applications were placed into test at The Geysers. Performance assessed to date indicate that the linings perform as desired to reduce corrosion.
- Laboratory characterizations for two new formulations for high-temperature CO₂-resistant lightweight cements have been nearly completed. Industrial collaborators (Halliburton Services and Unocal) are now participating in ongoing engineering-scale tests. These cements are expected to decrease costs for geothermal well completions due to reductions in lost circulation control episodes, and markedly increase the life of wells where geothermal fluids contain significant amounts of CO₂.
- Progress continued on the development of advanced biochemical process for the treatment of geothermal wastes and conversion of by-products to useful forms. Part of the work is now based on a CRADA between Brookhaven National Laboratory and CET Environmental Services.

Conversion Technology - Heat Pumps and Direct Heat:

- Sixty-five case studies comparing the performance of geothermal heat pumps (GHPs) to other energy sources were evaluated and compiled into a database. These data, will assist electric

utilities to promote GHPs in their service areas. Information was compiled from 35 utilities on their experience with GHPs as part of their Demand Side Management programs. Successes in deploying GHPs and continuing barriers to growth in use of GHPs nationwide. Cost comparisons of GHP's to other energy sources have been developed. The findings have been disseminated in a number of forms.

- The Geo-Heat Center of the Oregon Institute of Technology, Klamath Falls, continued to serve as a clearing house to provide technical assistance and information to those interested in the use of geothermal direct heat systems for space heating, process heat, greenhousing, etc. A study of failure modes of geothermal downhole production pumps in moderate-temperature service was begun in FY 94.

Environment:

- A project was initiated to invent additional commercial uses of the silica wastes that emanate from some geothermal power plants in Mexico and the U.S. Likely uses include both bricks for low-cost building construction and mixtures of silica and asphalt for paving low-volume roads.

EXPLORATION TECHNOLOGY

GEOCHEMICAL METHODS

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KEY WORDS

Hydrogeochemical models, Coso, Tiwi, tres virgenes, Steamboat Springs, fluid inclusions, hydrothermal alteration

PROJECT OBJECTIVES

Hydrogeochemical models form the basis for the exploration and development strategies used in the search of geothermal resources. During the early stages of an exploration program, these conceptual models are used to interpret geologic, geochemical, and geophysical observations and to site thermal gradient wells. Later, as new data are incorporated, these models are used to locate production and development wells. The current studies represent a continuation of work initiated at the request of the geothermal industry in 1989.

Technical Objectives

- Refine existing conceptual models of geothermal systems in specific geologic environments including granitic- and volcanic- hosted terrains.
- Characterize the physical and chemical boundaries within reservoirs in these geologic settings.
- Determine the extent and importance of different physical and chemical processes occurring within the reservoirs (e.g., boiling, mixing, conductive cooling, magmatic input).

Expected Outcomes

- Assist explorationists and developers in prioritizing potential resources and in targeting geothermal wells. The latter will reduce the number of dry holes drilled during the project.
- Provide information on the natural state of the reservoir needed for prediction of changes resulting from exploitation.

PROJECT BACKGROUND AND STATUS

During the past several years, significant progress has been made in improving our understanding of reservoir conditions, processes, properties and boundaries. For example, at Coso, California, where a large number of wells has been available for study, our investigations demonstrated that the thermal waters define an asymmetric plume that originates in the southern part of the field and then flows laterally to the north (Moore et al., 1980). Subsequent investigations have shown that even small amounts of

argillic alteration caused by the interaction of the thermal and ground waters can lead to substantial decreases in reservoir permeabilities (Moore et al., in preparation), although it was not established at that time whether other geologic factors such as rock type also influenced the geometry of the reservoir. In addition, we have been able to separate regions of the field that are still heating up from those that are cooling by comparing fluid inclusion and measured temperatures. The possible effects of rock type on the reservoir has been the focus of our current efforts on this system.

Studies of Steamboat Springs, Nevada, Tres Virgenes, Mexico, and Tiwi, Philippines, have been directed toward evaluating the source, properties, and distribution of the fluids within these reservoirs. All three systems are associated with recent magmatic activity, although it is not yet known whether this activity has provided more than just heat to the systems at Steamboat Springs and Tres Virgenes. In contrast, corrosive acid fluids formed by the condensation of volcanic gases at depth have been found at Tiwi. Fluid inclusion, isotopic, and mineralogic studies are currently in progress. These techniques provide information on parts of the reservoir that cannot be sampled directly. Thus, they provide data complementary to that obtained from chemical analyses of springs and well bore discharges.

One of the important conclusions of our recent studies was the observation that CO₂ contents of the reservoir fluids at Zunil, Guatemala, and Los Azufres, Mexico, are strongly zoned and closely related to the geometry of these reservoirs (Moore et al., 1992). The need for a more quantitative assessment of the gas contents of fluid inclusions trapped in geothermal systems led us to investigate the application of quadrupole mass spectrometry as an analytical technique. The utility of this technique was recently demonstrated in studies of The Geysers (Norman and Moore, 1994), Tiwi (Lutz and Moore, 1994, unpublished data), and the Valles Caldera (Musgrave and Norman, 1994). The measurement of fluid inclusion gas contents from several of the systems under investigation is currently underway.

Geologic investigations of Coso, and those of Tres Virgenes and Tiwi, were initiated in FY 94 while work at Steamboat Springs is part of an investigation begun in FY 93. The work on this project is approximately 50% complete. It is anticipated that studies of well LV-3 at Tres Virgenes and Matalibong 25 at Tiwi will be completed in FY 95.

APPROACH

The approach we have taken is one that integrates data on rock and mineral distributions with the results of petrologic studies and chemical analyses of the thermal fluids. This approach has been followed for each of the geothermal fields studied and can be summarized as follows:

1. Determine rock and mineral distributions and their relative ages using petrographic, X-ray diffraction, and scanning electron microscope techniques as appropriate. This work has been supported by the geothermal operators who have provided cuttings and cores, temperature and pressure surveys, production depths, chemical analyses, and other supporting data as needed. Data has been supplied by California Energy Company Inc. (Coso), Unocal (Tiwi), Far West Capital and Caithness (Steamboat Springs), and the Comision Federal de Mexico (Tres Virgenes).
2. Conduct microthermometric measurements on fluid inclusions to establish apparent salinities, temperatures, and gas contents. The data are interpreted using computer models developed by Adams (unpublished algorithms) and Brown (1989).

3. Quantify the gas compositions of the inclusion fluids using quadrapole mass spectrometry. This work is being done in collaboration with Dr. David Norman of New Mexico Tech.
4. Conduct isotopic analyses of rocks and minerals and combine these data with fluid inclusion analyses to characterize the isotopic compositions of the reservoir fluids.
5. Integrate fluid inclusion, chemical, and isotopic data to establish the physical and chemical processes occurring within the reservoir, the origins of the fluids, and possible directions of movement.
6. Combine the geologic and geochemical data to develop a conceptual hydrogeochemical model of the reservoir.

RESEARCH RESULTS

The present studies significantly expanded upon the results of earlier investigations. At Coso, we have documented the distribution of rock types and secondary assemblages in more than a dozen wells (Lutz et al., 1994a). Several different intrusive and metamorphic lithologies have been characterized. The data suggest that the igneous and metamorphic rocks behave differently within the reservoir and that the thermal plume is preferentially developed within the intrusive rocks. In several wells, the base of the intrusive rocks coincides with the 250°C isotherm determined from fluid inclusion data.

Studies of LV-3 at Tres Virgenes indicate that the geothermal reservoir is also developed in granitic basement rocks, despite the presence of a thick cover of more than 1000 m of volcanic and sedimentary lithologies (Lutz et al., 1994b). Alteration of the cap rocks resulted from interactions with fluids whose temperatures were less than about 200°C, as indicated by the clay mineralogy and the secondary mineral assemblages. Within the granite, the clay minerals are indicative of higher temperatures.

Mineralogic and fluid inclusion data from Steamboat Springs and Tiwi show evidence of complex histories. Studies of core hole TH-2 at Steamboat Springs has documented an early period of hydrothermal brecciation within the reservoir that was followed by multiple periods of quartz and calcite deposition. Fluid inclusion homogenization temperatures show that these minerals were deposited by fluids with temperatures and salinities similar to those of the waters currently being produced. The gas compositions of selected samples suggest that the fluids had boiled extensively.

At Tiwi, studies are being conducted on core hole Matalibong 25, which was drilled near the upwelling center of the field. This well reached a depth of 2439 m and encountered temperatures near 280°C. The core is highly mineralized and brecciated. Petrographic data indicate an early period of propylitic alteration that was followed by the influx of slightly acidic waters which deposited calcite and sericite. Fluid inclusion data has been obtained on several samples of vug filling minerals. Apparent salinities of these inclusions ranged from near 0 equivalent weight percent NaCl at 278°C, suggesting that the fluids represent trapped steam condensate, to approximately 1.7 equivalent weight percent NaCl. These higher salinities correspond closely to the present composition of the reservoir fluids.

FUTURE PLANS

We plan to continue our examination of these systems. Additional fluid inclusion measurements will be conducted on samples from Steamboat Springs, Tiwi, and Tres Virgenes. Our studies of Tiwi are

particularly interesting because this is a large, extensively drilled field in a volcanic terrain. We anticipate being able to expand our studies to include other parts of the system. Additional data on volcanic systems will be obtained from Meager Creek, Canada, as the drilling progresses.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Caithness California Energy Company, Inc. Comision Federal de Electricidad Far West Capital Unocal	Development of better models for the exploration of new fields and the optimum exploitation of their operating resources. All have provided contributions in kind.

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GEOPHYSICS RESEARCH - SELF-POTENTIAL STUDIES

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KEY WORDS

Self-potential, field studies, hot springs, exploration

PROJECT OBJECTIVES

The objectives of this project are to continue the evaluation of the Self-Potential (SP) method as a cost-effective technique for the geothermal exploration of covered areas, especially in the Basin and Range Province, and to assist state resource teams in the delineation of fluid upflow zones for resources nearing or in development.

Technical Objectives

- Complete detailed field surveys over selected resources of interest to state teams and/or potential developers which have sufficient supporting data to contribute to an understanding of the self-potential response.
- Complete qualitative and quantitative interpretations of the SP and supporting data, and present the results.
- Examine geologic and recording noise problems that confuse the SP expression of thermal systems, and reduce confidence in SP surveys as low-cost exploration tool.

Expected Outcomes

- Determine specific target areas for more costly geophysical studies or drill testing as possible fluid upflow zones.
- Build more widespread acceptance as a cost-effective exploration technique for low- and moderate-temperature resources.
- Reduce drilling cost for direct-heat users such as greenhouses and industrial heat users.

PROJECT BACKGROUND AND STATUS

The Self-Potential (SP) geophysical method is an established geophysical technique used since the 1800s for mineral exploration. The method, which measures naturally occurring voltage differences at the surface of the earth, has been used increasingly for engineering, hydrologic, environmental and geothermal applications since the early 1970s. Although SP anomalies have been observed at many geothermal systems, the expression may be positive, negative, dipolar or very complex. This mixed expression is confusing, and reduces confidence in, and use of, the method in geothermal resource

exploration and development. Theoretical studies generally support the occurrence of positive anomalies over geothermal upflow zones, but positive and negative anomalies are reported throughout the world over geothermal areas.

APPROACH

The objectives will be obtained by completing detailed SP surveys, thereby expanding the database of self-potential studies in geothermal areas, particularly covered areas or known low-to moderate-temperature resource areas where more expensive geophysical methods are not typically used.

RESEARCH RESULTS

Recent studies by UURI and state teams have mapped well-defined minima in close association with fluid upflow in Utah and New Mexico. Several systems have been mapped in some detail (Newcastle, Wood's Ranch, Thermo, Meadow Hatton, and Abraham Hot Springs, Utah; Rincon and Radium Springs, New Mexico) and survey results presented at the Geothermal Resources Council (see references). The dominant expression of these resources, using station spacings of 60 m, 30 m, or smaller, is an SP low. More recent results (Ross et al., 1993) show both positive and negative anomalies associated with two major hydrothermal systems with surface expression in Utah.

Self-Potential research was inactive during much of 1994 due to conflicts with higher priority (time-dependent) projects and to health problems. Progress was made on the statistical analysis of SP data taken under a wide variety of surface conditions at Pilgrim Springs, Alaska, and the interpretation of these data nears completion.

While at the Newcastle, Utah, geothermal area for temperature monitoring in May, Howard Ross and Robert Blackett (Utah Geological Survey) repeated two SP profiles across the Newcastle SP anomaly first mapped in November 1989. The observed anomaly minimum was only -78 mV compared to the -108 mV first observed in November 1989, but only slightly less than the -84 mV observed in June 1990. The anomaly amplitude has either decreased with time, or shifted laterally. Near-surface conditions (soil moisture and temperature) may reduce the observed anomaly in the spring. SP anomalies do change with time!

FUTURE PLANS

Plans for FY-95 include documentation and presentation of survey results from Nevada and from Pilgrim Springs, Alaska, and completion of surveys in Utah and New Mexico, as time permits. We intend to extend our statistical studies which seem useful in establishing typical SP responses for some near-surface geologic noise sources, and to expand our interpretation efforts. Some data have been transferred to Michael Wilt, Lawrence Livermore National Laboratory, for independent interpretation.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Oxbow Power Corporation	Siting drill targets at Carson Lake Prospect
The Geophysics Group	Methodology and SP technique development
Transpacific Geothermal	Methodology and SP technique development
ASARCO, Inc.	Siting drill targets at CAR leases, NV, and methodology and SP technique development
New Mexico State University	Possible power and greenhouse development at Rincon, NM; resource delineation
Utah Geological Survey	Geothermal exploration and resource delineation
Masson S.W. Inc.	Greenhouse development at Radium Springs, NM
Milgro, Inc.	Greenhouse development at Newcastle, UT
Pilgrim Springs Corp.	Possible development of Pilgrim Springs geothermal area, AK

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MAGNETOTELLURIC AND ELECTRICAL METHODS RESEARCH

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KEY WORDS

Magnetotellurics, electromagnetics, cross-borehole, instrumentation, algorithm

PROJECT OBJECTIVES

The general objectives of this project are to improve the methodology and interpretation of electrical geophysical techniques by making them more accurate, more efficient, and easier to implement so that they will be available for increased use by the geothermal industry and researchers. UURI has chosen to address the magnetotelluric (MT) and cross-borehole electrical techniques in particular.

Technical Objectives

- Improve the quality of MT field data through improved instrumentation and field techniques.
- Improve interpretation of MT and cross-borehole electrical data through new algorithm development.
- Demonstrate the improved capabilities of MT and cross-borehole methods through carefully selected field studies.

Expected Outcomes

- Demonstrate improved data quality and interpretation resolution.
- Increase use of the MT and cross-borehole techniques by industry, which will result in large savings in exploration and drilling costs.

PROJECT BACKGROUND AND STATUS

UURI has maintained a long-term (since the late 1970's) effort devoted to upgrading MT data acquisition and interpretation, and has received support from the National Science Foundation (NSF) and the Department of Energy (DOE) for this effort. UURI has developed and field tested a wideband MT system which includes simultaneous, dual-site measurement with each site acquiring five channels of electromagnetic (EM) field time series. Time series are transmitted in digital form via radio telemetry to the recording truck and processed in real time. Operation in the recording truck is carried out using an IBM compatible PC-80486 and a multi-tasking control program to prioritize individual jobs running under MS-DOS. UURI has taken a lead role in major crustal profiling studies completed in conjunction with other researchers, and these have been reported in the literature. The development of the MT system has been intended as insurance against the often fragile stability of MT contractors in the unsteady petroleum and geothermal exploration markets.

UURI has also had a lead role in the development of more efficient and accurate algorithms for the interpretation of electrical and electromagnetic (including MT) data for the geothermal, petroleum, and mining industries. Particular emphasis has been placed on developing two-dimensional (2-D) and three-dimensional (3-D) interpretation and inversion algorithms based on the integral equations (I. E.) method. These algorithms have demonstrated the resolution advantages of cross-borehole and borehole-to-surface resistivity and electromagnetic surveys for fracture detection.

The anticipated benefits of this research are reduced drilling costs and better evaluation of reservoir potential which reduce front end costs and facilitates better plant design. Reduced exploration costs and environmental impact stimulates regional scale exploration which will also facilitate integrated planning for power lines and markets. We estimate an additional power-on-line of 500 MW and an additional 200 acres of greenhouse development could be achieved by the year 2010 within the Basin and Range and Southern Rio Grande rift if significant cost reduction and risk could be achieved.

UURI has achieved the state-of-the-art in MT field instrumentation but seeks new advances in data acquisition efficiency and field noise reduction. We have designed a promising cross-borehole and borehole-to-surface resistivity/EM recording system and have completed the first field test of the method in a shallow, low-temperature environment.

APPROACH

UURI will continue to concentrate on the development of electrical geophysical techniques since they have broad applicability to mapping geothermal resources on both regional and detailed scales. UURI will continue to test existing methods, to improve techniques and equipment for gathering field data, and to improve interpretation algorithms and computer programs. Integrated geoscience interpretations will provide additional insight into these methods. Field surveys in developed areas and varying field conditions identify method limitations and practical resolution limits.

RESEARCH RESULTS

A schematic diagram portraying the broadband UURI field MT instrument (reported earlier) is shown in Figure 1. During field surveys in the eastern Great Basin, intercomponent EM interference was identified as the primary remaining problem in achieving an extremely low-noise MT instrument. In FY-94 UURI proceeded with the design, construction, and testing of through-normal and common-mode filtering stages for removing component EM interference in the MT field system. While this improves noise rejection and provides a rigorous circuit design, complete noise removal necessitated additional separation of field system components. In particular, coil-signal conditioner interference was cured with separation approaching 100 m. Radio modem communication cables were lengthened to 40 m as well to ensure against broadcast interference, and very low noise results were then obtained. A new base station power supply was developed to integrate base lap-top and radio-modem power and charging operations to allow complete, battery powered operation in the field. The electric field preamplifier module was redesigned, constructed, and tested to provide better high frequency performance, cultural rejection, and capability for measurements in high source impedance environments.

The MT field system successfully completed substantial field trials in the NSF/CD supported 560 km transect of the southern Appalachian orogenic belt, which proved to be a very high cultural EM noise environment. In August the MT field system began acquiring data across the Ruby Mountains core complex in north-central Nevada, again under the sponsorship of NSF/CD.

An extensive paper was prepared on our detailed MT investigations of the eastern Great Basin entitled "Anatomy of the southern Cordilleran hingeline, Utah and Nevada: inferences from deep resistivity profiling". The paper was submitted to the Geological Society of America Bulletin, revised and resubmitted for publication. Experience with MT in the eastern Great Basin strongly suggests little merit in mapping the regional deep conductor for prospecting for geothermal districts, as opposed to specific structural studies at a later stage in the exploration process.

Wannamaker completed 2-D resistivity sections for four detailed controlled source audio magnetotelluric (CSAMT) profiles of the extensive western Valles Caldera, New Mexico data set. This effort made extensive use of interpretation software for 1-D, 2-D, and 3-D resistivity modeling developed primarily under funding by DOE's Geothermal Division. Wannamaker also carried out development of his 3-D integral equations algorithm for simulating EM responses due to diverse sources. These included principally accuracy improvements in the secondary Green's functions which specify the field at a receiver due to a dipole of current in a layered earth. Low-frequency round-off error in loop-loop calculations was traced to an instability in a third-party Bessel transform routine. Improvements were obtained through double-precision calculation of the Bessel transform kernels and by determining a treatment for near-singular behavior of some kernels near the free-space spatial wavenumber. This involved doing a direct field evaluation for current source endpoint terms rather than a potential field evaluation.

Cross-borehole Resistivity Studies

UURI completed a borehole-to-surface direct current (DC) resistivity experiment in the Ferron Sandstone Member (Late Cretaceous), Emery County, Utah. The Ferron Sandstone has been the subject of numerous technical publications dealing with its fluvial-dominated deltaic environment. The availability of two 150 m drill holes and an extensive database made this area an appropriate low-temperature test of the UURI borehole resistivity system. The area between the two boreholes (roughly 500 m by 500 m) was covered by measurements with three different electrode configurations for each borehole. The field equipment performed to expectations and an extensive database was obtained.

The various resistivity data sets were reduced, plotted and resistivity maps prepared. Inspection of these maps for different electrode depths in each hole show dissimilar apparent resistivity distributions, with resistivity values that differ by as much as an order of magnitude. Preliminary interpretations suggest that the influence of a deep conductive layer is observed in some configurations. Quantitative interpretation continues using multidimensional resistivity inversion algorithms previously developed by UURI under DOE/GD funding.

FUTURE PLANS

Continued upgrade of the MT system is anticipated as new limitations of noise suppression and field efficiency are identified, but major field recording problems have been overcome. We plan to incorporate gradient resistivity/induced polarization (IP), magnetic IP, and downhole loop EM modeling with the 3-D integral equations algorithm for three components of source and receiver. Quantitative interpretation of the Ferron Sandstone borehole-to-surface data continues. We need to identify a moderate-to-high temperature geothermal area for our next test of this system.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
National Science Foundation	Crustal-scale MT surveys; MT equipment upgrades
Unocal - Geothermal Division	MT interpretation and equipment
Comision Federal de Electricidad	MT interpretation

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Figure 1. Schematic diagram portraying operational modes of UURI field MT instrument. Modes include 7-channel standard base-remote setup, 10-channel dual site collection, and 4-channel E-field profiling with 3-channel base H-field unit and remote reference.

TESTING THE USE OF REMOTE SENSING AND GIS FOR LOCATING HIDDEN GEOTHERMAL SYSTEMS

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KEY WORDS

Remote sensing, spectrometer, GIS, geobotany, geochemistry

PROJECT OBJECTIVES

The objective of this project is to test the use of remote sensing and geographic information systems (GIS) technology in the search for hidden geothermal systems in the western United States. As remote sensing data can be broken down into a hierarchy of components structured by spatial, spectral, and temporal resolutions, the study is based, in part, on a multitiered approach. The multitiered methodology allows the classification of remote sensing data at both the regional reconnaissance level and at a localized level. It is believed that the use of this multitiered approach will yield more useful information about surficial manifestations of hidden geothermal systems than the use of data produced from a single remote sensing platform. The remote sensing data is being coupled with ancillary data in a GIS system to allow modeling.

Technical Objectives

- Map faults, lineaments, and hydrothermal alteration from Thematic Mapper (TM) data.
- Map geochemical and geobotanical anomalies that are associated with, or that may be associated with, surficial and hidden geothermal systems using spectrometric methods.
- Create a GIS data base of the above data along with pertinent ancillary data for modeling and archiving purposes.

Expected Outcomes

- Develop a GIS database containing all of the classified regional remote sensing data plus all ancillary data. This will include lineament, hydrothermal alteration, and all ancillary data as discussed below.
- Develop a GIS database containing all of the local data. This will include all spectral, geochemical, and biogeochemical data. Anomaly probability contour maps will also be included in this database.
- Develop a geothermal probability map of the study area. This map will be based on the weighted factors included in the regional database.
- A comprehensive report detailing the methodologies used in the study and the results.

Expected Outcomes (continued)

- All of the above data will be stored on CD-ROM for maximum stability and distributability as public-domain data.

The successful outcome of this study will show the usefulness of remote sensing data in geothermal exploration. If the objectives are met with positive results, then remote sensing tools will enable cost effective and expedient exploration for geothermal indicators over wide areas. This study will also show the usefulness of GIS techniques in modeling the remote sensing data when coupled with ancillary data. The methodology developed from this project will allow similar exploration projects to be accomplished at a lower expense per unit area than most other exploration methods.

PROJECT BACKGROUND AND STATUS

Most developed geothermal areas originally exhibited surficial geothermal expressions that precipitated their discovery. New geothermal systems are presently being discovered in areas with no surficial manifestations. The discovery of these hidden systems has usually been the result water well drilling, mineral exploration drilling, or from testing geophysical anomalies. The crux of this project is to test the use of remote sensing and GIS techniques in the detection of subtle surficial features that might be associated with, and lead to the discovery of, hidden geothermal systems.

Certain surficial features and characteristics may be detected or associated with areas that have been subjected to thermal fluid flow, or in areas where thermal fluid flow is now occurring. These may include an increased density of fractures (lineaments and faults), geochemical anomalies, biogeochemical anomalies, and altered rock and soil mineralogy. Relatively small scale multispectral data, such as TM data, are useful in mapping lineaments, regional geologic structure, and areas of hydrothermal alteration that may be indicative of structures conducive to thermal fluid flow. Larger scale hyperspectral data, such as AVIRIS and hand-held spectrometer data, are utilized to detect subtle mineralogical changes in rock and soil, and geobotanical anomalies, which may be related to hidden thermal fluid circulation on a local level.

APPROACH

The plan for this study has been developed from knowledge gained from past studies done by the author relating to mineral and petroleum exploration. It is a hierarchical multitiered model based on the division of remote sensing data by resolution. It is tiered by the spectral and spatial resolution. Relatively low spatial and spectral resolution TM data is used to map regional features, such as faults, lineaments, and undifferentiated hydrothermal alteration.

High spatial and spectral resolution data from a portable spectrometer is being used on a local basis to determine if soil or geobotanical anomalies exist over known geothermal and hidden geothermal systems. These anomalies appear to exist. They are being tested and characterized through the use of multivariate techniques to quantify their relationship to soil and leaf chemistry.

The classified remote sensing data from both levels are being placed into a hierarchical GIS database for modeling along with ancillary data. The ancillary data includes geology, heat flow, seismic activity, geophysical, and mining district maps. These data are weighted according to their importance for probability modeling.

RESEARCH RESULTS

On a regional basis, several TM scenes depicting areas across the Great Basin have been downloaded and processed. Processing includes georectification to UTM coordinates, lineament mapping, and hydrothermal alteration mapping. Processed data has been converted to a GIS format and entered into a database. Specific processing procedures are discussed in last year's report.

On a local scale, spectral, geochemical, and biogeochemical data have been gathered at two locations in Nevada. The first, Kyle Hot Springs, is the site of two sinter terraces. One consists of travertine and is the site of a currently active hot spring. The other is a siliceous paleoterrace with no current surficial activity. The second site is located in Gabbs Valley. The Gabbs location is the site of a hidden geothermal system with no surficial indications of subsurface activity.

Transects were run across the systems at Kyle Hot Springs and Gabbs Valley. Data was collected at 0.1 mile intervals. Characterization of the data is currently in progress. It has been found that geochemical anomalies exist over both of the Kyle hot Springs sinter terraces. The anomalies were determined using cluster analysis with probabilities being generated by discriminant analysis. The overall accuracy of the mapped Kyle Hot Spring anomaly was over 78% with probabilities generally ranging in the ninetieth percentile. Verification was done through empirical observation of the site. Geochemical anomalies have also been mapped at the Gabbs Valley site. However, as no surface manifestations existed, only limited verification has been done at this time.

Biogeochemical data is currently being characterized and related to spectral data. Preliminary results using multiple regression techniques show that relationships may exist between soil chemistry components and certain spectral features in leaves.

FUTURE PLANS

Future plans will include the processing of several TM scenes for regional mapping. Gravity data will also be added to the regional database. After the database is complete appropriate multivariate techniques will be used to model probability of anomalies that may indicate hidden geothermal resources.

On the local level more spectral, geochemical, and biogeochemical data will be collected this spring and summer from known geothermal resource areas (KGRAs). Data will also be gathered from at least one area that is not presently a KGRA, but shows a high probability of containing a geothermal resource. This data will be used to determine the extent of which spectral data can be used to map soil and vegetation anomalies that are generated from geothermal activity.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	Spectral Geobotanical Analysis
BHP	Spectral Geobotanical Analysis
Asarco	Spectral Geobotanical/Soil Analysis

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MAPPING AND GEOLOGIC INTERPRETATION IN THE COSO GEOTHERMAL AREA

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KEY WORDS

Geologic studies, extensional features, strike-slip faults, Coso Range

PROJECT OBJECTIVES

The main aim of this study is to better understand the geologic development of the Coso Range, the site of the Coso Geothermal Area. The Pliocene to Recent volcanic rocks of the area are somewhat understood, but older rocks, mainly Mesozoic granitoids and their pendants which host the geothermal reservoir, are poorly known. In addition, there has been little systematic study of the structural geology of the area.

Technical Objectives

- Identify important structural geology features in the Coso Range.
- Determine the relative timing of major faults and intrusive events in the Coso Range.
- Evaluate the partitioning of strain in the area between strike-slip and normal faults active over the last 10 million years.

Expected Outcomes

- Understand the position of the Coso Geothermal Area relative to major Pliocene to Recent faults in the area. This is important for exploration models of the Coso Geothermal Area.
- Quantify the amount of extension recorded in the surface geology of the Coso Range. This will place limits on the amount of heat advected through structural unroofing and rise of geotherms.
- Understand the position of the Coso Geothermal Area in terms of the overall structure of the Basin and Range Province. This can aid in the development of geothermal exploration models for other areas of the Basin and Range.

PROJECT BACKGROUND AND STATUS

The Coso Range is located within the Mesozoic magmatic arc of the western Cordillera. Because of this, the bedrock geology of the region is dominated by Jurassic and Cretaceous plutonic rocks containing pendants of Paleozoic/Mesozoic metasedimentary strata. Previous investigations have only broadly delimited the extent and character of various pendant and plutonic phases. Pendant rocks, for example,

are grouped variously as metavolcanic or metaplutonic depending on the study (mainly by workers from California Division of Mines and Geology - CDMG - for large-scale maps of California), with little systematic study of protolith. Host plutons are also understood at the most rudimentary level. These plutons are characterized to be a composite intrusive complex consisting primarily of calc-alkaline granitoids with lesser amounts of gabbroic and alkalic intrusives. The most detailed published map of the area shows the plutons and pendants mainly as undivided igneous rocks (Duffield and Bacon, 1981). Important pre-Tertiary structural features transect the area. These structures are, at present, inferred to be part of the East Sierran thrust system that has been extensively studied by S.C. Moore (1976) and George Dunne (1978, 1986, 1993). The East Sierran thrust system is a belt of Jurassic, thrust-related deformation exposed in the southern Inyo, Argus, and Slate ranges. Structures associated with this belt are characteristically northeast- to east-vergent. Age controls are sparse, and structures are reported to range in age from approximately 185 Ma to 148 Ma suggesting that deformation was protracted over a period of at least 37 million years. In the central Argus and Coso ranges, rocks of the Sierran plutonic complex are cut by several southwest-dipping shear zones which are inferred to be cogenetic with the East Sierran thrust system although the exact nature and timing of these shear zones has not been evaluated. In fact, knowledge of the structural evolution of the study area, at least as far as East Sierran structures are concerned, is limited and on par with the understanding of the bedrock plutonic and pendant rocks.

The study area also resides in the Neogene to Recent Basin and Range Province. For this reason, it is cut by numerous normal and strike-slip faults of various orientations. These structures have not been studied in detail in the Coso Range. Movement history can partly be quantified where these structures interact with Pliocene volcanic rock. Elsewhere in the Coso Range, these structures are present only in the Mesozoic basement rocks. In these cases, understanding of the structures and intrusive history is critical to determining the kinematics of Basin and Range deformation: this is particularly true for the Coso Geothermal area, where volcanic rocks post-date much of the Cenozoic deformation.

Hence, any comprehensive model or understanding of the Coso area requires a detailed knowledge of both the Mesozoic and Cenozoic structural and lithologic elements of the area.

Work on this project started in June of 1994. The anticipated completion date is June of 1996. At present, about half of the study area has been examined (Figure 1). Samples have been collected and are being processed for age determinations. Samples for paleomagnetic analysis are also being gathered to understand the role of rotation and tilt in the development of the area. Structural and geologic data are currently being compiled and entered into a geographic data base. Ultimately, the structural data will be analyzed using a three-dimensional (3-D) geologic modeling program.

APPROACH

Field work follows normal practices of geologic mapping, e.g., walking the area to be studied and employing topographic maps aided by photographic or satellite images to delineate important geologic features. The crystallization ages of plutonic phases is currently being determined by U-Pb on zircon geochronology. Paleomagnetic poles are being determined for various igneous samples.

Mesozoic ductile deformation structures will be studied by normal petrographic techniques and polished slabs. Ages of deformation will be constrained variously by mineral isochrons, Ar/Ar thermochronology, or cross cutting relations depending of the geologic details present in the study area. Conditions of deformation and pluton emplacement will be determined through microprobe study of mineral assemblages.

Cenozoic faults will be understood by kinematic analysis using both the Mesozoic rocks and structures and Cenozoic rocks as markers. Where available, fault zone structures such as slickenside lineations and fault grooves will be used to determine fault motions.

Field work is primarily the responsibility of a University of Kansas graduate student, Richard Whitmarsh. All studies related to bulk rock geochemistry and isotopic signature, and crystallization and mineral geochronology will be done in the Isotope Geochemistry Laboratory at the University of Kansas (KU). Other studies will be done at Institutions where needed equipment is available (i.e., University of Missouri, Columbia for microprobe work and the Massachusetts Institute of Technology (MIT) for Ar/Ar studies).

About eight months of field work are anticipated to fully cover the proposed study area. Most of the effort will be spent on the Coso area. This is because the geology there is poorly known and both shear zones and intrusive relations are relatively extensive. Study of the other areas is more limited. Related laboratory work is less well partitioned, but will become clear once the field studies begin. Several months each of petrographic, isotopic, geochronologic, and geochemical work are anticipated.

RESEARCH RESULTS

Because the study has only started in the last 6 months, progress is still limited. Field work was done over the summer of 1994 and addressed problems related to the Mesozoic and Cenozoic geologic development of the area.

Mesozoic Geology

The Mesozoic plutonic complex of the southern Coso Range was mapped during the 1994 Summer field season (Figure 1). Many of the rock types that had been described by previous workers are now delineated on maps so that the internal structure of the plutonic complex may be analyzed. The western area is dominated by a mixed complex composed of gabbro, diorite, and granitic rocks. The granitic units, in particular, tend to occur as elongate, kilometer-scale segregations within the surrounding mixed complex, and both possess a subvertical foliation that strikes generally north to northwest. Locally, however, the foliation is oriented such that it dips moderately to the west. Several ductile shear zones have also been mapped, trending north-northwest, and kinematic analysis of these suggests that the area was subject to both east-west contraction and left-lateral shear at various times during the Mesozoic Era. In contrast, the areas to the east are underlain mostly by hornblende granodiorite, within which there are kilometer-scale inclusions of metamorphosed sedimentary strata that were mapped previously as metamorphosed volcanic rocks. Still other units that had been mapped as metavolcanic are now known to be shallow intrusive complexes that post-date the granodiorite. These shallow intrusives appear to be part of a suite of vertical dikes that trend west-northwest across the southern Coso Range, as well as the southern Argus Range. Furthermore, some of these dikes are demonstrably older than the shear zones described above, and hence they provide a critical datum for analyzing the structural development of the Mesozoic plutonic complex. Uranium and lead isotopes from several samples are currently being analyzed at KU in order to determine the absolute age relationships among these dikes, the rocks they intrude, and the ductile shear zones.

Cenozoic Geology

The older structure of the Mesozoic plutonic complex is being used to define the structures related to more recent deformation within the southern Coso Range. For example, the apparent offset of a

distinctive unit within the mixed complex suggests that there is approximately 1000 meters of vertical displacement along an east-dipping extensional fault that is exposed just to the east of Joshua Ridge. This fault may represent one of the older structures associated with the initial opening of Coso Basin, whereas the modern-day extension has produced cataclastic fracture zones along the western margin of the basin. Fieldwork has also elucidated numerous left-lateral displacements of older Mesozoic structures along subvertical faults that strike west-northwest across the range. It is expected that forthcoming paleomagnetic analyses will provide more quantitative estimate of the displacements related to extension, as well as a better understanding of how these fault systems are interacting to deform the range.

Future, anticipated results include:

- A detailed, small-scale (1:24,000 or better) geologic map which illustrates the structure and lithology of Mesozoic plutonic rocks exposed in the central Argus and Coso ranges. Particular emphasis will be placed on the distribution of the shear zones. In addition, this map will also show the major and important Pliocene to Recent structures.
- Evaluation of shear zones in terms of their kinematics and timing with respect to both the crystallization age of their host rocks and the timing of structures within the East Sierran thrust system.
- Understanding the intrusive history of Jurassic and Cretaceous rocks with respect to the development of the Sierran magmatic arc.
- Knowledge of the Miocene/Pliocene to Recent structures with transect the Coso Range and Geothermal Area.

FUTURE PLANS

Mapping is planned for December of 1994 and for the Summer of 1995. Additional samples for geochronologic study will be collected and analyzed. Ages will be determined for these sample during Fall 1995. In addition, structural analysis and analysis of paleomagnetic samples will be done over this period.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
California Energy Company	Geology of the Coso Range
Geothermal Program Office, China Lake	Geology of the Coso Range

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EXPLORATION FOR GEOTHERMAL RESOURCES IN FRONTIER AREAS OF SOUTHEASTERN OREGON

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KEY WORDS

Southeastern Oregon, geothermal resources, blind hot springs

PROJECT OBJECTIVES

The objective of this program is to locate new areas of geothermal resource potential in southeastern Oregon in order to stimulate exploration activity by industry. The project seeks to use geologic indicators of recent surface geothermal activity to locate blind or recently dead hot springs systems. An additional objective is to search for these resources in areas outside of existing Known Geothermal Resource Areas (KGRA's) and areas with obvious environmental concerns.

Technical Objectives

- Use air photo mapping of young faulting to locate areas of potential blind hot spring activity.
- Use satellite imagery to screen large areas for geochemical anomalies associated with past or blind hot spring activity.
- Use records of mineral exploration to locate alteration associated with Paleo hot springs activity.
- Field check target areas located by the above techniques to look for structural settings favorable to hot spring activity and alteration associated with paleo hot springs.
- Use detailed geochemical studies to characterize past geothermal activity.
- Recommend areas for future geothermal exploration.

Expected Outcomes

- Identify several new areas of geothermal resource potential which have minimal land use conflicts or environmental concerns and reasonable proximity to power transmission facilities.
- Develop a suite of indicators for blind or recent hot spring activity.

PROJECT BACKGROUND AND STATUS

This project began in 1993 as a joint project between Portland State University (Dr. Michael Cummings) and the Oregon Department of Geology and Mineral Industries (DOGAMI) (Dr. George Priest). Phase I of the project was funded by the Bonneville Power Administration, augmented in 1994 with funding from the U.S. Department of Energy (DOE) (EG&G Idaho PO # C94-170780, \$ 25,220), and a small (\$10,000) grant from Portland General Electric Company. Phase II has been proposed for 1995-96 with \$ 25,000 in funding from USDOE. Phase II should be complete in the spring of 1996.

APPROACH

Phase I focused on photogeologically identifying areas of recently active, closely spaced or crosscutting Quaternary faults along range fronts in southeast Oregon's Basin and Range. Air photos were used to map suspected faults, followed by field reconnaissance of promising areas. The field program involved reconnaissance mapping of photogeologically mapped features to determine which were faults and how recently each had experienced fault offset. The field program also included a search for wells suitable for temperature logging, alteration zones indicative of past hot spring activity and some local soil mercury sampling. In areas where geologic features looked promising, detailed mapping was carried out, along with a limited number of oxygen isotope analyses from hydrothermal minerals to estimate the temperature of paleo hot springs. Landsat (Thematic Mapper) imagery will also be examined to look for anomalies associated with known active hot springs and to search for similar anomalies in areas without known hot springs. Temperature logs collected from water wells were also compiled by Dr. David Blackwell of Southern Methodist University from this field work and from previous work by his research team.

RESEARCH RESULTS

Field work in 1993 was carried out by graduate students from the University of Oregon and Portland State University and centered largely on the location of potential temperature-gradient wells and study of alteration associated with active hot springs in southeast Oregon. Little Quaternary fault mapping was possible because air photos were not available until late in the field season. The air photos were interpreted over the winter of 1993-94 and possible Quaternary faults were mapped on ninety-two 1:24,000 quadrangles. Field work in 1994 was largely carried out by graduate students from the University of Oregon and University of Idaho, who evaluated the photogeologically mapped features along the northern Steens Mountains, Basque-Boghole Springs area, Catlow Valley, Guano Valley, Abert Rim, North Lake Abert area, Picture Rock Pass area and Winter Rim area (Figure 1). Of these areas, only the Basque-Boghole Springs area, north Lake Abert and Picture Rock Pass areas showed geologic features indicative of recent hot springs activity. The remaining areas showed little evidence of Holocene faulting, and no alteration associated with older Quaternary faults.

Basque-Boghole Springs Area

The most promising parts of this area are at Boghole Springs, an active hot spring in the Boghole Springs quadrangle, and at Mendi Gore Posue on the Basque quadrangle. At Boghole Springs, a small bedrock outlier is faulted against the Quaternary basin fill to the west. The fault, which is clearly Quaternary but not Holocene in age, is marked by extensive argillic alteration of the bedrock (of unknown age) and an active hot spring. At Mendi Gore Posue, there are numerous crosscutting NE and NW trending faults, of which one is clearly Holocene or latest Pleistocene, the remainder may be older than Quaternary.

Weak zones of quartz veining are associated with some of these faults. One well in Mendi Gore Posue has heat flow values of 96 mW/m^2 and well at Basque, just east of Mendi Gore Posue has heat flow values of 213 mW/m^2 (Peterson and others, 1982).

North Lake Abert Area

The area at the north end of Lake Abert is promising for geothermal potential because it is cut by closely spaced NE and NW trending faults, and has numerous Holocene travertine deposits and associated calcite veining in fractures in the fault scarps (or fault line scarps). The age of faulting is unclear, latest Miocene to early Pliocene Rattlesnake ash flow tuff is cut by all of the faults, and latest Pleistocene pluvial lakeshores are not cut. No deposits of intermediate age occur in the area. Travertine samples were analyzed for oxygen isotope ratios to estimate the temperature of the mineralizing fluids, and those results are pending. One well was temperature-logged, and has temperature gradient of 49°C/km for the bottom 65 m of a 115 m deep hole, a value that is low in comparison to regional values (Blackwell and others, 1978). This area has moderate potential based on the travertine mineralization, density of faulting, and proximity to transmission lines. However, more temperature profile data are necessary to determine whether the anomalously low gradient measured in the one well is representative.

Picture Rock Pass Area

The area immediately surrounding Picture Rock Pass on Oregon Highway 31 (Egli Rim quadrangle) is promising for geothermal potential because it has closely spaced crosscutting Quaternary faults, extensive alteration zones associated with faults, and is traversed by transmission lines. Numerous faults cut the Pliocene basalt bedrock (Figure 2) and many of the faults offset Pliocene or Quaternary channels, producing numerous ephemeral lakes by blocking the channels. Silica and carbonate mineralization occur in the channel gravels, and extensively in bedrock and colluvium along the steep east facing Egli rim escarpment which forms the southeastern margin of the Silver Lake Basin. Alteration mineral from several zones were collected and analyzed to estimate the temperature of the mineralizing fluids. Final analysis of the oxygen isotope data is pending, but preliminary calculations suggest that silica samples from the altered Holocene colluvium were deposited by water at approximately 70°C , strongly indicative of Holocene hot springs activity.

FUTURE PLANS

For 1995 and 1996 DOGAMI will continue the program with more detailed work at Picture Rock Pass, and further reconnaissance in several new areas. The Picture Rock Pass study will include temperature logging of several wells in the area (provided that access can be arranged), detailed soil mercury surveys to identify further areas of alteration, and coring of ephemeral lake sediments to put some constraints on the age of faulting.

At least three new areas will be studied with photogeology and field reconnaissance. Potential study areas are shown on Figure 3, and include the Durkee area near Baker City, the Stockade Mountain-Warm Springs Reservoir area, the Antelope Valley Graben, the Picture Rock Pass-Christmas Valley-Diablo Rim area and the north end Warner Lakes area.

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Figure 1. Location map of Southeast Oregon Showing 1993-94 study areas.

Figure 2. Geologic map of the picture rock pass area, after Walker and other, 1967. Box shows study area.

Figure 3. Location map of Southeast Oregon showing proposed study areas for 1995-96.

LOW-TEMPERATURE GEOTHERMAL RESOURCES RESOURCE ASSESSMENT

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KEY WORDS

Low temperature, direct use, state teams, resource inventory, Newcastle, sustainable

PROJECT OBJECTIVE

The objective of this program is to encourage increased utilization of the nation's low- to moderate-temperature geothermal resources and reduce our dependence on fossil fuels.

Technical Objectives

- Update the inventory of geothermal resources (20° to 150°C) in the West (initially ten states).
- Assist the Geo-Heat Center (GHC) of Oregon Institute of Technology (OIT) in a collocation study of resources and communities.
- Prioritize the more favorable resources for in-depth studies.
- Develop fact sheets and information that will encourage the increased use of geothermal heat pump (GHP) technology.
- Provide technical support for the sustainable development of the Newcastle geothermal resource.

Expected Outcomes

- An updated geothermal resource inventory will become available for ten western states. The data will be available in hard copy, a digital database, and a new resource map.
- A designated state agency or university group with current geothermal expertise will be available to assist community planners or industrial developers for these ten states.
- Those resources most suitable for near-term development will be identified and prioritized for additional technical studies.
- Technical data obtained through monitoring studies at Newcastle, Utah, will be available to aid in planning for long-term sustainable development of this resource.

PROJECT BACKGROUND AND STATUS

In 1991, Congress appropriated money for the Department of Energy (DOE) to begin a new program for the evaluation and use of low- and moderate-temperature geothermal resources, and for promoting geothermal heat pump technology. In FY 1992 EG&G-Idaho issued contracts to UURI, OIT, the Idaho Water Resources Research Institute (IWRRI), and OIT began subcontracting to the state resource teams which had been selected to complete the resource inventory. IWRRI is completing the resource inventory for Idaho. Figure 1 illustrates the geographic extent of this program.

UURI has coordinated efforts with the state teams to complete the digital databases, reports, and resource maps. UURI issued a revised water sampling manual and completed ten fluid chemistry analyses allocated to each state. UURI and the Utah Geological Survey hosted a meeting of the resource teams in Salt Lake City in July 1993 to standardize data formats and to resolve problems and procedures. UURI and OIT-GHC have reviewed reports, databases, and maps for errors and clarity.

APPROACH

State geothermal resource teams have reviewed and updated the geothermal resource inventories which were completed as part of the U.S. Geological Survey (USGS)-DOE national assessment from 1977 to 1983. Each state has prepared a comprehensive digital database in table format and a resource map at a scale of 1:1,000,000. UURI and OIT provided technical guidance and coordination, and UURI completed ten fluid chemistry analyses for each state. OIT has the lead role in a collocation study of resource occurrence and communities (or potential users), and the states, OIT, UURI, and IWRRI will prioritize resources for more complete studies. Promising resources for near-term development will be studied in more detail when Phase 2 funding becomes available.

A complimentary, but distinct, part of the program is directed toward educating utilities, contractors, engineers, and the public about geothermal heat pump technology. This is a cooperative effort between UURI, the Geo-Heat Center (OIT), and the Idaho Water Resources Research Institute. The portion of this program assigned to UURI was to produce fact sheets on commercial, residential, and institutional geothermal heat pump systems already in operation, and to host a local downsite for the Geothermal Heating and Cooling Teleconferences sponsored by DOE and others.

RESEARCH RESULTS

Low-Temperature Program

The state geothermal resource teams (State Teams) initiated their resource evaluation and database compilation efforts in late 1992 and early 1993 and have updated their resource inventories. Table 1 summarizes the catalog of more than 11,000 thermal wells and springs for these 10 western states, more than twice the number of the previous assessment in 1983. More than 900 low- to moderate-temperature resource areas are indicated, and perhaps a greater number of isolated (singular) thermal wells or springs. Direct-heat use of geothermal fluids is documented at more than 250 sites, including commercial and municipal buildings, rapidly expanding greenhouse and aquaculture industries and major space-heating districts in California, Oregon, Nevada, Idaho, and Colorado. More than 40 high-priority resource study areas have been identified, along with high potential for near-term, direct-heat utilization at 150 new sites. Preliminary estimates indicate that 254 cities in ten western states could potentially displace 64 trillion Btu per year (17 million BOE) with geothermal district heating. Table 1 indicates the tremendous potential for expanded utilization of these resources. Each state team has produced a new geothermal

resource map showing thermal wells and springs for their state. Results were presented at the 1993 and 1994 Annual Meetings of the Geothermal Resources Council.

Geothermal Heat Pump Technology

UURI completed two fact sheets which contain general information about geothermal heat pump systems, system performance, and economic analyses and benefits of particular case studies. Two brochures are nearing completion. UURI hosted a downsite for three heating and cooling teleconferences which targeted HVAC dealers, drilling contractors, utilities, and building contractors. Dr. Wright gave several presentations describing heat pump technology to national utility organizations and to the 1993 Geothermal Resources Council (GRC) Annual Meeting.

Geothermal Heat Pump Performance

OIT collected and interpreted engineering data on 217 case studies from across the U.S. on the performance of residential and commercial installations of geothermal heat pumps (GHP). The results that can be drawn from the energy comparative survey is that GHP technology is effective in saving energy over all other electrical heating systems, typically on the order of 15 to 35 percent over air-source heat pump (ASHP) systems and 25 to 60 percent on electric resistance systems. Compared to non-electric heating systems, the GHP was found to save significant energy costs (35 to 58 percent) over liquefied petroleum gas (LPG) systems but have little to no savings over natural gas systems.

The results of the peak power reduction survey are that a significant peak power (kW) reduction can be achieved for winter peaking utilities, on the order of 2-7 kW per home. Summer peaking reduction is slight and in some cases insignificant, typically on the order of 0-1.5 kW. Based upon contacts with 57 utilities, they see GHPs as a peak reducing demand-side management (DSM) tool and many offer incentives of some kind. Incentive programs offered by utilities include: average rebates of \$382/unit to residential and \$133/ton to commercial customers, low-cost loans, discounted electric rates (about \$0.01/kWh), and add-on rebates for desuperheaters. Barriers to market entry of GHPs are higher initial costs (\$2,000 to \$3,000 for a 3-ton unit) than other HVAC systems due to incremental cost of the ground loop and lack of an infrastructure of ground loop contractors and dealers.

More than 18,800 GHP installed systems (3-ton equivalent) have resulted from 34 of the utility programs contacted. The main benefits to utilities are load leveling, conservation, and customer satisfaction.

Newcastle Geothermal System Studies

A rapid expansion of the greenhouse industry utilizing the Newcastle, Utah, geothermal resource occurred in 1993 and 1994, with the construction of 9.5 acres of covered geothermal greenhouse by Milgro, Inc. The Utah Geological Survey (UGS) and UURI initiated a program of temperature and water level monitoring to help established and new greenhouse operators, and to guide the development of the resource.

Monitoring results from August 1993 to December 1994 have identified a general temperature increase in two of five observation wells and temperature decreases in two wells. A pronounced temperature decline (2.81 to 3.57 °C) was observed within the thermal aquifer near a production well (MN-1) between May 10 and August 31, 1994. This is believed to result from valley-wide production from the cool water aquifer, for summer irrigation of field crops. Water level declines of 1.5 m, 5.5 m, and 0.3m were observed during the same period. These results have been reported in detail to the GRC.

FUTURE PLANS

Seven state teams have completed their inventory, database listings, and resource occurrence maps. The remaining three state databases will be completed in FY-95. These will be reviewed and edited by UURI and OIT. OIT will complete the collocation study and with UURI and IWRRI, will prioritize resource areas for more detailed study. The results will be reviewed by, and discussed with, the appropriate state teams. Subject to new Congressional appropriations for Phase 2, the Phase 1 resource inventory will be extended to several additional states, and detailed resource investigations will begin on the highest priority resources identified in the initial ten western states. UURI and UGS plan to continue monitoring activities at Newcastle at a reduced frequency and to continue to gather data which will assist in the long-term sustainable development of this geothermal resource

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Numerous inquiries have been made to state resource teams in California, New Mexico, Colorado, Utah, and Nevada regarding geothermal resource location, quality, and suitability for development. A continuing, detailed interest is listed below.

Organization(s)	Type and Extent of Interest
Milgro Nurseries, Inc.	Temperature and water level changes in the Newcastle, Utah, observation wells. Continuing, detailed interest.

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Figure 1. Geographic extent of 1992-93 Low-temperature and Geothermal Heat Pump Program.

Table 1. State Geothermal Database Summary: 1992-93 Low Temperature Program.

	State PGA	AZ 1982	CA 1980	CO 1980	ID 1980	MT 1981	NV 1983	NM 1980	OR 1982	UT 1980	WA 1981
Thermal Wells and Springs	1993	543	979+	157	1,935	346	3,300	247	2,135	713	971
	PGA	501	635	125	899	68	1,376	312	998	315	368
Moderate Temp. Wells (100°C < T < 150°C)	1993	0	73	0	20	0	50	10	88	3	1
	PGA	0	48	0	0	0	35	3	79	3	1
Low Temp. Wells/Springs (20°C < T < 100°C)	1993	543	906	157	1,915	97	1,000	237	2,047	710	970
	PGA	501	587	125	899	58	700	309	925	312	367
Low Temp. Resource Areas (20°C < Tres < 150°C)	1993	29	58	93	28	16	300	29	275	161	17
	PGA	29	56	56	28	15	300	24	151	64	10
Direct-Heat Utilization Sites (Commercial, district, resorts)	1993	3	72	28	29	15	21	7	29	16	4
	PGA	0	54	24	20	2	8	0	23	9	0
Greenhouses, Aquaculture, Industrial Processes	1993	5	17	4	17	4	8	6	7	6	0
Areas, Potential Near-Term Direct Heat Utilization	1993	4	2	4	51	2	2	4	25	7	49+
Areas, High Priority Resource Study	1993	3	4	6	5	4	4	4	5	4	3

Comments: PGA = Previous Geothermal Assessment. Tres = Estimated reservoir temperature
The minimum low-temperature criteria is typically 20°C, but varies with climate.

GEOHERMAL RESOURCE EVALUATION BASED ON HEAT FLOW AND THERMAL CONDUCTIVITY FOR THE UNITED STATES

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KEYWORDS

Eastern U.S., Central U.S., geothermal potential, temperature, heat flow, thermal conductivity, heat mining

Technical Objectives

- Increase the precision and accuracy of geothermal resource estimates and assessments, and to regionalize resource quality, in the eastern and central United States. These objectives are to be met by developing and making available for the process the most up to date heat flow, geothermal gradient, and thermal conductivity information for the central and eastern United States in detailed and useful formats.

Expected Outcomes

- The specific results described are, first, an updated heat flow data base and, second, a series of digital data bases for the central and eastern United States (the region of 25° to 50° N Latitude by 75° to 115° W Longitude) designed with the goal of estimating temperature in the depth range 3 to 5 km at a resolution of 5' in latitude and longitude (about 4 to 5 km). Thus, on a regional basis, the most accurate techniques of analysis will be used for resource estimates. The updated heat flow data base is available in computer compatible form. The 5'x5' heat flow, surface temperature, thermal conductivity, sedimentary thickness, and geothermal gradient data are available in digital form.

PROJECT BACKGROUND AND STATUS

This project extends the published evaluations of Muffler (1979) and Reed (1985). The project is based on the uniquely complete and 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). The project was initiated in 1992. Previous reports on the status of the project are contained in Blackwell et al. (1993, 1994, 1995).

APPROACH

This is a multiyear project to evaluate the geothermal conditions at depths of several km in the United States, focusing initially on the area east of the Rocky Mountains. Geothermal resource estimates and assessments are to be supported by making available for the process the most up to date heat flow, geothermal gradient, and thermal conductivity information in useful digital formats. Distribution of the results in digital form is part of the project.

RESEARCH RESULTS

Specific results described include a series of maps based on digital data bases for the central and eastern United States (the region of 25° to 50° N Latitude by 75° to 115° W Longitude and east of the Rocky Mountains) designed to be used to estimate temperature in the depth range 3+ km at a resolution of 5' in latitude and longitude (about 4 to 5 km). Results also include, statistics on the distribution of temperature at a depth of 4 km as an example of the use of the combined data sets. These results have special application to hot dry rock (heat mining) resource evaluation and the evaluation of moderate- and high- temperature geothermal fluid potential from the deep part of sedimentary basins.

Heat flow Data Base A data base of all available heat flow measurements in the United States was prepared and published by Blackwell et al. (1989). The heat flow data base was used in the preparation of the (DNAG) 1:5,000,000 Geothermal Map of North America (Blackwell and Steele, 1992, see also Blackwell et al., 1991, 1992). That heat flow data base has been updated with the addition of about 100 new heat flow sites that have become available since compilation of the 1989 data list. The new data fill in some gaps in the existing heat flow data distribution. However, large gaps in heat flow measurements remain in some areas such as the Gulf Coast, the southern Great Plains, and the Ohio Valley region.

As a second part of this first task, a 5' interval digitized version of the revised heat flow map has been prepared. The digital form of the heat flow map allows quantitative analysis of the heat flow on a geographically weighted basis as opposed to the somewhat biased analysis based on data sites alone. This new heat flow map is shown in Figure 1. The distribution of heat flow has been discussed in detail in the references mentioned above. The results of using this data base in the calculation of a map of temperature in the eastern and central United States as a function of depth and in the statistical evaluation of that temperature distribution are briefly described here.

Thermal Properties Data Bases One important geothermal resource base in the eastern United States is represented by regions of hot, but relatively impermeable, basement rocks at depth. The exploitation (heat mining) of this hot dry rock (HDR) energy may be economic at the present time if suitable resource temperatures can be found at depths of 3 to 4 km (Tester and Herzog, 1991, Tester, 1992). Unlike most of the presently exploited hydrothermal resources in the western United States where the high temperatures are local in geographic extent, the HDR resource is more regional in character. Thus, the methods of evaluation differ. One objective of this project, to develop and realize a rationale of a resource exploration and evaluation technique for HDR, is demonstrated in this report.

To allow calculation of the temperatures at depth, a number of types of information are needed. These must be available at the same scale as the heat flow data, a data spacing of 5' of latitude and longitude. The surface temperature distribution used is based on temperature in shallow water wells and is, of itself, useful from the point of view of shallow groundwater heat pump resource estimates (Gass, 1982). Thermal conductivity as a function of depth and position is also needed. Obtaining the thermal conductivity distribution is a difficult task and additional data bases have been constructed to accomplish the goal of predicting the geographic variation of thermal conductivity. These data sets include the thickness of sedimentary rocks and their lithologies. Since the heat mining resource target is in relatively impermeable basement rocks, areas with sedimentary thickness greater than a particular design depth can be excluded, although this data set is not limited by this assumption.

The thermal conductivity is assumed constant in the sedimentary section for the purposes of this study. The geographic variation of the lithology of the sedimentary section was estimated from a set of 178 stratigraphic correlation sections published by the American Association of Petroleum Geologists (the

Correlation of Stratigraphic Units of North America, COSUNA, series). The information on the geographic variation of the lithology percentages was turned into mean thermal conductivity values for the sedimentary section using typical thermal conductivity values for the different lithologies.

A map of the results is shown in Blackwell et al. (1995). There are variations in the mean thermal conductivity of the sedimentary section of almost 100%. The highest thermal conductivity values (> 3.4 W/m/K on a regional basis) are associated with the areas where Paleozoic carbonates dominate the section such as in the Michigan, Illinois, and Delaware basin regions. The lowest thermal conductivity values (< 2.6 W/m/K on a regional basis) are in areas where a significant part of the section is shale such as in the Great Plains (Williston Basin and Anadarko Basin) and in the northern Allegheny area. The thermal gradient is inversely proportional to the thermal conductivity so for the same heat flow there can be at least a 50% variation in temperature at depth due to variation in thermal properties alone.

A data base of the thickness of sedimentary cover was also developed. This data set was prepared by digitizing the elevation of basement map published by the AAPG (1970). The elevation of basement was turned into thickness by subtracting its value from the digital topography data set. The resulting map is illustrated by Blackwell et al. (1995). This map localizes areas that might be of interest for hydrothermal development (areas with sediment at a particular depth) and areas of interest for heat mining (the areas with basement deeper than a particular depth). With the exception of the Anadarko basin, the Gulf Coast, and the east edge of the Allegheny basin, the thickness of sedimentary rock does not exceed 4 km except in very localized regions in the area east of the Rocky Mountains.

The thermal conductivity values can be divided into the heat flow to calculate the mean thermal gradient in the sedimentary section (Figure 2). The variation in the gradient is from less than 15 to over 35°C/km on a regional basis. Within an individual well, the geothermal gradient can vary by up to 500% depending on the lithology in a particular depth interval. However, the whole sedimentary section is averaged in this approach. Figure 2 illustrates one problem with the present stage of the analysis. There are large gaps in the heat flow data. For example Kentucky, has no heat flow data at all and there are large gaps in several other areas. Areas of the Appalachian basin may have low thermal conductivity and high heat flow as is the case in northwestern Pennsylvania, but there are no data in this important area.

Temperature at 4 km An example of the results for one major object of the study is illustrated in Figure 3. In Figure 3 the data sets for: 1) heat flow; 2) mean thermal conductivity of the sedimentary section; 3) thickness of sedimentary rock; 4) geothermal gradient (Figure 2, from heat flow and thermal conductivity); and 5) surface temperature have been combined to calculate temperature at a depth of 4 km (Figure 3). To calculate this map the gradient in basement between the base of the sediment and 4 km (where the sediments are less than 4 km deep) was calculated from the heat flow assuming a constant thermal conductivity for the basement of 2.8 W/m/K.

This map shows that, in terms of the temperature at a depth of 4 km, there are major regional variations in the geothermal resource potential in the central and eastern U.S. At a depth of 4 km, temperatures on a regional basis range from less than 70 to over 150 °C. Thus, as is the case for hydrothermal resources in the western U.S., some exploration is necessary to maximize success. There are large regions of relatively high temperature in the central plains states, and an area that includes southern Arkansas, northern Louisiana, and the Texas Gulf Coast. Elsewhere the regions of highest temperature are smaller in size; in eastern Iowa, in western New York/northwestern Pennsylvania, and in the southeast. In contrast, there are large areas of quite low temperatures in the Appalachians, west Texas, southeastern New Mexico, and the Superior Shield region in Wisconsin and Minnesota.

This type of map can be used to direct possible exploitation plans to appropriate areas and to evaluate the sizes of areas that might be exploited assuming different conditions and parameters. For this example, it is assumed that the most favorable situation is an area with a high heat flow, low thermal conductivity, and sediment section just less than 4 km in depth (to minimize drilling costs).

Discussion Detailed equilibrium temperature-depth data in deep wells are rare in the eastern U.S. However, there are several such sites in the central part of the United States that were described by Blackwell et al. (1993). The temperature-depth data from these wells are consistent with the predictions of temperature shown in Figure 3. For example, the Mosley well in northeastern Louisiana, with a measured temperature of 130°C at 3 km (10,000 ft) and a projected temperature at 4 km of 150+ °C, demonstrates the existence of high temperatures, even in the tectonically stable eastern United States, given the combination of low thermal conductivity and high heat flow. This well also demonstrates the validity of the high temperatures shown in Figure 3 for the northern Louisiana area.

The temperatures illustrated in the map in Figure 3 can be used both for regional and subregional resource evaluation, and in a statistical sense for quantitative geothermal evaluation. The distribution of temperature at 4 km is also shown in Table 1. The distribution of temperature at 4 km is log normal with about 82 % of the area having temperatures between 70 and 110°C at 4 km. About 3% of the area has temperatures less than 70°, and about 15% has temperatures above 110°C. A significant part of the central and eastern United States (about 5% of the area contoured in Figure 3) is underlain by temperatures of over 130 °C at 4 km! Smaller areas, of course, may have even higher temperatures, so to optimize sites, detailed exploration in the areas of identified high potential, such as northern Louisiana/southern Arkansas, north central Nebraska/ southcentral South Dakota, northeastern Pennsylvania, and eastern Virginia, is still needed.

This discussion of the temperatures at 4 km is meant to illustrate how the data bases can be used to develop and demonstrate the geoscience rationale for rating or evaluating various regions in the eastern and central U.S. as to their suitability for various types of geothermal use. This type of analysis, combined with an economic parameter analysis, can be used to obtain quantitative, realistic evaluations of the potential value of the geothermal resource base there.

FUTURE PLANS

Use of gravity data to interpolate heat flow in areas of low heat flow data density are being developed. Ground truth information will be collected in the case of the thermal anomaly in northern Louisiana. The methodology, with appropriate modifications, will be applied to the western U.S.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Geothermal Power, Inc.	Temperature in Northeast U.S.
New York State Energy Office, Department of Geophysics and Astronomy	Temperature in New York

Organization(s)	Type and Extent of Interest
U. B. C.	Paleoclimate, heat flow distribution
Department of Geography, U. Ontario	Geographical information system (GIS) comparison of heat flow and mineral resources
Energy Laboratory, Massachusetts Institute of Technology	Temperature for Heat Mining Economic Analysis

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Table 1. Percent of area with a given temperature at 4km. The contoured area in Figure 3 is included in the calculation.

<u>Temperature (°C)</u>	<u>% Area</u>
< 70	3.2
70-80	19.9
80-90	28.5
90-100	20.2
100-110	13.3
110-120	5.6
120-130	4.4
130-140	3.5
> 140	1.4

Figure 1. Heat flow map of the United States. The contours are updated from Blackwell et al. (1989) and the GSA DNAG map (Blackwell and Steele, 1992) with heat flow data to 1993.

Figure 2. Gradient in the sedimentary section/basement in the central and eastern US east of the Rocky Mountains. Sites of heat flow measurements are shown.

Figure 3. Temperature at a depth of 4 km in the central and eastern US east of the Rocky Mountains. Areas of sediment thickness greater than 4 km are outlined in white.

DRILLING TECHNOLOGY

DEVELOPMENT OF ADVANCED SYNTHETIC-DIAMOND DRILL BITS FOR HARD-ROCK DRILLING

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KEY WORDS

Polycrystalline diamond compact (PDC), synthetic diamond bit, impregnated diamond, thermally stable polycrystalline (TSP), hard-rock drilling, geothermal drilling, single cutter testing

PROJECT OBJECTIVES

Predictions have shown that doubling drilling penetration rate and bit life results in a 15% reduction in the overall cost for a geothermal well and a 20% reduction in overall cost for a deep, natural gas well. The hard, abrasive, and fractured rock formations drilled to access these reservoirs are generally considered beyond the capabilities of current synthetic-diamond bit technology. However, the inherent cutting efficiency and lack of moving parts of synthetic-diamond bits make them an ideal prospect for future increases in penetration rate and bit life in hard formations. The hard-rock drill bit program is a national lab/industry cooperative research program aimed at developing synthetic-diamond drill bits capable of drilling into hard-rock formations.

Technical Objectives

- Extend the range of application of synthetic-diamond bit technology into harder formations.
- Increase bit life and penetration rate in these hard formations over roller-cone bits.

Expected Outcomes

- Develop polycrystalline diamond compact (PDC) cutters that more efficiently fail hard rock and are more impact-resistant, better able to survive the high loads associated with hard-rock drilling.
- Develop advanced thermally-stable polycrystalline (TSP) drill bits, capable of handling the higher temperatures associated with hard-rock geothermal drilling.
- Develop an optimized claw PDC cutter design combining the abrasion resistance of diamond and the impact resistance of tungsten carbide.
- Optimize a Track-Set PDC bit, effectively reducing lateral vibrations and impacts in hard rock.
- Develop advanced impregnated diamond bits utilizing new diamond coating technology and specifically developed to increase penetration rates in hard rock.

PROJECT BACKGROUND AND STATUS

A recent study by Maurer Engineering found that about 70% of the total time associated with drilling a deep gas well is spent drilling ahead and tripping. The bit penetration rate and bit life, therefore, both have major impacts on well costs. If both penetration rate and bit life could be doubled, an average 20% reduction in drilling costs would result. A study by Sandia National Laboratories reached similar conclusions for geothermal drilling. A generic well-cost model was used to examine the cost impacts of various potential technology improvements. A 15% reduction in well costs was predicted to result from a hypothetical doubling of bit life and penetration rate. Technology development in the field of synthetic-diamond bit design has the potential for providing such improvements in bit performance in both petroleum and geothermal hard-rock drilling.

Companies were contacted and a comprehensive program proposal was developed during 1992. The proposal was presented to the Drilling Engineering Association for review and evaluation in February 1993. Upon favorable review, the Department of Energy (DOE) Office of Fossil Energy approved funding for the program under the Oil Recovery Technology Partnership. This funding was received in August 1993. Joint work, cost-shared contracts were placed with each company and the program was begun at the end of October 1993. DOE Geothermal Division funding was received in FY94 including additional funding from the Oil Recovery Technology Partnership. Overall funding for the program is shared equally by industry, DOE Fossil Energy Division, and DOE Geothermal Division.

At the conception of the program in its current state with several company partners working on a variety of topics, it was anticipated that the initial effort would be completed within two years. The end of FY94 marks 11 months since the contracts were placed with the companies. Due to a variety of reasons (less funding than expected, the need to build new testing equipment, mergers and reorganizations of the companies) not all of the projects will be completed in two years; it is expected that some will be completed in 2-1/2 to 3 years.

APPROACH

Several drill bit and cutter companies have teamed with Sandia National Laboratories to work on five projects as part of a cooperative effort to advance the state-of-the-art in synthetic-diamond drill bit design and manufacture. Each project explores a different approach to synthetic-diamond cutter and bit design and builds on each respective companies' capabilities and current product interests. Sandia's role is to assure integration of the individual projects into a coherent program and to provide unique testing and analytical capabilities where needed.

Research and development is being conducted in the design of PDC cutters and bits, impregnated-diamond bits, and thermally-stable polycrystalline (TSP) bits. The objective of each project is to develop drill bits and cutters which drill faster and last longer in hard-rock formations. The development of these hard-rock bits would mean cheaper and faster drilling in natural gas, oil, and geothermal reservoirs.

The companies that have teamed together to work with Sandia on these projects include:

- **Smith International and Megadiamond** are developing advanced hard-rock PDC bits by gaining a more fundamental understanding of both cutter and rock failure mechanisms. The project will result in cutters that can better withstand the downhole vibration environment, and both cutters and bits that more efficiently fail hard rock.

- **Dennis Tool Company and DBS** are optimizing the design of the claw cutter by combining single-cutter wear testing with thermal and stress numerical modeling. The project will result in a claw cutter that has been optimized for hard rock drilling. (After the program began, DBS merged with Security Diamond Products to become Security/DBS. We do not yet know how that will effect this project.)
- **Security/DBS** is optimizing the design of their Track-Set drill bit. A variety of cutter tests will be performed to analyze the track-set cutting structure. The results of the tests will be utilized in a force/wear bit model for track-set bit design.
- **Hughes Christensen Company** is improving impregnated bit performance in hard rock. A mechanistic drilling model for impregnated bits is being developed with the aid of laboratory drilling tests. The final model will be used to develop bit designs for specific hard-rock applications.
- **Maurer Engineering and Slimdril International** are improving the design of TSP drill bits in hard rock by using results from single-cutter wear testing to design and fabricate three different TSP bits. The bits will be evaluated both in the laboratory and in the field.
- **Amoco Production Research** participates in the program by providing expertise related to field testing and use of PDC bits and by making available their Catoosa Test Facility for use in evaluating concepts related to hard-rock synthetic-diamond bit design.
- **Sandia National Labs** provides technical program management, single-cutter wear testing, linear testing of cutting force and rock/cutter interaction, analysis of rock failure mechanisms, rock property measurements, dynamic test development, and thermal/mechanical stress numerical analysis.

RESEARCH RESULTS

Significant accomplishments have been made in each of the five projects in FY94. Items general to the overall program will be discussed first, followed by those specific to each project.

Contracting - Although not technical, a significant accomplishment for early FY94 was that auditable contracts for the joint and cost-shared work were placed with each of the five company teams. This represents a significant amount of work and marks the true beginning of the project.

Benchmarking - Four benchmarking studies documenting the performance and limitations of current synthetic-diamond and roller cone bits have been completed. Results of this benchmarking study have included (to date) complete documentation of lithology and bit performance in hard-rock formations in the U.S., the North Sea, and Germany, as well as some documentation of bit performance in other locations. In addition, the performance of several current technology bits drilling hard rock in laboratory drilling simulators has been documented. These results will be used to gage improvements in technology under this program.

Single-Cutter Wear Testing - During FY93 a method was developed for wear-testing synthetic-diamond cutters in hard rock. A large vertical boring lathe was instrumented and cutters were used to face off the top of a large block of Sierra White Granite. A significant amount of testing of conventional, claw, and

TSP cutters has been completed on this machine. (Details under specific company projects.) Using this machine, we were able to determine a correlation between wear rate and table rotational speed. Further tests were conducted to determine the exact cause of this effect (strain rate, temperature, etc.) However, because of the limitations of the machine, we were not able to make an absolute conclusion. This, as well as other limitations in machine capabilities and access, led us to work on the design of a more versatile testing machine.

New Single-Cutter Wear Testing Machine - Significant progress was made on the new single-cutter testing machine. The new machine will be able to handle the high loads associated with rock cutting and more closely simulates actual drilling. The test cutter is installed on an instrumented coring-type bit and holes are drilled into a granite block which can easily be moved to complete several tests. The tester has been designed to produce 6000 lbs of vertical force and 560 ft-lbs of torque, at a constant shaft rotational speed and either a constant penetrating force or a constant feed rate. The new machine is a large, versatile structure; the design process has been very complex, including a great deal of design analysis and clever engineering. Detailed component design, analysis, and documentation is complete and has been reviewed and approved by a design review group. The machine structure, load head, and drill shaft assembly have been fabricated. The hydraulic power unit for the system has been installed including the hydraulic cylinders and hydraulic motor. A compressed air system to move the rock and a coolant flow and collection system have been designed; fabrication will begin soon. Detailed design of the instrumented cutter holder is complete; fabrication will begin soon. When the apparatus is complete, we will have the capability to perform cutter wear testing and small scale drilling tests at Sandia.

Linear Cutting and Cutter Performance Testing - Instrumentation and test development of a linear cutting machine and procedure for performance testing of cutters was completed. A significant amount of time was spent trying to duplicate results previously published in the literature. After testing and examining everything we could possibly think of, we realized there are some subtle differences between standard PDC cutters of today and those of a few years ago. We obtained a cutter from China which is very similar to US older technology and were able to repeat the data. A significant amount of testing was then done with standard PDC cutters cutting Sierra White Granite. The effects of both back rake and side rake were analyzed. Further testing has been planned but postponed due to the machine breaking down.

Optimization of Impregnated Diamond Drill Bits with Hughes Christensen Company (HCC) - HCC has made a great deal of progress in the development of optimized impregnated diamond drill bits. HCC completed preliminary laboratory tests of thin-walled core bits to measure wear patterns and diamond exposure. The results of these tests were used to develop and define further specific tests and testing procedures which were then completed. Test results led to the redesign of both the segment holding mechanism and the bit itself. Redesigns are complete and have been tested with good results. HCC also completed single-point cutter tests with impregnated and single layer brazed diamond grit to determine the force distribution between the diamond grit and the matrix material. This data was used in the computer model of the impregnated bit drilling process. A preliminary mechanistic model of this process is complete. Results of lab tests will be used to refine the model.

Advanced TSP Drill Bit Development with Maurer Engineering and Slimdril International - A method for mounting a variety of TSP cutter sizes and styles for single-cutter wear testing was developed and preliminary testing was performed on a 5 mm sharp-set cutter. The results of this test were used to determine operating parameters of further tests. Maurer Engineering obtained a variety of shapes and grades of TSP cutters for testing. They mounted 11 of the cutters in a matrix material and machined them for testing at Sandia. Wear testing of ten of the cutters was completed at Sandia on the modified

vertical lathe in September. Preliminary analysis showed that the TSP material was more abrasion resistant than the comparable PDC material, but the cutters exhibited catastrophic failure at only moderately high loads. Detailed data analysis continues. Maurer Engineering completed the testing of the first TSP bit designed specifically for hard rock drilling. The bit exhibited significant wear and failure after just a few feet of drilling; obviously, redesign continues.

Advanced PDC Cutter Development and Bit Design with Smith International and Megadiamond - Characterization and prioritization of field-worn and failed cutters has been initiated. The results will be used to develop laboratory failure tests. The most significant project accomplishment to date is that two of four planned tests at the Catoosa Test Facility were completed. In the first test, a standard PDC bit with a proven field history was run while measuring both downhole and uphole dynamics. The drilled formation contained shale with hard-rock stringers. Of particular interest were the impacts measured at the soft/hard rock interface. In addition, several types of PDC cutters from different manufacturers were installed on the bit to get a direct comparison between different cutters. Catastrophic failure of the bit was not obtained during the first test, so another test was conducted under harsher conditions. The second field test at Catoosa Test Facility was completed. Again, dynamic measurements were made as the bit was drilling, and periodic inspections were made to correlate the measurements with cutter wear and failure. In the second field test, the bit was run until catastrophic failure occurred.

Claw Cutter Optimization with Dennis Tool Company and DBS - A three-dimensional analysis of both the thermal and mechanical stress in a baseline claw cutter has been completed. This analysis has been used to determine a more simplified numerical mesh for further parametric studies. Several claw cutters have been wear-tested on the vertical boring lathe. Tests of early prototype cutters showed that the claw cutters wore significantly faster than standard PDC cutters. This was attributed to the early prototype manufacturing process, and several new claw cutters were subsequently manufactured with a new process. These cutters were then wear-tested under the same conditions. After exposure of the claw, the cutters emitted a high-pitched noise during cutting and wore at a faster rate than conventional cutters. This is contrary to what has been seen in the field where claw cutters have outlived conventional cutters. The noise and increased wear were attributed to cutter chatter which is a function of the stiffness of the machine. The decision was made to postpone testing of claw cutters until a new, stiffer machine built specifically for cutter testing is complete.

Optimization of Track-Set Cutting Structure with Security Diamond Products - During early 1994, Security Diamond Products merged with DBS. This merger delayed the project slightly as a significant amount of time was spent evaluating the two companies respective research programs and redirecting their efforts. A machine for performing linear cuts with single PDC cutters was obtained and installed. Preliminary linear cutting tests were completed on the machine (see above.) Documentation of existing drilling models including strengths and limitations was completed. A detailed matrix of the tests which must be conducted to model the track-set cutting structure was established using the results of the model documentation. However, due to machine failure, these tests were not completed in FY94. A new machine has been located and will be installed in early FY95.

FUTURE PLANS

Plans for the future include a significant amount of documentation of results to date. Results of a benchmarking study, laboratory wear tests, dynamic field tests, and laboratory drilling tests will be documented in several internal reports.

Work will continue on each of the projects. The parametric design optimization of the claw cutter will be completed. A new linear cutting machine will be installed, and track-set cutting tests will be completed. Laboratory drilling tests of TSP bits will be conducted using the results of the single-cutter tests. The new single-cutter testing machine will be completed and preliminary testing will be completed in FY95.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Smith International Maurer Engineering Hughes Christensen Security/DBS Dennis Tool Company Slimdril International	Industry partner, 50/50 cost share of joint work
Amoco Production Research	Industry advisor, makes field site available for testing

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LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROJECT

Loss-Zone Characterization Hardware

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KEY WORDS

Drilling fluid hydraulics measurement system

PROJECT OBJECTIVE

The objective of this project is to develop and transfer to industry a reliable and accurate method for measuring the inflow and outflow rate of fluid flow in geothermal wells while drilling. More accurate measurement of these flow rates would allow lost circulation to be more quickly recognized and characterized. This would allow more rapid and accurate diagnosis of loss zones, leading to better decisions on treating the loss zones, saving rig time, reducing drilling costs, and reducing the costs of on-line geothermal power.

Technical Objectives

- Develop the rolling float meter for use in measuring drilling fluid outflow rates in geothermal drilling. If successful, develop procedures for the proper use of the rolling float meter on drill rigs.
- Determine the feasibility of using acoustic Doppler flowmeters to accurately measure drilling fluid inflow rates in geothermal drilling. If feasible, develop procedures for the proper use of Doppler flowmeters on drill rigs.
- Develop operating procedures and data acquisition algorithms for monitoring, recording, and analyzing drilling fluid inflow and outflow rates for the purpose of identifying and characterizing lost circulation zones.
- Demonstrate to industry how accurate inflow/outflow measurements and analysis can be used to reduce rig time and make more informed decisions. Advise geothermal service and operating companies interested in using this technology on their drill rigs.

Expected Outcomes

- Reduce down time and costs associated with lost circulation are the expected outcome of this project. With a rig rate of \$300-500/hr and a single cement treatment (including rig time) costing \$10,000, small improvements in the efficiency of dealing with loss-zones can have a significant effect on total wellbore costs. For example, detecting drilling fluid loss by monitoring mud pit levels, the standard practice, may require 10-30 minutes of time for each loss zone, whereas the technology under development in this project is able to detect such

Expected Outcomes (continued)

fluid loss as soon as it occurs. Also, by knowing exactly when fluid losses begin, it is possible to make sure that at least ten additional feet of hole are drilled in order to uncover the loss zone fully before cementing. Premature cementing can waste cement plugs because the loss zone may leak when it is fully drilled through later.

PROJECT BACKGROUND AND STATUS

This project began in 1989 when it was observed that geothermal drillers did not have an effective means for detecting and evaluating lost circulation zones. The idea for the rolling float meter was conceived and reported to a geothermal industry advisory board, which enthusiastically supported its development. Design and laboratory testing proceeded, and a prototype rolling float meter was field tested in the Long Valley Exploratory Well in 1991. Improvements in the manufacture of the float and bearing assembly were undertaken to correct problems encountered in the field test. Two conference papers and a comprehensive report were written that describe the rolling float meter and its development (Refs. 1-3). A loan program was set up in which eight rolling float meters were loaned to various service companies in the geothermal and petroleum drilling industries. Results of the evaluations by those companies are included in this report.

One of the results of the rolling float meter testing program was the realization that a better technique for measuring drilling fluid inflow rates is needed. Acoustic Doppler flow meters would be good for this application because they are non-intrusive, having transducers that clamp onto the outside of the rig standpipe. Testing of this type of flowmeter was done on a core rig in the Steamboat Geothermal Field in 1993. It was shown that rig noise was too intense for the meters unless further signal processing could be done. Results of further evaluations in the laboratory are reported in this year's progress report.

It is estimated that most development work related to this project will be completed within the next two years. It could take several years of low-level effort to fully transfer this technology to industry.

APPROACH

The approach taken in this project has been concept development, hardware design, laboratory testing at Sandia, and field testing in cooperation with industry. This approach allows feedback from industry to be incorporated into the hardware design. By loaning rolling float meters to industry participants willing to test them, data about their expected performance under a wide variety of conditions was obtained.

RESEARCH RESULTS***Rolling Float Meter***

Rolling float meters have been undergoing independent field testing and evaluation by the various industry participants for over a year. Experience to date with the rolling float meter has been mixed. The accuracy and longevity of the meter under conditions for which it was designed have been confirmed. Good performance has been obtained under a variety of geothermal and petroleum well drilling conditions. Some meters have withstood months of operation in drilling mud without significant degradation in performance.

Problems encountered by industry participants have been related to improper use or use under conditions for which the meter was not designed. Improper adjustments to the unit's counterweight, improper use of signal dampening, and damage to the units from extremely rough handling have been encountered. For example, one unit fell 25 feet because it was not properly attached to the flow line; another unit had something fall on it. Reluctance by rig owners to modify their flow lines to install the rolling float meter has also been experienced. One company that built five additional units had very good experience with their meter on land rigs using water-based mud. However, they found the meter to be unreliable on offshore rigs and with heavy-weight mud, conditions for which the rolling float meter was not designed. Furthermore, the company changed the design of the meter by using a different-sized float and pivot arm, both these parameters were found to affect meter performance in our laboratory testing.

Despite the mixed experience with the rolling float meter by industry, interest in the meter remains high. The two geothermal service companies involved in the testing program are still testing their meters in the field. One of the petroleum service companies has stated that they do not manufacture mud logging sensors but would be interested in buying rolling float meters if they become commercially available. Another petroleum service company stated that the rolling float meter would be a viable outflow transducer if it could be reduced in size to make installation more straightforward. A company that manufactures testing equipment has expressed interest in manufacturing the rolling float meter.

As one of the industry participants has stated, full benefit of the rolling float meter can be realized only if an improved method for measuring drilling inflow rates to the well is developed. The current technique of counting mud pump strokes and converting to flow rate is inadequate because of changing pump efficiency that occurs during normal drilling operations. Consequently, a project was undertaken during the past year to evaluate potential alternative inflow meters for use on drill rigs (see below). An ideal system that employs the rolling float meter would utilize an accurate inflow meter, data acquisition hardware, and expert system software to detect, diagnose, and offer suggested treatments for loss zones when they are encountered. Such a system is the ultimate goal of this work.

Ultrasonic Doppler Flowmeter Testing

A significant amount of testing was conducted with an acoustic Doppler flowmeter in our Wellbore Hydraulics Flow Facility. A straight section of 4-inch pipe was installed in a flow loop. The flowmeter transducers were strapped onto this pipe to simulate a typical drill rig standpipe. A plate was welded onto the pipe for attaching an acoustic vibrator to simulate rig noise. Long-term testing of the meter was performed both with and without the simulated noise. Lab test results confirm the field test finding that rig noise is a problem for what were state-of-the art Doppler flowmeters in 1993.

At the end of FY94, plans were being made to test a new type of Doppler flowmeter that will soon become available. The new meter reportedly performs a fast Fourier transform (FFT) on the received acoustic signal and isolates the transducer signal to achieve greater accuracy. A long-term field test of the meter is planned in the near future.

FUTURE PLANS

A field test will be conducted using the rolling float meter on the outflow line and a Doppler flowmeter on the inflow line of a geothermal drill rig in early FY95. Magnetic flowmeters and pump stroke counters will also be used to measure inflow rates. Loss zones will be monitored and evaluated with these flow meters and compared with fracture locations identified with a borehole televiewer. This will

allow the accuracy and utility of a good drilling hydraulics data acquisition system to be demonstrated. It will also allow us to work directly with industry in installing, calibrating, and using these instruments. Based on these and past results, we plan to renew our effort to locate a company interested in marketing the rolling float meter. Integration of the rolling float meter and the Doppler flowmeter into a stand-alone drilling fluid hydraulics measurement system will begin.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Tecton Geologic, Inc.	Rolling float meter testing, Doppler flowmeter testing
Baker Hughes INTEQ Martin Decker Totco Halliburton Services Schlumberger-Anadril International Logging Japan, Inc. Electro-Flow Controls, Ltd.	Rolling float meter testing

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LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROJECT

Downhole Tools and Materials for Treating Loss Zones

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KEY WORDS

Lost circulation tools, lost circulation treatment materials

PROJECT OBJECTIVE

The objective of this project is to develop and transfer to industry tools and materials for treating lost circulation zones in a more economical manner than conventional cementing operations. Because of the wide variety of loss zones encountered in geothermal drilling, multiple techniques for plugging loss zones are being studied and developed. These include the drillable straddle packer, the porous packer, and cementitious muds. The purpose of these tools and materials is to increase the effectiveness of the plugging operation in order to eliminate the need for multiple treatments in the same loss zone, saving rig time, reducing drilling costs and the costs of on-line geothermal power.

Technical Objectives

- Develop a drillable straddle packer to improve the plugging efficiency of cementing operations, eliminating the need for multiple cement plugs in a single loss zone.
- Develop a wireline-deployed porous packer that emplaces polyurethane foam into a loss zone, eliminating the need for tripping the drillstring into the hole and eliminating time waiting for cement to set up.
- Foster the development of cementitious muds for lost circulation control by participating in laboratory and field testing of these materials.

Expected Outcomes

- Reduce down time and costs associated with lost circulation are the expected outcome of this project. With a rig rate of \$300-500/hr and a single cement treatment (including rig time) costing \$10,000, small improvements in the efficiency of sealing loss-zones can have a significant effect on total wellbore costs. For example, some loss zones require ten or more cement plugs to seal them; many require at least two plugs. A technique capable of reliably plugging loss zones with a single treatment would significantly reduce costs.

PROJECT BACKGROUND AND STATUS

This project began in 1979 with the development of unique laboratory facilities for testing lost circulation materials (LCMs) for geothermal drilling environments. Many types of materials were tested under high-temperature, high-pressure conditions. A number of materials were identified that are suitable for

moderately high temperatures and could be used to advantage in a wide variety of drilling environments. Mathematical models were developed that describe the LCM plugging process and describe the effects of numerous variables on the plugging capability of a given material, such as size, shape, elastic modulus, and tensile and compressive yield strengths (Reference 1).

The LCM testing and modeling also indicated that if the aperture of a loss zone fracture is too large, it cannot be plugged with LCM materials that are simply added to the drilling mud. This, not temperature, is probably the reason why most loss zones in geothermal drilling are plugged with cement rather than LCMs. It is therefore necessary in order to reduce lost circulation costs to improve upon the conventional cementing operation. The concept of the drillable straddle packer was initiated in 1988 and reported to a geothermal industry advisory board, which enthusiastically supported its development. A laboratory facility for testing the drillable straddle packer components was designed and constructed in 1990. Testing of various designs of the packer's inflatable bags began in 1991. References 2 and 3 describe the drillable straddle packer concept and its development history. All key component testing for the packer has now been completed, as reported in this year's annual progress report.

The porous packer concept arose from our experience in a project to investigate the use of polyurethane foam as a loss-zone sealant in the 1980s. That work showed that the foam will undergo sufficient expansion downhole to be effective if it is confined in a bag that prevents jet mixing with wellbore fluids before the chemical reaction that causes foaming is complete (Reference 4). The porous packer would perform this function. A laboratory facility was designed and constructed for testing porous fabrics that might be used in the packer. Early progress in this area was reported in References 2 and 3. Because of staffing limitations, this project has proceeded more slowly than the drillable straddle packer; however, the bag fabrication technology developed for the drillable straddle packer can be utilized in the design of the porous packer.

We have worked with Brookhaven National Laboratory for several years on the development of cementitious muds. In 1989, we designed and constructed a laboratory-scale tester for Brookhaven to use in the study of encapsulated accelerators for cementitious muds. We have also loaned Brookhaven our cement consistometer for this work and have developed specifications for cementitious muds for Brookhaven to use in their work.

In 1993, we were approached by Halliburton Services and California Energy Services for assistance in evaluating a cementitious mud developed by Halliburton in a Cal Energy well to treat lost circulation zones. Over the past year, we developed a proposal for this work and requested funding from the Geothermal Drilling Organization (GDO), as described in this year's progress report.

Most development work related to the drillable straddle packer has been completed. Testing of the hardware with cement will be completed within the next year, with a series of field test to follow that. It could take several years of effort to fully transfer this technology to industry if successful. The porous packer is about two years behind the drillable straddle packer in its development stage. Cementitious mud testing will one to two years to be completed.

APPROACH

Significant industry interaction has taken place during the life of this project. In some cases, we have transferred technology we have developed to industry. In other cases, we have participated in field testing industry's ideas and materials in the laboratory and in the field.

RESEARCH RESULTS

Drillable Straddle Packer

Development of the fabric bag for the drillable straddle packer progressed significantly during this reporting period. We have been working with Petersen Products Co. of Fredonia, Wisconsin, to develop fiberglass-fabric bags using their patented swaging process. This process is used to attach the ends of a fabric tube to a rigid metal tube passing through the bag to provide closure of the fabric tube. Petersen currently manufactures "stopper bags" made of canvas and neoprene fabric swaged onto steel pipe nipples. These bags are used in the utility industry to temporarily plug sewers and pipelines for repair. Our drillable straddle packer bag design utilizes silicone-coated, fiberglass fabric for high-temperature capability and aluminum through-tubing for drillability.

Seven different bag configurations were designed, fabricated, and laboratory tested during the reporting period. These designs investigated the effects of several variables, most notably the effects of:

- Using elastic bands to control bag inflation so that the center of the bag inflates before the ends inflate;
- Swaging the fabric tubes to a single, composite through-tube consisting of aluminum end nipples threaded to a connecting CPVC tube, to minimize the amount of aluminum used in the bag;
- Swaging the fabric to a fully annealed (versus heat-treat-hardened) aluminum through-tube to enhance drillability;
- Using a single fiberglass fabric tube versus two nested fabric tubes;
- Using an inner fiberglass fabric tube and an outer canvas fabric tube; and
- Using a single fiberglass fabric tube with almost twice the fabric thickness of the fiberglass fabric used in the previous tests.

All seven bag designs were burst-tested in our Packer Test Facility. The design employing a single, thicker fiberglass fabric tube burst at 52 psi. The failure mode in this case was movement of the lower swage, rather than tearing of the fabric. This test was very encouraging because the failure pressure significantly exceeded our original burst-pressure goal of 40 psi. With further development and control of the swaging process for the fiberglass fabric/aluminum tube combination, it is now believed that a burst pressure exceeding 50 psi can be reliably attained. The thicker fiberglass fabric used in this bag has only recently become commercially available.

The highest burst pressure achieved was 66 psi with the bag design that utilized a fiberglass fabric tube inside a canvas fabric tube. In this case, the inner fiberglass fabric tube failed while the canvas fabric tube remained intact. This was not surprising because of the canvas fabric's higher tensile strength, as compared with that of the thinner fiberglass fabric. Canvas does not have the high-temperature capabilities of the fiberglass fabric; however, this test demonstrated that the swaged connection on an aluminum tube can hold pressure as high as at least 66 psi if the swaging process is properly controlled.

Other significant findings from these tests include the following:

- The use of elastic bands to control bag inflation appears to be successful in preventing the bag ends from inflating before the center of the bag inflates. In so doing, the bag can achieve a "pumpkin" shape with hemispherical ends that minimize the stress in the fabric. Inflation of a bag inside an acrylic tube verified the operation of the elastic bands.
- One of the swages on the bag design that employed a fully annealed aluminum through-tube failed at 38 psi, indicating that full annealing of the through-tube may soften it too much to allow the swage to hold at higher pressures. It may, however be just a matter of optimizing the swaging process for annealed aluminum. Alternatively, partial annealing of the aluminum may enhance its drillability sufficiently without jeopardizing the swaged connection.
- There apparently were no problems associated with swaging onto the aluminum portion of the composite aluminum/CPVC through-tube. The bag utilizing that design bursted at 46 psi, which was actually higher than previous tests using the same type of fiberglass fabric tubes and a continuous aluminum through-tube.
- The bag design using a single, thin fiberglass fabric tube burst at 12 psi, confirming the expectation that a single tube of that fabric thickness is not sufficiently strong to achieve the desired burst pressure. As mentioned above, using a single fiberglass fabric tube constructed of fabric with nearly twice the thickness increased the burst pressure to 52 psi, a factor of 4.3 higher. This indicates that the typical fabric tears that occur at the swage are not due to simple tensile failure, but rather bending failure associated with the tight bend the fabric makes at that point. The thicker fabric uses more individual strands of fiberglass fiber with the same diameter as those used in the thinner fabric; thus, the bending radius is greater and the bending stress is lower at a given bag pressure with the thicker fabric.

Two packer bags were later fabricated by Petersen Products, Inc., using different swaging pressures in order to allow us to examine the effects of swaging pressure on swage failure. Both swaging pressures were within the range of pressures Petersen normally uses in fabricating our bags. We tested the bags in our Packer Test Facility and found that there was no swage failure on either bag. The first bag tore at 36 psi, and the second one tore at 49 psi. In both cases, the failure mode was a tear along the top swage, but the swages themselves did not fail. In view of these results, it was determined that further testing of the bag design was not needed.

The conclusion of our lengthy packer bag design and testing process is as follows. We have developed a bag design in conjunction with a commercial supplier that should perform well for its intended purpose in the drillable straddle packer. A series of ten bag tests have led to an optimized design that has a failure pressure of 36-52 psi. Our original failure-pressure goal of 40 psi has, therefore, been nominally achieved. The bags can thus be operated at a pressure of 20-25 psi with a significant safety factor and reliability.

Laboratory testing of other key components of the drillable straddle packer have also been completed. Both the drillstring coupler and the shroud mechanism were successfully tested several times in the Packer Demonstration Facility. In these tests, the activation balls were emplaced in the mechanisms, the mud pump was started, and pressure was allowed to build upstream of the ball until the shear pins broke,

causing the mechanisms to activate. These test proved that these simple mechanisms are very reliable, and the drillstring pressure provides a positive indication that they have been activated downhole.

The development of a laboratory prototype drillable straddle packer is now considered complete. The next step in the project is to test the prototype with cement in the Packer Demonstration Facility (see below). Further laboratory tests will also be conducted to determine the self-centering capability of the packer assembly in order to determine the need to run a stabilizer or flexible hose above the packer assembly in a wellbore. Eight packer bags have been fabricated for these various tests.

Finally, a conference paper that describes the drillable straddle packer development process has been written for presentation at the World Geothermal Congress next May in Florence, Italy.

Packer Demonstration Facility

The Packer Demonstration Facility will be used to test full-scale packer assemblies with cement at full-scale flow rates. The facility consists essentially of a 15-ft concrete cube with an open top and one open side. An engineered loss zone can be emplaced in the cube by alternating layers of clay and gravel, representing impermeable and permeable zones, respectively. A 16-inch, vertical concrete tube with side openings will be placed in the center of the facility to simulate the wellbore into which the packer assembly will be placed.

Internal wellbore flows will be initiated by pumping into one or more of the gravel layers and flowing out of the layer representing a loss zone. In this manner the pressure-gradient conditions that occur in an actual wellbore under lost circulation conditions can be simulated. Cement at full-scale flow rates will be pumped through the packer assembly to test the packer's operation under such conditions. Post-mortem analysis can be performed by removing the clay and gravel from the facility while mapping the location of the injected, solidified cement. In this way, the effectiveness of the packer in sealing off internal wellbore flows and injecting most of the cement into the loss zone can be determined.

Construction of the Packer Demonstration Facility was nearly complete at the end of FY94. Because of other commitments by project personnel, construction of the facility has not progressed as quickly as we would have preferred. Nevertheless, the structure of the facility was completed during this reporting period, and most of the facility plumbing was installed. Planning is now underway for the first test, in which cement will be run through open-end drill pipe to determine the behavior of cement in a typical, conventional lost circulation treatment without a packer. Following that test, a drillable straddle packer will be tested under identical conditions to demonstrate the effectiveness of the packer in improving plugging efficiency for a lost circulation zone.

Cementitious Mud Testing Project

Planning was initiated for a Geothermal Drilling Organization (GDO) project to test cementitious mud in a geothermal well drilled in the Coso Geothermal Field by California Energy Company. Halliburton Services has formulated muds that are chemically compatible with bentonite drilling mud and set up much faster than conventional cement. The purpose of the field tests is to determine the effectiveness and cost savings that result from using such mud for lost circulation control. Sandia will participate in the project by contributing our expertise in instrumenting the well to detect and quantify lost circulation and in interpreting downhole logs that will be used to help evaluate the tests. The rolling float meter will be used to measure outflow from the well, and commercial magnetic flowmeters will be used to measure

inflow rates. In addition, a new type of acoustic Doppler flow meter will be tested to measure inflow rates.

GDO approval was granted in early October, allocating \$200k to the project (\$50k for Sandia, \$150k for Cal Energy). Cal Energy and Halliburton will cost-share in the project by providing \$100k each in in-kind services. The project began in early November.

FUTURE PLANS

Testing of the drillable straddle packer will be performed over the next year in the Packer Demonstration Facility. Confirmation of the sealing capabilities of the packer with cement will be sought. Tests will also be conducted in the Packer Demonstration Facility with open-end drill pipe to demonstrate the results of conventional cementing practices. Following these tests, planning for a field test of the drillable straddle packer will begin.

The cementitious mud field testing project will continue. Reports and conference papers will be written that document the results of the project.

Laboratory and field testing of polyurethane foam pumped from the surface may also be undertaken within the next year. This technique could prove effective for sealing unconsolidated or fractured formations in shallow lost circulation zones, for example within 500 ft of the surface. Discussions have been held with a major geothermal operator interested in investigating this approach. Such tests would also provide data useful in the development of the porous packer.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
California Energy Company Halliburton Services	Cementitious mud testing
Unocal Geothermal	Polyurethane foam testing

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INSTRUMENTATION DEVELOPMENT IN SUPPORT OF THE GEOTHERMAL INDUSTRY

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KEY WORDS

Logging and logging tools, slimhole tools, high-temperature tools, downhole measurements, memory tools, pressure, temperature, spectral gamma, fluid/gas sampler

PROJECT OBJECTIVES

Downhole measurement tools are used by the hydrocarbon industry to calibrate surface geophysical experiments, to establish reservoir parameters, and to provide engineering data for drilling and production. Such measurements are not common to the geothermal industry. It is not that suitable tools cannot be built, but rather a lack of market has stymied progress. Thus, Sandia is building a suite of tools that will be made available to industry to demonstrate efficacy. When mature, this technology and the associated intellectual knowledge will move into the industrial sector.

Technical Objectives

Develop instruments that:

- Are low cost, yet provide high data quality;
- Are transportable by common air carrier;
- Are two inches in diameter or less so suitable for slim, diamond-cored holes;
- Can operate to 400°C (750°F);
- Can operate on a "slick line," not an electric wireline; and
- Can be programmed for different operations and operating conditions.

Expected Outcomes

- Establish a viable downhole measurements service industry.
- Provide downhole data for drilling, reservoir evaluation, and remediation.
- Establish a bridge between the hydrocarbon and geothermal logging industries.

PROJECT BACKGROUND AND STATUS

Hostile environment tools found in the traditional logging service industry are capable of operation to 260°C (500°F), and thus are applicable to some, but not all, geothermal applications. Furthermore, size constraints are imposed by the diamond coring techniques used in some geothermal operations. Taken together, the temperature and the tool diameter provide initial criteria for the design of logging equipment. Given present needs and realistic technologies, a modern tool will be operable at 400°C (752°F) and will be about 50 mm (2 inches) in diameter.

Conceptually, two classes of tools are able to meet these criteria. The first class utilizes an electrical wireline to transmit power and data between the tool and the surface, and it is exemplified by tools common to the logging industry. The second class is completely self-contained in that power is obtained from batteries, and data are stored in a memory system. Even though memory tools have been around for decades, they have not found common usage due to past limitations. This situation is changing rapidly due to improvements in digital technology.

Both classes of tools were used to make high-resolution temperature measurements in the VC-2B scientific corehole to 295°C (563°F). While data were of equivalent quality, the tool using an electric wireline failed about one-half of the time due to wireline or cable-head difficulties. Significantly, the memory tool has never experienced a data loss. This record includes the faithful recording of fishing exercises made when the tool was twice dropped through 2.5 km (8,200 feet) of internal upset drill pipe.

Cost considerations weigh heavily in the establishment of logging services, and memory tools are effective due to a number of issues. These tools are programmed at the surface by linking the tool to a personal computer running a simple, menu-driven program. This fact, coupled with the point that the tools are rugged and mechanically simple, minimizes operator training. It has been found that personnel will become operators after a day or so of hands-on experience. Secondly, the slick line deployment system is almost always available on site so exercises may be undertaken on the spur of the moment and without the mobilization and maintenance of a special truck. Finally, while the development cost of prototype tools is understandably high, it is envisioned that simple tools will become inexpensive almost to the point of being expendable (estimated to be 0.1 % of hole cost). Memory tools then will be suitable for high-risk duty.

While memory tools are inexpensive, logging engineers raise the point that the memory concept is flawed by the lack of communication between the tool and the operator. The greatest concern is that a tool will fail, yet the logging run continues due to lack of information. Perhaps future tools will possess some means of communicating a failed condition to the surface. In any event, memory tools must possess reliability to be creditable.

In the same vein, logging strategies are often evolved on the basis of real-time data. Memory tools preclude this approach. This point is not as valid now as it was in the past since newer computer systems support languages that are "intelligent." Thus, a logging strategy that contains contingencies may be programmed into the tool. Finally, the power available in a battery operated tool is limited. This means that power-intensive measurements are constrained to short duration.

The Sandia Memory Tool Program was initiated in 1990. It has reached a stage where tools are either in hand, or in the late test stage. The next step involves an increasing interaction with the geothermal industry to demonstrate their usefulness.

APPROACH

Three memory tools form the backbone of the initial Sandia tool suite. These tools meet the temperature and size criteria noted above. The background and status of these tools is discussed in the following paragraphs.

Pressure/temperature measurements are necessary for the evaluation of geothermal reservoirs, and they are relatively simple to make. Thus, the initial Sandia program concentrated on such a tool, and it has been successfully used in the field (see next section). This tool will form the basis for future tools since many engineering principles were proven in its evolution.

The second tool in the Sandia suite measures the gamma ray emissions from formation materials. These emissions originate in the decay of potassium, and uranium and thorium daughter products. Each element produces gamma rays of a characteristic energy, and the tool resolves the overall spectrum into its component parts. Thus, an assay for a few elements is available. Past work by the hydrocarbon industry has tied these assays into useful geologic information. Such work remains to be done in geothermal formations.

The final tool in the Sandia suite collects specimens of borehole fluids and gases. This tool is based on the pressure/temperature tool in that many component parts are identical. The programming capabilities of the former tool are used to "trip" the sampler at appropriate states in the borehole. This tool is supported by the Department of Energy (DOE) Office of Basic Energy Sciences.

RESEARCH RESULTS

The pressure/temperature tool was used extensively in the DOE-funded Sulfur Banks Drilling Program. Work here was in support of an industry/national laboratory/academia consortium to better understand the interactions of fluids with rock material in The Geysers Geothermal Field. Data were incorporated into the projects data bank; they are currently being evaluated by the science team. The pressure/temperature tool worked satisfactorily in all respects. A paper detailing the design and construction of this tool may be found in the Proceedings of the DOE Geothermal Energy Program Review XII, 1994.

The pressure/temperature tool was also used at The Geysers by Unocal in a log-inject-log experiment. In this work, a preliminary log was made of a well that had been quiescent for several weeks. Fluids were then injected, and they moved into regions that were permeable, and cooled them. A second log then identified the permeable zones. These data are currently being evaluated by the Unocal team. Data such as these identify production zones as well as lost-circulation zones in non-reservoir portions of a hole.

The spectral gamma tool was run for the first time in the Sulfur Banks hole. This test was the first ever in the world for a memory spectral gamma tool. The tool records emissions from potassium, and the daughter products of uranium and thorium. It can also resolve other spectra such as that produced by radioactive tracers used in inter-well tests.

Figure 1 shows the potassium signal as the tool was moved through a region of alternating fractured and competent rock. Measurements were made through a slotted liner that was placed in the well to preclude collapse. Note that the counts peak in the vicinity of a massive lost circulation zone located at 1370 feet,

and at several other locations. A detailed correlation of these data with core is in progress; an early assessment suggests that potassium-bearing minerals have been deposited in existing fractures. Stationary, long-duration tests were used to establish counting statistics. This test must be viewed as a preliminary experiment since parameters such as data acquisition rates and logging speeds were unknown. Data are currently being evaluated. They do indicate fracture zones that were mineralogically perturbed by the deposition of water-soluble materials.

These data will be entered into the Sulfur Banks data bank when a final calibration is available. The tool is easily joined to the pressure/temperature tool so that multiple logs can be made during a single pass in a well.

A workshop was held in conjunction with Lawrence Berkeley Laboratory and Unocal to better define the problems associated with acid build-up at The Geysers. One outcome from this workshop was design criteria for the fluid/gas sampling tool. These criteria were incorporated into the tool, and it is approaching the test phase.

Finally, it is recognized that the initial Sandia tool suite will be completed in FY95. Thus, with a view to the future, an industry consultant was hired to assess the directions of the geothermal industry, particularly in regard to foreign versus domestic activities. The results of this investigation are preliminary, but they indicate a very strong movement to Indonesia and the Philippines, with a lesser thrust into Latin America.

FUTURE PLANS

FY95 will see the completion of the initial phase of the instrumentation program. A useful tool suite will be in hand, and the transfer of the technology and intellectual output of the tools to industry will be underway. FY96 will see a major thrust in this latter area. Preliminary indications are that the tools will see use abroad, and means for implementing such work must be found. Perhaps Sandia can best proceed by finding a service company willing to take over the day-to-day operations of the tools. However, the industry is fragile. Favoritism shown to one company will be at the detriment of the others. Just how to proceed is a subject for discussion with representatives of the geothermal industry.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	<i>Pressure/Temperature Tool</i> Slim-hole measurements in remote locations, Reservoir evaluation
Cal Energy	Lost circulation evaluation
Sulfur Banks Consortium	Reservoir evaluation
Unocal Sulfur Banks Consortium	<i>Spectral Gamma Tool</i> Fracture identification, mineralogy
Hydrocarbon Companies	Tracer studies using decaying isotopes
Unocal Calpine	<i>Fluid/Gas Sampler</i> Acid corrosion at The Geysers

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Figure 1. Potassium Spectral Gamma Log, Sulfur Banks Well, The Geysers Geothermal Field.

Potassium counts per ten-second interval as the tool was moved three times through a region of alternating fractured and competent rock. The upper and lower horizontal lines denote a three-standard-deviation variation about an arbitrary count value of 14.5.

SLIMHOLE DRILLING FOR GEOTHERMAL EXPLORATION

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KEY WORDS

Exploration, slimhole, flow testing

PROJECT OBJECTIVES

In the broadest terms, the research objective is to demonstrate that industry can increase exploration, through lower-cost slimhole drilling, to expand proven geothermal reserves. The crucial question to be resolved is whether slimholes can provide sufficient data to characterize a geothermal reservoir. Specific tasks derived from the research objective include:

Technical Objectives

- Join industry partners in a cost-shared, slimhole, exploration drilling program.
- Collect data from slimhole and production wells in existing geothermal fields.
- Correlate production and injection test data between slimholes and production size wells.
- Develop and validate a coupled wellbore-reservoir flow simulator that can be used for reservoir evaluation from slimhole flow data.

Expected Outcomes

- Drill at least two more exploratory slimholes which provide cost and performance data.
- Analyze and compare these data with corresponding data from at least one production-size well subsequently drilled near each exploratory slimhole.
- Publish all results and transfer slimhole exploration-drilling technology to industry so that it becomes an accepted method for geothermal reservoir identification.

PROJECT BACKGROUND AND STATUS

Geothermal development costs must be reduced by utilities and operators to be competitive in meeting the expanding requirements in the West for environmentally benign, alternative energy sources. An industry survey in 1992 identified drilling costs associated with exploration and reservoir assessment as a major factor affecting future geothermal development. Industry participants were generally enthusiastic about the concept of lowering these costs with slimhole drilling, but were strongly in agreement that the technique needed adequate demonstration. Slimhole drilling has been shown to reduce oil and gas

exploration costs by 25 to 75%, but the more hostile conditions for geothermal resources present technology challenges which must be solved before the cost impact there can be thoroughly evaluated. Once demonstrated, slimhole drilling technology will have application to geothermal exploration and reservoir assessment in both the U. S. and international markets.

The principal experimental work in this program to date has been drilling an exploratory slimhole in the Steamboat Hills geothermal field near Reno, Nevada. Data from this well includes drilling reports, core logs, and cost reports submitted daily, many temperature logs during drilling, and downhole pressure-temperature-spinner (PTS) logs taken during four series of flow and injection tests performed in the 3.9-inch diameter, 4000-foot deep hole. In-house analysis of these data is complete, and a detailed report on the project has been published.

APPROACH

We have a coordinated working group including personnel from Sandia, Lawrence Berkeley Laboratory, University of Utah Research Institute, U.S. Geological Survey, geothermal operators, and independent consultants focused on this program. This group is involved to a greater or lesser extent in all decisions affecting the direction of the research. In addition to the Geothermal Research Department staff directing this program, other Sandia organizations such as the Fluid Flow and Transport, Computational Fluid Dynamics, and Thermal and Fluid Engineering Departments are providing significant support.

RESEARCH RESULTS

Drilling operations at the Steamboat Hills (SH) well SNLG 87-29 were completed in September 1993, but analysis of the data continued into FY94. There have been two major aspects of this:

Compare wellbore flow simulators – During analysis of the Steamboat Hills flow tests, three different wellbore simulators were run and compared with each other and with the field downhole data. The simulators were GEOTEMP2, developed by a Sandia contractor and modified in-house to improve its capabilities; WFSa, developed primarily by Hadgu at LBL; and GEM, developed in Sandia's Thermal and Fluid Engineering Department. Each of the codes gave reasonable agreement with field data, although GEOTEMP2 was not used extensively because of its tendency to deviate significantly from field data near the surface. All these codes require specification of either downhole pressure at the feed zone or mass flow rate, with the simulator then calculating the other quantity. In an extremely permeable reservoir such as this one, the codes' assumption of a constant pressure at the feed zone may be acceptable, but in other reservoir types it will not be realistic. This points to the need for a coupled wellbore/reservoir simulator for more general slimhole modeling.

Organize and analyze Steamboat Hills test data – When this project was conceived, one of the major incentives was the operator's desire to learn whether a higher-temperature reservoir underlies the one currently produced. The 1993 drilling showed that this is not the case, at least down to 4000 feet (see Figure 1), but test results did show high permeability and economically useful temperature down to almost total depth. Results of the drilling and testing also validated the basic data collection strategy for both downhole and surface measurements. This work is described in detail in Reference 4, but conclusions and recommendations for further slimhole testing are given below.

Conclusions: We believe that field results validate our testing strategy for this slimhole. Because drilling and testing conditions are so site-specific, we do not claim that the procedures used at Steamboat Hills

are a universal recipe, but this is a solid first step toward developing a general method for slimhole exploration. In particular, we have compared test measurements with wellbore models, and have made a convincing case for the ability to predict flow in this type of reservoir. Other conclusions are below.

1. Slimholes can be flow-tested, with successful surface and downhole measurements. Relatively cheap and simple surface measurements (James tube and weir box) can give flow rate and enthalpy.
2. Internal flow in the wellbore greatly complicates the analysis of attempted pressure transient (build-up or fall-off) tests. This emphasizes the need for better definition of intra-wellbore flow.
3. The strategy used for the SH tests appears to have produced the necessary test data, taken with appropriate accuracy, to evaluate the commercial potential of a larger well at this location.
4. Numerical simulation of flow in the wellbore can yield a predictive curve of flow rate versus wellhead pressure. Applied to a larger diameter well, this same simulation will give the same kind of production curve, giving a measure of the reservoir's commercial potential. Extrapolation from the SH slimhole data to the wellbore diameter of a near-by production well gave a reasonable estimate of the larger well's actual flow rate for a given wellhead pressure.
5. The deeper, hotter reservoir postulated in this field was not encountered down to 4000'. There is, however, significant permeability below the 815' production zone, implying that water hotter than 300°F can be pumped from deeper zones, or water from a power plant could be injected into these zones.
6. The Steamboat Hills reservoir is extremely permeable; calculations of transmissivity are probably lower bounds.

Recommendations: Although the test results in SNLG 87-29 are encouraging, this highly fractured, highly permeable, reservoir may not be generally representative of other geothermal resources. Exploratory drilling and testing in reservoirs with different flow characteristics, and comparison of those results with production wells in the new reservoirs, will resolve the question of broad applicability.

A consequence of moving to other types of reservoirs will be the increasing need for better modeling capability, especially in terms of coupling a reservoir simulator to a wellbore simulator. As briefly described above, the assortment of wellbore models used to date give reasonable predictions of flow behavior, but the codes' performance is enhanced, or perhaps even made possible, by the extreme transmissivity of this specific reservoir, which allows the assumption of a fixed pressure at the feed zone to be realistic. In other reservoirs, this may not be the case.

There are also areas in which the instrumentation and data-collection strategy used in these tests could be improved. An enhanced instrumentation development could be a collaborative effort between Sandia and industry, or could be stimulated in industry alone by increased commercial slimhole exploration. Specifically, the following testing concerns should be addressed:

1. Spinner measurements should be done with a tool which can distinguish flow direction (up or down); this feature is presently available in some commercial logging services, but is not always used. Data from most spinner tools is probably only good when the tool is moving bow-on into

the flow (logging down), so data acquired logging up (flow stern-on) should be disregarded. Logging at a slower line speed will increase the probability that flow is bow-on to the tool, but the lower relative velocity makes the spinner more likely to stick. Careful analysis of the internal flow seems to be more important for slimhole exploration than in conventional production-size well testing because of the increased emphasis on down-hole instrumentation in the slimhole testing.

2. As an aid to interpretation of the internal flow, accurate static pressure-temperature logs should be run at regular intervals, particularly when drilling data or core indicate that new high-permeability zones have been penetrated. Examination of the points on these logs where deviation of the pressure gradient coincides with changes in the temperature gradient should reveal sources and sinks of intra-wellbore flow.
3. Optimum logging speed should be established; most of the service companies run their tools at 50 to 100 feet/min, which may be too fast for the pressure and temperature resolution needed in comparison of modeling and field data.
4. Data drift caused by internal heating of the downhole electronics became significant because of the distortion of the data and because of the limitation this placed on the time available to do certain tests, particularly pressure transients. If these tests are thought to be valuable, a different testing technique, perhaps capillary tubing from the surface, or the use of tools with longer high-temperature-residence times may be necessary.
5. During development of slimhole testing methodology, commercial PTS logging tools should do static temperature logs at the beginning and end of each test series. These temperature logs could then be compared with each other and with some reference standard, such as the Sandia temperature tool, to evaluate the drift in the tool during the tests.
6. Static water level in the well should be measured at regular intervals, probably daily, to keep track of the formation pressure in the permeable intervals penetrated to date.

Finally, the experience during the Steamboat Hills project showed the value of real-time, on-site data analysis. Software which could have compared downhole data with a wellbore simulator during the test sequence would have indicated malfunctioning instrumentation, or reservoir anomalies, quickly enough to have either taken remedial action or have changed the testing methodology appropriately.

FUTURE PLANS

For slimhole exploration to become widely useful, it must be applicable to different reservoir types and must be accessible to the small, independent geothermal developer. The best strategy for demonstrating applicability is a continuation of cost-shared drilling projects with industry, choosing these projects carefully to gain experience in a variety of locations and reservoir types. Sandia has signed Letter Agreements with two companies (see below) for drilling on their leases in Oregon. We expect these holes to provide data in reservoir types significantly different from Steamboat Hills, but we are still awaiting confirmation of funding before proceeding with contracts for the drilling operations.

To help bring slimhole exploration into common use, we propose to work toward at least the following products:

- Guidelines for drilling and completing exploration slimholes;
- Recommended test procedures and strategies, including data requirements, for the slimholes;
- Improved downhole instrumentation to collect needed data;
- Data interpretation techniques, possibly in the form of a PC-compatible flow simulator which could be distributed at a nominal expense to independent developers. Use of this software would allow basic reservoir evaluation from slimhole data and, once accepted as an industry standard, would be considered sufficient support for development financing; and
- Publication of analysis and experimental procedures which have led to the above products.

Successful technology transfer will require broad dissemination of our test results and analysis. This can be done by sponsorship of industry workshops, publication in technical journals, appearances at professional meetings and reviews, and personal contact through the working group and industrial partners.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Far West Capital	Cost-shared exploratory drilling at Steamboat Hills, NV (complete)
California Energy Company, Inc.	Cost-shared exploratory drilling at Newberry Caldera, OR
Trans-Pacific Geothermal Corporation	Cost-shared exploratory drilling at Vale, OR

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Figure 1

J. T. Finger, R. D. Jacobson, C. E. Hickox, R. R. Eaton, "Steamboat Hills Exploratory Slimhole: Drilling and Testing," Report SAND94-0551, Sandia National Laboratories, Albuquerque, NM, 87185-1033.

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ACOUSTIC DATA TELEMETRY

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KEY WORDS

Acoustic telemetry, measurement while drilling (MWD), waveguides, communications, production monitoring

PROJECT OBJECTIVES

Develop a new communication link between downhole instruments and the surface. The new link using acoustic data transmission through pipe has the potential to greatly increase data rates, thereby expanding the availability of downhole data at the surface. Improved data acquisition is expected to significantly reduce drilling costs.

Technical Objectives

- Provide MWD technology with higher data capacity.
- Provide MWD technology for air drilling.
- Provide wireless data link for production-monitoring technology.

Expected Outcomes

- Reduce drilling costs. Both banking and industry sources have estimated that successful deployment of an MWD system with increased data capacity would double or triple the MWD industry's gross income over a few years. This is a potential payoff of \$1 to \$2 billion in short-term growth of annual revenues to an industry which is critical to the future reduction of geothermal drilling costs.
- Improve reservoir management. Currently production monitoring tools are deployed with hardwire connections. This wireline represents 80% of the tool cost and 85% of the tool failure. Wireless telemetry could potentially eliminate these undesirable factors. The wireless telemetry project is expected to result in a less expensive tool available to a broader segment of the market.

PROJECT BACKGROUND AND STATUS

Collection of navigation data at the drill bit and transmission to the surface rig is done in real time on virtually every off-shore drilling rig in the world. Logging data is often included in this transmission. This technology is called "Measurement-While-Drilling" or simply MWD. The hardware to transmit data from the drill bit to the surface is the key to the success of the measurement-while-drilling industry.

Current commercialized technology is based upon mud pulse telemetry in which pressure pulses are generated in the mud by periodically constricting the flow through the drill string. This critical service is expensive (about \$10,000/day) and, therefore, relatively inaccessible to the geothermal industry.

The transmission rates using mud pulse telemetry are also slow (< 1 binary bit/second), which limits the service primarily to collecting drilling navigation data. It is virtually axiomatic that these data rates are a factor of 10 to 100 too slow to accommodate the customer demands for real-time transmission of drilling parameters and formation data. Acoustic telemetry can meet this need by transmitting data via elastic waves in the steel pipe of the drill string. More comprehensive logging data could be transmitted in this type of system. Because of these advantages, acoustical telemetry was first attempted in the 1940's, but due to the complex wave physics associated with this type of data transmission, no successful commercial system has yet been developed.

Numerous advances have been made, including feasibility studies which demonstrate that even weak elastic waves will propagate over a mile in drill strings. This work has produced several patents, numerous technical publications, and active industrial participation. Novel hardware has also been designed and successfully field tested.

APPROACH

In Sandia's past work, the empirical approach of industry was augmented with a more systematic approach directed at the fundamentals of acoustic telemetry. Computer simulations, experimental data, and field test results were assembled which demonstrated the existence of acoustic transmission bands strongly correlated to theoretical predictions. Another past objective was to demonstrate that transducer arrays could be developed and used to directionally project and measure acoustic energy in the drill string.

Several MWD devices have been designed, built, patented, and licensed to an industrial partner, Baker Hughes/INTEQ. Recently, the work has branched into another application of acoustic telemetry. A wireless telemetry tool is being developed with another industrial partner, Baker Oil Tools. This tool will monitor reservoir temperature and pressure. It is designed as a low data rate tool for monitoring reservoir parameters in a production well. Costs are being shared with the Natural Gas & Oil Technology Partnership (Department of Energy) and Baker Oil Tools.

Sandia originally conceived this project because of their familiarity with wave propagation in solids with periodic structure. It was quickly realized that physical concepts, computer algorithms, and experimental methods that had been developed for studying stress wave phenomena in missile heat shields could be directly applied to the telemetry problem. Throughout this work, exceptional correlations between this model and field test data have been demonstrated and significant advances have been made. Recent analysis and field test of the attenuation mechanism has yielded significant insight into this aspect of the problem. It is evident that the majority of signal loss is due to coupling between axial, torsional, and bending motion in the drill string.

Work on an advanced transducer design, as well as the evaluation of array responses, is now in progress. Deployment of a new downhole signal generator (the Oracle) was delayed due to funding restrictions but is nearing completion. This equipment will be used to test signal modulation methods in test wells. Other future work will build upon the existing system code, the surface simulation facility which has recently been expanded to ~ 1400 feet, and the field test system. Field test devices will emerge which can

more economically collect information on attenuation on ambient noise. Finally, the surface simulation facility will serve as a testbed for full-scale transducer arrays.

RESEARCH RESULTS

A series of field tests to evaluate the acoustic transmission characteristics of production tubing have been completed. The data reveal the existence of transmission bands at higher-than-expected frequencies. These frequencies approach ~2500 Hz. In the same series of tests, sound transmission qualities of various completion equipment were also tested. For example, the data show that downhole packers block less than 4 ~dB of the data transmission signal. The initial layout of a new transmitter design has also been completed. This design avoids many of the difficult assembly problems inherent in the original transducer design used by Teleco.

During this year, the length of the surface simulation facility has been increased to 1400 ~feet. The acquisition and outfitting of a mobile laboratory has also been completed. It has seen extensive use in the field (see paragraph above) and is currently being used to measure ambient noise levels in various types of production wells. These measurements are critical to the determination of transmission range for the new tool being developed for Baker Oil Tools. Work has progressed on the Oracle—the downhole, microprocessor-controlled transmitter. Work on this device was slowed considerably by funding restrictions; however, most of the programs for controlling the power supply are completed. The normal problems associated with debugging any feedback circuit have been experienced, but the system will be ready for field operation by late summer.

FUTURE PLANS

Two tools will be developed simultaneously. The first tool is the Oracle. This tool will demonstrate a capability to send and receive data transmitted through a drillstring which is rotating off bottom. This tool will be used in a series of field tests designed to acquire key information for the future design of a prototype transmitter for high-data-rate transmission during drilling operations. The second tool is a new transmitter for production applications. This tool operates at a much lower data rate, and will not be used during drilling operations. Prototype development is in progress. By the end of fiscal year 1995, the prototype tool will be installed in the surface simulation facility. Upon completion of a series of surface tests, the tool will be fielded in a commercial well.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Baker Hughes/INTEQ	Patent license, loan of equipment and test data.
Baker Oil Tools	Active prototype-tool development program, (1.5 FTE). Cost sharing of field testing.

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LONG VALLEY EXPLORATORY WELL

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KEY WORDS

Exploration, magma, caldera, Long Valley, instrument test bed

PROJECT OBJECTIVES

Expansion of geothermal energy's market share depends on three major factors: identification of promising thermal sources, evaluation of their commercial productivity, and technology development that will permit access to them. The goals and objectives of this project are directly tied to each of those factors.

Identification of promising thermal sources - Much future geothermal development will, in general, depend on the presence of large thermal reservoirs in young silicic calderas. It is believed that very large heat sources exist in formations such as Long Valley caldera (USGS Circular 790 estimates 4800 quads there), and heat flow measurements in the caldera tend to confirm that belief. On the other hand, it is uncertain that caldera heat sources with much of their thermal energy in molten rock can be reliably detected with surface measurements. The Long Valley well is located at the point of maximum uplift on the caldera's resurgent dome and above a widespread aseismic zone at depth. The aseismic zone (below which no earthquakes occur) is believed to be associated with the brittle-ductile transition for basement rock, indicating a temperature above 350°C. The Long Valley Exploration Well (LVEW) is therefore ideally located to investigate the nature of deep heat sources within the caldera.

Evaluation of commercial productivity - In spite of the evidence indicating great thermal resources beneath Long Valley, and even after significant commercial exploration, power on-line in Long Valley remains limited. The principal reason for this, and for the wide variation of temperature at a given depth, is that coupling between the heat source and the hydrothermal system is not well understood. Lateral groundwater transport can, and apparently does, mask the presence of a deep heat source from surface or shallow downhole measurements. By getting below the lateral flow, we can not only get a measure of the deep heat flow (critical for long-term strategies such as magma or hot dry rock), but can evaluate the permeability of the reservoir at the productive interval (necessary for conventional hydrothermal development.)

Technology development - To gain access and acquire useful information from holes at great depth and extreme temperature, improvements are necessary in both the drilling hardware and the instrumentation. Most geothermal drilling equipment is derived from the oil and gas industry, but there is little incentive for that industry to address geothermal problems because of the relatively small number of geothermal wells drilled each year (~ 0.1% the number of oil and gas wells.) To advance the state-of-the-art in geothermal exploration, evaluation, and production, public funds are necessary for the required research, and this is the Department of Energy's (DOE) rationale for sponsorship of geothermal research projects such as this. Even after laboratory development, however, proof tests in the field are imperative before the technology can be transferred to industry, and, since the projected drilling is expected to reach temperatures near 350°C, there will be an opportunity to test hard-rock bits and high-temperature logging

tools under development at Sandia National Laboratories, as well as to evaluate new products proposed by service companies.

As a separate issue, it should be noted that the scientific value of deep drilling in Long Valley is unique, since access to the near-magmatic environment in a young caldera is available nowhere else. The existing well is already the deepest exploration of the caldera, and Phase III is predicted to penetrate the basement rock's brittle/ductile transition zone.

Technical Objectives

- Improve definition of the hydrothermal resource in the caldera. Determine whether crustal magma exists at depths less than 8 km (25,000 feet). Test new drilling technology, and to further scientific understanding of the caldera formation and evolution process. Improvement of the hydrothermal resource definition will expand commercial development in this region of extremely high thermal potential.
- The first two phases of this deep exploratory well have been drilled on the south-central part of the resurgent dome in Long Valley caldera. The location is coincident with a large number of shallow (5-7 km) geophysical anomalies identified through many independent investigations. Phase III, the next stage of the hole, will reach a depth of approximately 14,000 ft, or into the brittle-ductile transition zone.

Expected Outcomes

After completion of Phase III, the following activities may be possible, partly depending on whether the hole reaches the granite carapace of the hypothesized magma chamber:

- Investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor, thus evaluating the commercial hydrothermal potential of this area;
- Unequivocal identification of the geophysical anomalies thought to be magma;
- Determination of the amount of collapse and subsequent resurgence of the central portion of Long Valley caldera;
- Determination of the intrusion history of the central plutonic complex beneath the caldera, and establishment of the relationship of intrusive to eruptive events;
- Tests of advanced drilling and instrumentation hardware in a rigorous, realistic environment; and
- A definitive assessment of the local thermal resource, provide a stringent test of the hypothesis that magma is still present within the central plutonic complex, and calibrate the geophysical techniques used to identify this location as a thermal target.

PROJECT BACKGROUND AND STATUS

This is a phased project. Phase I, drilled in 1989, reached 2568 feet with big hole and an additional 185 feet of continuous core; Phase II (1991) deepened the large-diameter hole to 6825 feet and extended a core hole to 7578 feet; and Phase III is projected to reach approximately 14,000 feet. Preliminary Phase III work (including cementing a tie-back casing, installing a high-pressure wellhead, and directionally re-drilling the 12-1/4" hole below the casing shoe) was done in 1993. Scientific investigations in the wellbore have been done in the previous intervals between drilling operations, and are now planned to run before and concurrently with Phase III drilling. This well will yield significant improvements in geothermal resource assessment, scientific knowledge, and advanced drilling technology that can be obtained in no other way.

FY94 activity comprised: support for a Sandia experiment in acoustic telemetry development; remedial cementing to repair an uncemented portion of the 13-3/8" casing; running tie-back casing from the top of the 13-3/8" liner (at approximately 1600 ft) to surface; and directionally re-drilling 12-1/4" hole to 7188' to reduce the hole deviation below the 13-3/8" casing shoe in preparation for Phase III core drilling.

Scientific interest in this hole is also exceptionally high. A proposal to support Phase III drilling has been submitted to DOE Office of Basic Energy Sciences. This would involve a change in hole design, allowing Phase III to be continuously cored for greater scientific benefit, but this is still completely consistent with the aim of better understanding deep fluid circulation in the caldera.

APPROACH

DOE's approach is to coordinate the drilling and scientific activities on this well to satisfy a wide spectrum of needs defined by government agencies, the scientific community, and the geothermal industry. In addition to DOE funding, the project has already been supported with \$1.5 million from the California Energy Commission, and we will continue to pursue cost-sharing for the remainder of the project.

RESEARCH RESULTS

The acoustic telemetry experiment, which is described in detail with that project's annual report, involved suspending an instrument package in the wellbore on approximately 6000 ft of drill pipe. A unique requirement for these experiments was the necessity of arranging the joints of drill pipe in order of length. This involved laying out over 200 joints of pipe on racks, measuring each to $\pm 0.01'$, and arranging them on the racks such that they would be picked up by the drill crew and run into the hole in the proper order. Since the drill rig was already in use for another experiment, which only involved one or two men from the crew, this pipe handling was done at little extra expense and contributed to a very significant advance in the acoustic telemetry program. The difficulty and expense of doing this critical experiment elsewhere illustrates the value of this site as a test bed for many types of drilling hardware development.

Remedial cementing of the 13-3/8" liner was required because a malfunction in the cementing equipment during Phase II drilling had left the zone from approximately 3300' to the top of the liner (at $\sim 1600'$) with no cement behind the pipe. This is important because the Bureau of Land Management requires testing the casing lap to 3000 psi before further drilling. Once the remedial cementing was complete, the lap

was pressure-tested and tie-back casing (13-3/8") was run from top of liner to the surface. This allowed attachment of a higher-pressure (5000 psi) wellhead to accommodate the blow-out prevention equipment required by the BLM for Phase III core drilling.

Directional tools with measurement-while-drilling (MWD) were then used to drill out the shoe at 12-1/4" diameter and straighten the hole. Deviation was approximately 2.75° at the shoe, but decreased to 1.5° at the final depth of 7188'. With the high-pressure wellhead and relatively low deviation, the hole is now in excellent condition to be deepened by a third major drilling phase. Another encouraging factor is the significantly improved bit life in the directional drilling, compared to that experienced in drilling this same formation in 1991. This supports an earlier speculation that bottom-hole-assembly design was a major contributor to inadequate bit life in Phase II drilling.

In conjunction with the drilling and cementing operations, we cleaned and backfilled one of the drilling sumps, reclaiming it to a condition suitable for later abandonment. This disposes of a large quantity of drill cuttings from Phase II and provides room for mud cooling equipment, if required by subsequent drilling.

FUTURE PLANS

FY95 funding is insufficient to carry out Phase III drilling, so the principal effort will be directed toward support for additional scientific experiments, with maintenance and preparation of the site for subsequent drilling. Other activities such as road and fence repair, sump liner inspection and repair, and water well maintenance will require manpower and money.

Any remaining balance of FY95 funds will be carried over to FY96, to be coordinated with expected FY96 support from DOE Office of Basic Energy Sciences and the California Energy Commission, for Phase III drilling.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Both Vulcan Power, who holds the lease for the LVEW location, and California Energy Company, who gained leases in Long Valley through the Magma Power acquisition, have expressed strong interest in further data from the Long Valley Exploratory Well.

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J. Finger, R. Jacobson, "Drilling, Coring, and Downhole Testing at the Long Valley Exploratory Well"

C. Forster, R. Morin, M. Sorey, "Hydrologic Testing and Hydrothermal Modeling at the LVEW"

D. Hill, "Evidence for the Depth to the Brittle-Plastic Transition Zone and the ca. 400°C Isotherm Beneath the LVEW Site"

P. Kasameyer, P. Harben, "Seismic Monitoring in the LVEW"

P. Nelson, J. Kibler, J. Mikesell, "Geophysical Logs in the LVEW"

A. Romero, R. Gritto, T. Daley, E. Majer, J. W. Rector, "Analysis of VSP Data from the DOE Exploratory Well (LVF 51-20) at Long Valley Caldera, Eastern California"

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GEOHERMAL DRILLING ORGANIZATION

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KEY WORDS

Geothermal Drilling Organization, drilling technology, cost sharing, DOE/industry joint ventures

PROJECT OBJECTIVE

The Geothermal Drilling Organization (GDO) identifies and cost-shares short-term projects that result in a new drilling product or service for the geothermal industry directed at reducing drilling costs.

Technical Objectives

- Improve overall geothermal drilling operations while cutting costs.

Expected Outcomes

- Develop DOE/industry jointly-funded technologies that reduce costs and improve the drilling process.

PROJECT BACKGROUND AND STATUS

Geothermal drilling technology is based on oil and gas technology. The service industry that provides drilling and logging equipment has their primary market in the oil and gas business. Since the geothermal market is relatively small, modification of technology for geothermal applications usually requires payment of development costs. The GDO provides a mechanism for the geothermal industry to pool their resources to develop a product or service of direct (and usually broad) use to the geothermal industry.

Current on-going projects are: (1) improved Positive Displacement Motors for operation at high temperature with air - under development by Baker Hughes INTEQ; (2) development of new cement formulations for better casing protection in corrosive geothermal environments - being developed by Brookhaven National Laboratory, Halliburton, and Unocal; (3) adaptation of a retrievable whipstock to geothermal well conditions - being developed by AZ Grant International; (4) development of rotating head rubbers by AZ Grant International; and (5) testing of cementitious muds for lost circulation control in a geothermal well with California Energy Company, Inc., providing the test bed, Halliburton providing a proprietary cementitious material, Sandia providing some instrumentation, diagnostics, and additional subcontractor assistance - primarily mud logging.

APPROACH

The GDO is composed of geothermal operators and service companies. Potential projects are screened by an executive committee with the criteria that completion should result in a new product or service in

the near-term. Project proposals are then presented to the members at periodic meetings. Projects require at least two industry participating members with the Department of Energy (DOE). Cost sharing by industry is at least 50% in the form of cash or in-kind services. Most of the development work is completed by industry.

RESULTS

(1) POSITIVE DISPLACEMENT AIR MOTOR FOR HIGH TEMPERATURE

Two prototype 8 inch high-temperature air motor assemblies for high-temperature drilling have been developed by Baker Hughes INTEQ. Prior to final assembly, the sections of the assembly underwent extensive testing in the Baker Hughes INTEQ facilities in Houston, and Celle, Germany. These units were shipped to Bakersfield, California, and one unit was tested on December 8, 1994 in The Geysers field. The motor appeared to work. However, the temperature tabs indicated an unrealistically high temperature during the field test, in excess of 550°F. At this time, this unrealistically high temperature is believed to be due to some unwanted friction. The tool has been shipped to Houston where disassembly and diagnostics are to be performed, probably in January, 1995.

Cost: \$163,000 Duration: 2/17/93 to present

(2) RETRIEVABLE WHIPSTOCK FOR GEOTHERMAL WELL

A prototype 13 3/8 inch diameter retrievable Anchor Stock (whipstock) assembly has been developed by AZ Grant International. This combination anchor and whipstock provides a means of sidetracking in a cased hole. Portions of this assembly have undergone extensive testing in the AZ Grant Laboratory facilities in Tulsa and Houston. This prototype has been shipped to Healdsburg, California where it is awaiting arrangements for a field test to be completed. The 13 3/8 inch size is used primarily for geothermal drilling. Because there is little domestic geothermal drilling underway, and there is little oilfield drilling at this hole diameter, some difficulty has been encountered in securing a test for this unit.

Cost: \$31,000 Duration: 7/7/93 to present

(3) DEVELOPMENT OF ROTATING HEAD RUBBERS

AZ Grant International is optimizing a rubber compound for a rotating head and strippers. These compounds have been tested in the AZ Grant laboratory facilities in Houston. The earlier compounds proved to be too short lived, leaked too much, or both. Additional compounds are to be tested now that the AZ Grant laboratory facilities have been relocated.

Cost: \$30,000 Duration: 7/7/93 to present

(4) EVALUATION OF CEMENTITIOUS MUDS TO STEM LOST CIRCULATION

California Energy Company, Halliburton and Sandia conducted a preliminary field test of cementitious mud in California Energy Company's Coso well. This cementitious mud is for control of lost circulation. Tests took place throughout November and December, 1994. Additional testing will begin in January, 1995. Results are being analyzed.

Cost: \$200,000 Duration: November 1994 to present

FUTURE PLANS

The industry is taking an active role in identifying new projects for future funding. New projects that are in the pre-proposal stage include a scheme for generation and injection of CO₂ gas in geothermal wells during drilling to retard corrosion, a very high-speed air motor, and high-temperature logging tools.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Below are the names of specific present collaborators with the DOE and their particular interests. However, it should be emphasized that the entire GDO membership is interested in improving the overall geothermal drilling operation while cutting costs. It is hoped that the operating companies will take up the new technology in their operations.

Organization(s)	Type and Extent of Interest
Baker Hughes INTEQ	Positive displacement air motor
AZ Grant	Retrievable Whipstock Rotating Head, Stripper Rubbers
Halliburton	Development of new cement formulations Evaluation of cementitious muds
California Energy	Evaluation of cementitious Muds

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Geothermal Drilling Organization - Charter

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GEOHERMAL HEAT PUMPS

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KEY WORDS

Geothermal heat pumps, ground source, space heating, air conditioning, HVAC, energy efficiency, Strategic Environmental Research and Development Program (SERDP)

PROJECT OBJECTIVE

Geothermal Heat Pumps (GHPs) have gained international attention as a proven means of energy conservation and demand reduction. However, the high first cost for residential and commercial heating and cooling applications is a major obstacle to market penetration of this technology. Our research program is aimed at reducing installation costs of the ground heat exchanger and, therefore, increase the marketability and effectiveness of the GHP technology.

There is also a general lack of awareness about this technology in the heating, ventilating, and air conditioning (HVAC) community. Our program includes outreach with the professional trade groups to help improve awareness. A comprehensive measurement program for installed GHP systems (funded by SERDP) has also been initiated. This measurement activity has the goal of solidifying the data base on system performance and identifying performance problems.

Technical Objectives

- Identify, demonstrate, and commercialize new drilling systems to reduce the installed cost of drilled ground source heat exchangers by 50%.
- Evaluate light-weight drilling hardware capable of installing a residential heat exchanger with minimal landscape damage in one day or less.
- Develop and document a set of case histories for GHP installations, including quantitative evaluation of system performance, cost, and design quality. This set will include four or more installations covering a wide range of weather and geological conditions.

Expected Outcomes

- Develop a vital industry-supported R&D program focused at reducing the first cost of GHP hardware. The high first cost of ground heat exchanger is a significant barrier to penetration of GHP technology.
- Establish a clear set of performance measurements of installed hardware which will allow the industry to more accurately set design specifications for existing technology, and to identify areas needing improvement.

PROJECT BACKGROUND AND STATUS

Sandia National Laboratories (SNL) initiated a modest GHP program in FY 92, funded through a combination of the Department of Energy's (DOE) Geothermal Division (GD) and the Department of Defense's (DOD) Strategic Environmental Research and Development Program (SERDP) sources. The tasks prior to FY 94 focused mainly on drilling technology applied toward installation of vertical ground source heat exchangers, acquiring data at a few GHP installations, and working with the California Energy Commission to evaluate GHP options in California. The arrival of the SERDP program and the Geothermal Heat Pump Consortium (GHPC) expanded the program emphasis to the three areas of drilling and completions, demonstration projects and tech transfer.

The use of GHPs is rapidly growing because the electric utilities, the Environmental Protection Agency (EPA), DOE, DOD, and the grass-roots GHP industry are aware of its outstanding potential to reduce energy and emissions associated with space conditioning. Our challenge for the next few years is to provide technology transfer services and solid research and development for this emerging technology, with the goal of increasing annual GHP sales from 35,000 units to 400,000 by the turn of the century.

APPROACH

The program consists of four basic elements:

- Performance of existing GHP hardware will be monitored with automated data acquisition equipment and documented so that the energy savings expected from this technique can be confirmed and areas for improvement identified.
- Advanced concepts for constructing improved geothermal heat exchangers will be developed and their performance confirmed through analysis and testing using a simple test loop at SNL or other test facilities at universities or organizations involved in GHP research. Suggestions for further research for drilling techniques and equipment will be made and implemented.
- A vertical loop handbook and training manual will be written to enable water of oil/gas drillers to enter the GHP marketplace.
- Finally, we will provide technical support for the DOE efforts to market and increase awareness of the GHP concept among A&E (architectural and engineering) firms, building owners, utilities, researchers, and government agencies.

All of the R&D work will be published in appropriate journals and/or presented at conferences and workshops.

RESEARCH RESULTS

- Four demonstration projects have been created on military bases (SERDP funding). All include comprehensive energy and performance measurement programs that are ongoing. Sites with SERDP funded demonstrations and/or measurement programs initiated in FY 94 include Fort Polk, Louisiana (two sites); Fort Hood, Texas; and Patuxent Naval Air Station, Maryland. Ground work was done for several additional projects for FY 95: Dyess Air Force Base, Texas; Camp

Merrill, Georgia; Selfridge Air National Guard Base, Michigan; Fort Leavenworth, Kansas; Fort Riley, Kansas; and Guam.

- Sandia established a jointly funded project with the Electric Power Research Institute (EPRI), Atlantic Electric, and Stockton College to acquire short-term and long-term performance data on the Stockton College GHP installation, where most of the campus was converted to GHPs. This project and the SERDP demonstrations are now yielding key engineering and cost data on the effectiveness of GHP systems.
- SNL installed and instrumented a GHP vertical test loop in Albuquerque. This facility identified a number of issues needing further research.
- SNL has consulted with many interested parties in government and the private sector on the advantages of GHP technology. SNL has provided consulting time to encourage developing GHP options for buildings at SNL itself, the SERDP military installations, Jemez Indian Pueblo, United World College, and the Danbury, Connecticut, Civic Center.
- A survey of vertical heat exchanger drilling techniques now in use around the country has been completed. This document has been useful for identifying inadequate drilling practices such as using worn-out or inappropriate drilling bits and educating potential drillers about the costs of vertical installations.
- Initiated interest in California by working with utilities and the California Energy Commission to complete a study on potential in California for GHP penetration. Two favorable areas (Sacramento and Truckee-Donner) were identified and demonstration projects defined. These projects will be jointly funded with industry in FY 95.

FUTURE PLANS

We want to develop families of improved heat exchanger concepts and drilling methods for GHPs and refinements of current technology. Our goal is to reduce installation costs of GHP heat exchangers by 50%. We plan to reach this goal by developing and testing improved drilling equipment and heat exchanger concepts. This involves thorough analyses of current GHP performance at several sites we are currently measuring to identify areas for improvement. The results of the measurement program and determination of improved heat exchanger concepts will be published in journals and presented at relevant conferences and workshops to increase the GHP technology awareness and ultimately increase the GHP market penetration within the HVAC industry. Our efforts at developing heat exchanger improvements will have a strong emphasis on using industry partnerships, and joint work with the Geothermal Heat Pump Consortium.

Education of the design firms and installation industry will be necessary to support an expanded use of GHPs. We intend to develop a training infrastructure to enable conventional water and/or oil/gas drillers to enter this field and quickly learn the appropriate technologies and equipment for this market.

We plan to maintain and expand our measurement program to determine the long-term maintenance and thermal performance of GHP systems. We will continue our efforts at technology transfer and consulting with potential end-users of GHP technology.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

There is a developing industry in this area which needs nurturing and is amenable to technology transfer and joint activities. The following industry entities have programs with the SNL/DOE GHP program. We anticipate expanded efforts in joint activities through FY 1995.

Organization	Type and Extent of Interest
Geothermal Heat Pump Consortium (GHPC)	Serve on R&D advisory panel
Atlantic Electric/EPRI	Joint program at Stockton State
Ground Source Energy, Inc.	Development of Coil Tubing drilling rig
California Energy Commission	Revision of Title 24 specs for GHPs
TU Electric	Joint measurement program at Fort Hood
WTU Electric	Joint measurement program at Dyess Air Force Base

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RESERVOIR TECHNOLOGY

GEOCHEMISTRY OF ALUMINUM IN HIGH-TEMPERATURE BRINES

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KEY WORDS

Aluminum, solubility, complexation, potentiometry, permeability, alteration

PROJECT OBJECTIVES

The objective of this research is to provide quantitative data on the principal aqueous species and the properties of aluminum minerals sufficient to model reliably the changes in permeability and brine chemistry associated with fluid/rock interactions in the recharge, reservoir, and discharge zones of active geothermal systems.

Technical Objectives

- Aluminosilicates are the dominant mineral phases controlling permeability and brine chemistry in geothermal systems. In order to model adequately changes in these critical reservoir parameters, a precise knowledge of the aqueous speciation of aluminum in aqueous brines is required, spanning the temperature and fluid composition ranges encountered in active systems.
- Detailed solubility measurements of aluminum minerals and potentiometric titrations of aluminum solutions are utilized to constrain the speciation and stability constants of dissolved aluminum species.
- New experimental methods and equipment are developed in order to perform accurate and unambiguous measurements at extreme conditions. A particular emphasis is placed on control and measurement of solution pH *in situ*.

Expected Outcomes

- A consistent set of thermodynamic parameters will be generated which will quantitatively describe the prevalent aqueous aluminum species and the chemical composition of solutions in equilibrium with rock-forming minerals at geothermal reservoir conditions.
- The results will be modeled in such a way as to be immediately incorporable into chemical reaction and transport computer codes in common use by the geothermal industry.
- New approaches developed in this program will be applied to other critical needs in the development of geothermal energy. Problems that will be addressed in future studies include brine reinjection, scaling, and corrosion in down-hole and in-plant systems.

PROJECT BACKGROUND AND STATUS

Prior to the initiation of this program there was considerable disparity among the sparse data sets available and quasi-chemical approximations employed in modeling aluminum transport in natural systems. Predicted solubilities and species distributions differed by orders of magnitude, especially when compared with actual field observations. We began with a systematic study of gibbsite - $\text{Al}(\text{OH})_3$ - solubility in NaCl brines as a function of pH at moderate temperatures (0-100°C). Independent supporting studies of the interaction of the aqueous aluminum species with pH-buffering agents, brine components, and water itself (hydrolysis) were carried out in parallel by other approaches, including potentiometry, Raman spectroscopy, and solubility. New methodologies for analyzing the aluminum content of experimental solutions to very low (sub-ppb) concentrations were also developed, utilizing ion chromatography. To date, 11 papers have been published as a result of this research, and the low-temperature geochemistry of aluminum is no longer in question.

Controversy remains, however, regarding the behavior of aluminum at temperatures above 100°C, where predictions based on extrapolation of our low-temperature data are in conflict with some recent studies, which also disagree with one another. Our current program is focussed on the solubility of boehmite - AlOOH - in the 100-300°C range, using a newly-developed potentiometric cell which allows continuous pH monitoring in conjunction with periodic sampling and analysis of the aluminum concentration in the aqueous phase.

APPROACH

The thermodynamic properties at infinite dilution, and the activity coefficients of $\text{Al}(\text{OH})_y^{3-y}$ ($y=0-4$) in zero to 5 molal NaCl brines are determined using a variety of solubility and potentiometric methods. Experimental studies have focussed on the solubility of gibbsite and boehmite, and the hydrolysis of Al^{3+} over a wide range of temperatures and salinities.

This effort benefits substantially from two projects funded by the Department of Energy (DOE) Office of Basic Energy Sciences, Geoscience Research Program, entitled "Fundamental Geochemistry of Geothermal Systems," and "Hydrogen-Electrode Potentiometric Studies of Geochemical Processes," as well as the project entitled "Physical Chemistry of Aqueous Solutions to High Temperatures and Pressures", funded by the Office of Basic Energy Sciences, 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.

The results of this research are provided directly, in the form of preprints, to John Weare at Scripps Institute of Oceanography, Harold C. Helgeson at University of California - Berkeley, and Everett Shock at Washington University, who are the active leaders in the development and distribution of fluid/rock interaction modelling codes for use by the geothermal community.

RESEARCH RESULTS

Much of our previous work has been summarized in a series of articles published recently in *Geochimica et Cosmochimica Acta* (Wesolowski, 1992; Palmer and Wesolowski, 1992; Palmer and Wesolowski, 1993; and Wesolowski and Palmer, 1994), in which we demonstrate that no additional experimental information is needed in order to model the speciation of aluminum in brines and the solubility of aluminum minerals below 100°C in dilute to concentrated brines over the accessible pH range at the low

concentrations of aluminum dictated by solubility constraints. Enhancement of aluminum mineral solubility by specific interactions of aqueous aluminum species with organic and inorganic ligands is being addressed in the companion projects listed above (see **APPROACH** section).

Experimental results obtained during the last year include extensive studies of boehmite solubility in 1 molal NaCl at 150, 200, and 250°C, and work is now in progress at 150°C in 0.1 molal NaCl. These results demonstrate that the solubility of boehmite is readily and precisely reversible over the entire pH range studied (i.e., the same equilibrium concentration is obtained by approach from super- or undersaturation at a given temperature and pH). Furthermore, forward and back pH titrations of the solid spanning periods of up to one month in a continuous experiment give precisely reproducible results, demonstrating the effectiveness of our newly-designed potentiometric concentration cell. Finally, boehmite is the only solid phase observed in both the initial and final experimental charges, as demonstrated from X-ray diffraction measurements.

Equivalent experiments using conventional methods would have: a) taken more than ten times as long; b) required the use of buffering agents to control pH, necessitating additional studies of the strength of the interactions between the buffers and the aqueous aluminum species; and c) would have been inherently less precise, due to the large uncertainty eliminated by making direct *in situ* pH measurements. This study serves to demonstrate the general utility of our new apparatus that will have a wide-reaching impact on both kinetic and thermodynamic studies of fluid/solid interactions in a variety of scientific disciplines and industrial applications.

Observed boehmite solubilities in strongly acidic and basic NaCl brines at these elevated temperatures are consistent with extrapolations based on our previous low-temperature results and modelling (Wesolowski and Palmer, 1994). We are currently working to develop an analytical approach which will permit quantitative analysis of aluminum in small samples collected near the solubility minimum (around pH 4-5). The neutral $\text{Al}(\text{OH})_3$ aqueous species, which was not needed in order to model our previous results at low temperature (<100°C), also appears to be significantly less abundant than would be predicted by other recently published boehmite solubility studies.

FUTURE PLANS

Studies of boehmite solubility will be completed in 0-1 molal NaCl brines and a quantitative model for the speciation of aluminum in high-temperature brines will be developed, consistent with our previous results at lower temperatures. Our efforts will then shift to a detailed examination of the reaction rates and thermodynamic properties of aluminosilicate reactions likely to control the acidity of geothermal brines and steam, such as the hydrolysis of feldspars according to the reaction

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Magma Power Company	Corrosion problems in Imperial Valley plants

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SALT EFFECTS ON STABLE ISOTOPE PARTITIONING

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KEY WORDS

Isotope, oxygen, hydrogen, brine, steam, mineral, partitioning, tracer, geothermometer

PROJECT OBJECTIVES

Technical Objectives

- Determine experimentally the partitioning of oxygen and hydrogen isotopes between geothermal waters and other phases (steam and alteration minerals formed in geothermal reservoirs) at elevated temperatures, and the effect of dissolved salts on the isotope partitioning.

Expected Outcomes

- Develop a set of internally consistent, precise results on the partitioning of oxygen and hydrogen isotopes among geothermal materials (waters, brines, steam, and minerals) at elevated temperatures, 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.

PROJECT BACKGROUND AND STATUS

The distribution of the stable isotopes of oxygen, hydrogen, and other light elements, which partition as a function of temperature and the bonding characteristics of individual phases, is widely studied in geothermal systems in order to constrain the time-temperature history of geothermal systems, the sources and fluxes of fluids, the extent of boiling and mineral deposition from the fluids, and the temporal relationship among alteration minerals. Numerous investigations of isotope partitioning at room temperature have demonstrated that there exist composition-dependent salt effects on the partitioning of D/H and $^{18}\text{O}/^{16}\text{O}$ ratios between brines and coexisting phases, such as steam, other volatiles (CO_2 , CH_4), and alteration minerals. However, at elevated temperatures encountered in geothermal systems, there are insufficient experimental data or theoretical models to predict salt effects on isotope partitioning.

The limited data available at elevated temperatures are conflicting, but indicate potentially significant isotope salt effects in the 100 to 300°C range, leading to errors on the order of 50°C in calculated temperatures and gross misinterpretation of fluid sources and fluxes, particularly in highly saline geothermal systems such as the Salton Sea and Guaymas Basin. Even in less-saline geothermal systems, the boiling processes associated with steam separation and mineral precipitation can produce deep-seated

highly saline fluid reservoirs. In order to model isotope partitioning during boiling/condensation and mineral precipitation/alteration involving brines, very accurate knowledge of the salt effect on isotope partitioning is required.

The current project started several years ago, together with complementary experimental programs at Oak Ridge National Laboratory (ORNL). Recently, substantial progress has been made on liquid-vapor equilibration experiments of salt solutions up to 350°C, and emphasis is being shifted toward hydrothermal experiments in mineral-water systems.

APPROACH

Utilizing the unique experimental facilities and expertise at ORNL, the salt effect on isotope partitioning is measured by means of salt solution-water vapor equilibration and salt solution-mineral exchange methods at temperatures up to 400°C. Changes in the partitioning of D/H and $^{18}\text{O}/^{16}\text{O}$ between liquid water, and water vapor and minerals as a function of the concentration of dissolved salts are modeled in terms of the activity coefficient ratios of the isotopic water molecules in the brines, in order to construct simple empirical equations for predicting the isotope salt effect in natural complex brines over a wide range of temperature.

This project benefits substantially from the program "Fundamental Geochemistry of Geothermal Systems" funded by the Geoscience Program of the Department of Energy Office of Basic Energy Sciences, in which more detailed, complementary studies are performed. This project is part of a program "Physical Chemistry of Geothermal Systems" at ORNL. The general objective of this program is to conduct laboratory experimental research utilizing unique facilities and expertise at ORNL for studies of selected chemical equilibria, thermodynamics of brine systems, liquid-vapor solute and isotopic partitioning, and other phase behavior.

RESEARCH RESULTS

Experimental studies of liquid-vapor equilibration of 0-6 molal NaCl solutions were completed from 50 to 350°C. Dissolved NaCl lowers appreciably (as much as 10 ‰ for 4 molal NaCl solution) the hydrogen isotope fractionation factor between liquid water and water vapor over the entire temperature range. In contrast, NaCl has little effect on the oxygen isotope fractionation factor at temperatures below about 200°C. However, with increasing temperature to 350°C, the oxygen isotope fractionation factor between liquid NaCl solutions and water vapor starts to deviate to more positive values compared to that between pure liquid water and water vapor. The largest oxygen isotope effect (0.84 ‰) was observed for a 5.4 molal NaCl solution at 350°C. The magnitude of the effect of dissolved NaCl on the liquid-vapor isotope fractionation factor, defined as $10^3 \ln \Gamma = 10^3 \alpha_{\text{L-V(pure water)}} - 10^3 \alpha_{\text{L-V(NaCl soln)}}$, is proportional to the molality of NaCl solutions at a given temperature. Our results are at notable variance with the literature data, which show large isotope effects of NaCl with very complex dependencies on temperature and NaCl molality. Based on our results coupled with low-temperature data from the literature, precise empirical equations were developed for predicting the isotope salt effects of NaCl solutions, which are valid from room temperature to 350°C in 0-6 molal NaCl brines.

Experiments for determining the effect of dissolved CaCl_2 (1 to 4 molal) on the oxygen and hydrogen isotope partitioning between liquid water and water vapor are nearly completed at temperatures to 200°C. It was observed that dissolved CaCl_2 changes measurably the partitioning of the both oxygen and hydrogen isotopes even at 200°C. The measured hydrogen isotope fractionation factors between liquid

CaCl_2 solutions and water vapor were always lower (up to 14 ‰) than that of pure water at a given temperature. The magnitude of the hydrogen isotope effect of CaCl_2 is nearly proportional to the molality of CaCl_2 . However, a close examination of the results indicates that the magnitude of the hydrogen isotope effects of CaCl_2 flattens slightly with increasing molality at 150-200°C. The effect of dissolved CaCl_2 on the hydrogen isotope partitioning changes little between 120 and 200°C. In contrast, the oxygen isotope fractionation factors for CaCl_2 solutions were always higher (up to 1.0 ‰) than that of pure water. The magnitude of the oxygen isotope effect of CaCl_2 is approximately linear with the molality of CaCl_2 at a given temperature, and decreases slightly with increasing temperature to 200°C.

Hydrothermal experiments of partial isotope exchange were carried out on calcite-water $\pm$ NaCl at 300°C and 1 kbar for a duration of 126 days, and on brucite-water $\pm$ NaCl at 200°C and 21 bar for a duration of 180 days. A calculated equilibrium oxygen isotope fractionation factor, $10^3 \ln \alpha(^{18}\text{O}/^{16}\text{O})_{\text{calcite-pure water}}$, was 5.88 ± 0.83 ‰. From the experiments of calcite-1, 3, and 5 molal NaCl solutions, we obtained $10^3 \ln \alpha(^{18}\text{O}/^{16}\text{O})_{\text{calcite-NaCl soln}}$ values of 5.65 ± 0.91 , 4.99 ± 1.02 , and 4.79 ± 0.21 ‰ for 1, 3, and 5 molal NaCl solutions, respectively. Calculated oxygen isotope salt effects ($10^3 \ln \Gamma(^{18}\text{O}/^{16}\text{O}) = -0.23$ to -1.09 ‰) are consistent with those obtained from the liquid-vapor equilibration method at 300°C. From the brucite-water $\pm$ NaCl experiments at 200°C, we obtained $10^3 \ln \alpha(\text{D}/\text{H})_{\text{brucite-water}}$ values of -28.8 ± 3.0 , -31.2 ± 2.2 , -26.7 ± 1.5 , and -24.5 ± 2.9 ‰ for pure water, and 1, 3, and 5 molal NaCl solutions. Calculated hydrogen isotope salt effects ($10^3 \ln \Gamma(\text{D}/\text{H}) = -2.4$ to $+4.3$ ‰) are also consistent with those obtained from the liquid-vapor equilibration method at 200°C.

Our new results on the liquid-vapor isotope partitioning are currently being used at geothermal plants in the Imperial Valley in order to trace injected fluids to production sites. Since water and steam separated at flash-steam plants have distinct isotopic signatures, injected fluids of water and condensed steam can be traced isotopically for a long distance. Different natural waters (i.e., meteoric and magmatic waters) also have distinct isotopic signatures, which help researchers at geothermal plants to identify the origin and flow patterns of reservoir fluids.

FUTURE PLANS

Measurements of salt effects on oxygen and hydrogen isotope partitioning between vapor and liquid water will continue until we have completed studies of the system Na-K-Mg-Ca-Cl-SO₄ to 350°C, including several mixed salt solutions resembling natural geothermal brines (i.e., Salton Sea). We will continue and expand our experiments of mineral-water isotope exchange in the presence of salts. Brucite was found to exchange with water more rapidly than calcite, and will be used further for the effects of NaCl, KCl, and MgCl_2 . For the effect of dissolved Ca^{2+} on isotope partitioning, the system portlandite ($\text{Ca}(\text{OH})_2$)-water will be investigated at 300-400°C. In order to examine the effects of mixed salt solutions containing Mg^{2+} and Ca^{2+} , isotope exchange experiments of quartz (SiO_2)-water will be conducted. Use of very fine grains (1-10 μm) of quartz and small amount of mineralizer (e.g., NaF) is known to enhance the isotope exchange rate.

Because HCl is a prominent species in The Geysers geothermal system, and known to produce large oxygen isotope effect at low temperature (-0.8 ‰ per molal at 25°C), we will investigate its oxygen isotope effect at elevated temperatures.

INDUSTRIAL INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	Using our results to monitor injection

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THERMODYNAMICS AND PHASE RELATIONS OF SYNTHETIC GRANITE MELTS AND ASSOCIATED AQUEOUS FLUIDS

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KEY WORDS

Silicate melts, geothermal fluids, fluid-rock interactions, thermodynamics, phase equilibria, modeling, granite, corrosion in geothermal power plants

PROJECT OBJECTIVES

This project is part of the program "Physical Chemistry of Geothermal Systems" at the Oak Ridge National Laboratory (ORNL). The immediate goal of the research is to perform laboratory experiments which elucidate the phase relations and thermodynamic mixing properties of haplogranitic (synthetic granite) melts and associated aqueous fluids. The resulting fundamental thermochemical data can be applied in quantitative modeling of heat and fluid flow in geothermal systems associated with granitic intrusions. The ultimate aim of the work is to develop thermodynamic models for granitic magmas and high-temperature geothermal fluids. Thermodynamic models developed by previous investigators do not accurately predict melt-crystal-fluid chemistry in geothermal systems associated with granitic plutonism; consequently, they cannot be used to calculate the quantities and compositions of magmatic fluids in these systems.

Technical Objectives

- Determine the solubility of water in haplogranitic melts at 500-2500 bars, 680-1000°C.
- Acquire new and more accurate data on the boundaries of melt-crystal phase fields in haplogranitic systems at 500-2500 bars, 680-1000°C.
- Determine the alkali aluminosilicate composition of aqueous fluid in equilibrium with haplogranitic melt at 500-2500 bars, 680-1000°C.

Expected Outcomes

- The new experimental data will be used to develop thermodynamic equations of state for: (1) predicting the solubility of water in granitic melts; (2) calculating the hypersolidus phase relations of granitic systems; and (3) estimating the quantities and compositions of magmatic fluids in geothermal systems associated with granitic intrusions.

PROJECT BACKGROUND AND STATUS

There are numerous locations worldwide where it is evident that geothermal resources are linked genetically to granitic magmatism. Two phenomena that relate directly to this link are heat transfer from granitic magmas to superjacent geothermal systems, and mingling of magmatic fluids with meteoric

waters. Concerning the latter event, it is important to recognize that: (1) the initial chemical compositions of magmatic fluids are strongly influenced by the bulk composition and thermodynamic mixing properties of the granitic magma; (2) incompatible melt components are preferentially partitioned into the aqueous fluids that separate from granitic magmas; and (3) various geochemical reactions can potentially produce significant changes in the compositions of magmatic fluids prior to the time that they mix with circulating meteoric waters. These and other geochemical processes pertinent to the granitic intrusion-geothermal system association have been considered qualitatively in numerous field studies of active and fossil geothermal fields; however, complementary experimental and theoretical investigations, which are essential for quantitative modeling of igneous-geothermal processes, are few in number. A significant fraction of the data required to perform such modeling can be obtained from experiments on "simple" synthetic chemical systems that serve as analogs for natural granitic rocks. Thus, it is noteworthy that the "haplogranite" (synthetic granite) system is widely regarded as an excellent geochemical analog for natural granites. This system, comprising the components $\text{NaAlSi}_3\text{O}_8$ (albite), KAlSi_3O_8 (sanidine), Si_2O_6 (quartz), and H_2O (water), has been examined experimentally by numerous investigators in the past, but the resulting data are of questionable accuracy, and relate principally to H_2O -saturated haplogranitic melts.

The research described below commenced in FY 92. Initially, emphasis was placed on developing provisional thermodynamic models for albite-water and albite-quartz-water melts. As this modeling proceeded, much time and effort was spent designing, constructing and testing laboratory equipment for hydrothermal experimentation. In so doing, it became evident that new sample preparation techniques and experimental methods would be required to obtain the desired laboratory data. Ultimately, all of these efforts were successful and, consequently, the project has now progressed from a development stage to a production stage. Already, numerous experimental data have been collected; however, more data are needed to prepare papers for publication. These data are being collected at the present time, and descriptions of the results are being written as experiments are being performed. It is anticipated that submission of manuscripts to geochemical journals will begin in the middle of CY 1995.

APPROACH

Melt-crystal-fluid experiments are being performed in an internally-heated pressure vessel, and in cold-seal hydrothermal apparatus. 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. The resulting fundamental thermochemical data are being analyzed quantitatively to determine the thermodynamic mixing properties of haplogranitic melts and associated aqueous fluids.

RESEARCH RESULTS

A. The Solubility of Water in Albite-Water and Albite-Quartz-Water Melts

The solubility of water in albite-water and albite-quartz-water melts has been measured by: (1) mass balance (weight loss); (2) vacuum-extraction/manometry; and (3) the vapor-dimple technique. Solubilities for albite-water melts are slightly higher than those measured by previous investigators. Data for albite-quartz-water melts indicate that: (1) H_2O solubility is nearly independent of albite/quartz ratio between 740 and 800°C, but decreases slightly with decreasing albite/quartz ratio at 900°C; and (2) H_2O solubility decreases from ~55 mole % at 740°C to ~50 mole % at 900°C. These results are in good

agreement with data obtained by previous investigators, except at near-eutectic temperatures, where our data indicate that water solubilities are slightly higher than those measured by earlier investigators.

B. Melt-Crystal Equilibria in the Albite-Quartz-Water System

Experiments were performed to determine the hypersolidus phase relations and thermodynamic mixing properties of albite-quartz-water melts at 2500 bars, 720-1000°C. Phase-equilibrium data were obtained by seeding gels with small amounts of crystalline albite or quartz, and noting after experimentation whether these seeds grew or were partially dissolved in the melt. Data obtained at 720-740°C indicate that the temperature of the ternary eutectic is between 730 and 740°C, and the composition of the eutectic is between $X_{ab} = 0.60$ and $X_{ab} = 0.70$. Results obtained using albite-quartz gel, fine-grained crystalline albite + quartz, and coarse-grained crystalline albite + quartz reactants suggest that gels tend to form metastable melts at temperatures below the eutectic, and that coarsely crystalline materials react sluggishly at near-eutectic temperatures. Additionally, the limits of the *L* (melt) phase field were determined at 740, 800 and 900°C. The shapes of this phase field at these temperatures suggests that $\text{NaAlSi}_3\text{O}_8$ and Si_4O_8 do not mix ideally in albite-quartz-water melts.

C. Fluid-Composition Experiments

Experiments are being performed to determine the alkali aluminosilicate composition of aqueous fluid in equilibrium with haplogranitic melt at 2500 bars, 700-1000°C. Starting materials for these experiments are distilled and deionized water, and coarsely ground hydrous haplogranitic glass. Nine different hydrous glass compositions are being studied (anhydrous bulk compositions in weight percent, with *ab* = $\text{NaAlSi}_3\text{O}_8$, *or* = KAlSi_3O_8 , and *qz* = Si_4O_8 : *ab*_{100.0}, *ab*_{63.8}*qz*_{36.2}, *ab*_{69.7}*or*_{30.3}, *or*_{57.7}*qz*_{42.3}, *ab*_{42.8}*or*_{27.4}*qz*_{29.8}, *ab*_{40.7}*or*_{25.8}*qz*_{33.5}, *ab*_{32.9}*or*_{33.6}*qz*_{33.5}, *ab*_{48.9}*or*_{17.6}*qz*_{33.5}, and *ab*_{39.0}*or*_{24.7}*qz*_{36.3}). Experimental samples are prepared as follows. First, hydrous glass is loaded into two 3 mm x 10 mm Pt "inner" capsules, which are welded shut at one end prior to loading, but are left open at the opposite end. After ~35 mg of glass is loaded into one of these capsules, a small wad of Pt mesh is stuffed into the open end of the capsule to ensure that glass remains inside the capsule for the remainder of the loading process. This process is repeated for the second inner capsule. Next, ~100 mg of distilled and deionized water and the two inner capsules are loaded into a 5 mm x 38 mm Pt "outer" capsule. The two inner capsules are inserted with their open ends up. This orientation is retained during experimentation; i.e., all samples are run in a vertical orientation, with the two inner capsules oriented open-end up. This technique ensures that, during experimentation, aqueous fluid can gain access to the silicate melt in the two inner capsules, but melt can't flow out of the inner capsules into the outer capsule. The samples are allowed to equilibrate at experimental *P-T* conditions for 2-10 days, and are subsequently quenched to room temperature and then depressurized to 1 atm. The final mass of H_2O in the fluid phase at experimental *P-T* conditions is determined by weighing the mass of water that is transferred from the quenched sample by vacuum distillation. The alkali aluminosilicate material that was dissolved in the fluid phase at experimental *P-T* conditions, which precipitates on the inner wall of the outer capsule, and on the outer walls of the two inner capsules, is dissolved in a lithium metaborate-tetraborate mix and analyzed by ICAP emission spectroscopy. The water contents of the two masses of glass (quenched melt) in the inner capsules are determined by vacuum-extraction/manometry. Preliminary compositional data obtained from experiments with hydrous albite glass indicate that the techniques described above not only permit melt-fluid equilibrium to be achieved, but also ensure that – during quenching – the silicate material precipitated from the aqueous fluid remains completely separate from the silicate material in the inner capsules.

D. A New Thermodynamic model for Albite-Water Melts

A two-parameter Margules method for calculating the thermodynamic mixing properties of albite-water melts (Blencoe, 1992) has been used to develop an excess free energy equation for these liquids at 100-6000 bars, 730-1000°C (Blencoe et al., 1994). The equation is based upon – and is therefore consistent with – all of the high quality phase-equilibrium, volumetric, and calorimetric data for high-temperature phases of the albite-water system. Calculated excess molar volumes for albite-water melts derived from the equation are strongly negative below 2 kb, and slightly negative near 6 kb. Calculated excess enthalpies are strongly negative below 750°C, and slightly negative near 1000°C. With increasing mole fraction of water in the melt (X_w^L) from $X_w^L = 0.0$, calculated excess free energies decrease sharply (become strongly negative), level off, and ultimately increase to near 0.0 as the melt becomes saturated with water. The latter result is consistent with the H₂O dissolution model for silicate melts advanced by Stolper and coworkers (Silver and Stolper, 1985, 1989; Silver *et al.*, 1990).

FUTURE PLANS

The project has just shifted from a development stage to a production stage; therefore, plans for the immediate future call for completing the work that has already been initiated. At an appropriate later time, we plan to start investigating crystal-fluid reactions in synthetic granite systems at subsolidus pressures and temperatures (200-2500 bars, 200-600°C). This research would complement the melt-crystal-fluid research that we are currently performing.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The expertise that we have acquired from our geochemical research is being applied to help private companies solve practical problems in geothermal resource areas. Currently, we are assisting Ogden SIGC Geothermal Operations, Inc., and the PSC Geothermal Services Company in their efforts to identify the geochemical reactions that are causing corrosion of carbon-steel pipes in the Heber and East Mesa power plants near El Centro, California. Corrosion is ubiquitous at the Heber plant, but is found to be more extensive in the cooler parts of heat exchangers, and in Ts located immediately downstream from the heat exchangers. At the East Mesa plant, corrosion is most severe along the bottoms of horizontal sections of injection pipe located immediately upstream from expansion loops. At both of these plants, it is possible that corrosion is exacerbated by sand-sized particles of rock entrained in the geothermal fluid. It can be theorized that transport of these particles by saltation, and "sand-blasting" in zones of turbulent fluid flow, mechanically abrade the thin layers of solid material that form on the inner walls of carbon-steel pipes when saline geothermal fluid reacts with the steel. This abrasion would tend to completely erode solid corrosion products in isolated sections of pipe, thus causing underlying steel to be continuously exposed to the corrosive action of the fluid. Over an extended period of time, this corrosion/erosion process could lead to severe pitting of the steel, and ultimately to breaching of pipe walls. These hypotheses are being tested by examining samples of corroded pipe from the two power plants. At the present time, emphasis is being placed on examining the solid materials formed by corrosion. These solids are being identified and characterized by X-ray diffraction and ion probe microanalysis.

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TRACER DEVELOPMENT

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KEY WORDS

Tracers, tracer tests, fluorescein, rhodamine WT, tinopol CBS-X, amino G, aromatic acid tracers

PROJECT OBJECTIVES

Chemical tracers are an invaluable tool for evaluating the efficiency of injection into geothermal fields. Prior to this project, few were available and their stability under geothermal conditions was unknown. The overall objective of this research project is to identify and test compounds for use as geothermal tracers and to develop techniques for their use. In order to be useful to the geothermal industry, a tracer must be inexpensive and have detection limits in the range of parts per billion to parts per trillion. Furthermore, it must be relatively nontoxic, thermally stable or have easily quantified rates of decay under geothermal conditions, have minimal rock-tracer interactions, and fractionate to the appropriate phase.

Technical Objectives

- Prove the stability of several compounds that can be used as geothermal tracers. 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 using them simultaneously in individual tracer tests that follow the fluid paths from multiple injection wells.
- Develop and/or program numerical methods for evaluating the information that tracers can provide, such as surface area, steam fraction, reservoir volume, and fracture attributes.

Expected Outcomes

- We expect to provide a minimum of ten affordable tracers that are stable at temperatures of 250° to 300°C.
- User-friendly programs will be written for interpretation of tracer tests. These programs will accept tracer data as input and will yield estimates of various reservoir properties.

PROJECT BACKGROUND AND STATUS

In most geothermal fields, the spent, cooled brines must be injected back into the reservoir. The purposes of injection are to avoid surface and ground water pollution and to maintain reservoir pressures. The locations of the injection wells within the three-dimensional network of fractures that form the reservoir are critical to the successful exploitation of the field. Properly located wells lead to higher

power production from enhanced pressures, less reservoir scaling from boiling around the production wells, and reduced thermal breakthrough. Improperly sited wells either give no benefits or result in rapid thermal breakthrough. Unfortunately, prior to the field start-up only the pressure aspects of the hydrologic connections are known, not the pathways and velocities that the injection fluid will take between wells. The latter data can only be obtained by using evidence of mass transfer, i.e., chemical data. Introduction of a tracer into the injection-production loop is the most efficient and quantitative method of obtaining data that describe the subsurface flow of injected fluid.

At the inception of the tracer development program in 1982, there were very few tracers in use by the geothermal industry. The poorly quantified stability of the geothermal tracers that were known in 1982 produced a lack of confidence in the results of tracer tests, which considerably lowered their utility as a reservoir tool. Surveys of the geothermal industry by the Department of Energy (DOE) indicated a strong belief that tracer tests would be very valuable if stable geothermal tracers could be developed. It was on this basis that the tracer development project was founded. And, whereas a significant number have subsequently been developed and field-tested, the need persists for new tracers, especially for easily analyzed, liquid-phase fluorescent compounds that are relatively inexpensive and that are mutually compatible. Thus, we estimate that the project is approximately 50% complete.

APPROACH

Our approach to the development of new tracers for the geothermal industry has been, first, to search the literature for promising candidates. Since good liquid-phase geothermal tracers have all of the qualities of good groundwater tracers in addition to the attribute of reasonable thermal stability, the groundwater-tracer literature was the likely place to begin the search. Next, the candidate compounds are screened for thermal stability and adsorption, based upon thermodynamic and kinetic data found in the literature. The surviving candidates are then subjected to a series of laboratory experiments in high-pressure autoclaves in 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 experiments and field tests are published in the open literature. These methods provide for rapid evaluations of candidate compounds and immediate and up-to-date access to our results for the geothermal community.

All of our field tests are designed to maximize the return of reservoir information as well as data on tracer stability. Because of this balance between research and application, industry is always willing to cost-share our field tests. To date we have cost-shared tests with Oxbow Geothermal, Unocal Geothermal, California Energy Company, Calpine Corporation, Northern California Power Agency (NCPA), and Far West Capital, Inc.

RESEARCH RESULTS

In the early stages of our research we tested 39 aromatic acids and fluorescein under conditions similar to those found in a geothermal environment. The experimental parameters included temperatures up to 300°C for periods of up to one month in fluids of various salinities, the presence or absence of rocks, and atmospheric levels of molecular oxygen (Adams et al., 1992). Of the compounds tested, 24 can be used in geothermal systems with temperatures up to 200°C, 15 can be used up to 250°C, and seven are stable to at least 300°C. Several of these compounds were subsequently field-tested in a cost-shared test conducted at the Dixie Valley geothermal system (Adams et al., 1989).

Since 1990, we have tested several other dyes for their thermal stability. Although most dyes decay significantly at temperatures above 260°C, they are easily detectable using field-portable, inexpensive filter fluorimeters. Because the dyes display measurable decay rates in the temperature range of most geothermal systems, we have performed a series of experiments to define the reaction kinetics some of these dyes. These decay rates can be used to correct the concentrations measured in the field in tests where the temperature of the reservoir are sufficient to degrade the dyes. To date, we have conducted laboratory stability studies of fluorescein (Adams and Davis, 1991), rhodamine WT (Rose and Adams, 1994), amino G (Adams, 1995), and tinopol CBS-X (unpublished data). We have also tested fluorescein, rhodamine WT, and tinopol CBS-X in the field (Rose and Adams, 1994; Adams, 1995).

Some of the dyes displayed variations in their decay rate that were dependent on other chemical species in the solution. For instance, the decay rate of the blue dye amino G decreases while that of the red dye rhodamine WT increases in the presence of phosphate ions. Data from a field test of rhodamine WT at Steamboat Hills indicates that its decay rate is affected similarly by species that occur naturally in geothermal waters, such as bicarbonate (Rose and Adams, 1994). If the decay rate of Amino G is affected in the same manner, its half-life in geothermal waters will be lengthened by a factor of ten and it may be an acceptable geothermal tracer.

We have used field tests in order to simultaneously prove the utility of tracer technology, transfer the technology to industry, and deduce additional properties of the tracers. For instance, the data from the Dixie Valley test were used to demonstrate that no significant adsorption of fluorescein took place during its transit through the reservoir. The effective temperature of the injection-production flow path was also deduced, by comparing the change in the concentration ratio of the two tracers during the test. As discussed above, we used the data from the Steamboat Hills test to show that rhodamine WT decays at nearly identical rates in geothermal systems and in phosphate-buffered laboratory solutions.

Our most recent tracer test was conducted at the Beowawe geothermal system. The purpose of this test was to evaluate the performance of the blue fluorescent dye tinopol CBS-X. The benefit derived from the test by the operators was a determination of the connectivity of a new injection well with the three production wells in the field. The results, shown in Figure 1, demonstrated that tinopol CBS-X is far from a conservative tracer. The shape of the return curve and the ratio of tinopol CBS-X to fluorescein in the produced fluid indicate that tinopol adsorbed onto the reservoir rock rather than decaying.

FUTURE PLANS

Our current emphasis on fluorescent dyes reflects the requests that we have had from industry. Most operators prefer a tracer that can be easily and inexpensively analyzed on site. The fluorescent dyes can be analyzed with a filter fluorometer, which requires a minimum of pretreatment and is simple to use. To date, only fluorescein and rhodamine WT have proven to be stable enough for use as a geothermal tracer. However, our initial laboratory data indicate that Amino G may be stable in a moderate-temperature geothermal environment. Another candidate is Eosin Y, a bromide derivative of fluorescein. We plan on testing both Amino G and Eosin Y in the laboratory in the coming year. We also hope to initiate a tracer test in which all of the injection wells in a field are tagged with dyes, to completely describe the flow patterns in the field.

We also hope to pursue the use of analytical solutions of solute transport and fluid flow equations during the coming year. We have already initiated a project in conjunction with Idaho National Engineering

Laboratory (INEL), in which we will compare the results of numerical simulations with analytical models of the Beowawe tracer test.

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Figure 1. Fluorescein and tinopol CBS-X curves for Beowawe Well Ginn 2. The two compounds were injected at the same concentrations. The relationship between the two curves indicates that tinopol CBS-X was absorbed on formation rock.

USER FRIENDLY MODELS FOR CHEMICAL AND THERMOPHYSICAL PROPERTIES OF GEOTHERMAL FLUIDS

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KEY WORDS

Brines, gases, computer models, reservoir, scaling, rock/water interactions, simulation, solubility, thermodynamic data, ph, high temperature, gas breakout, phase transitions, geothermal, chemistry, energy

PROJECT OBJECTIVES

The objective of this program is to improve the productivity of geothermal resources by providing modeling tools for predicting and mitigating chemical problems associated with the extraction of energy from geothermal brines (see Table 1). These easy to use models will provide reliable predictions of the behavior of a resource (*e.g.*, scaling and breakout) under arbitrary conditions, thereby providing operators, engineers, and designers with the ability to rapidly analyze potential problems and to test strategies for problem abatement and resource enhancement. Our project objective also includes effective communication with the geothermal industry in order to exchange ideas and transfer technology.

Technical Objectives

- Construct thermodynamic models for predicting the chemical behavior (*e.g.*, scaling, gas breakout, reservoir degradation) of geothermal brines to high concentration, temperature, and pressure. These models must accurately reproduce measured thermodynamic properties, *e.g.*, solubilities, liquid/vapor coexistence, enthalpies. They must be able to handle the special computational difficulties of calculating multiple phase equilibria in complex mixtures for variable temperature and pressure. The species treated in these models must allow application to a wide range of geothermal operations.
- Develop new simulation technology for incorporation in our modeling programs.
- Develop user-friendly application packages for PC's and Macintosh's to facilitate the use of our software.

Expected Outcomes

- **TEQUIL APPLICATION PACKAGE:** This series of computer programs will include variable temperature ($T < 250^{\circ}\text{C}$) solubility models of geothermal brine components at liquid density. Reservoir-brine interactions, scaling and gas-breakout as well as mixing, pH, reinjection compatibilities, spent brine storage effects, etc., can be calculated using this package.

Expected Outcomes (continued)

- **GEOFLUID APPLICATION PACKAGE:** This series of computer programs will include models for calculating pressure, volume, and temperature (PVT) and vapor/liquid equilibration from subcritical to supercritical temperatures and pressures. Both equations of state parameterized by experimental data and the results of first principle molecular dynamic simulations will be incorporated in the package. Applications of these programs include: gas breakout, fluid inclusion study, solubility of gases, and rock-fluid interactions.
- **GEOHEAT APPLICATION PACKAGE:** This series of computer programs will include specific heat and enthalpy calculations, and will provide heat contents, liquid/gas ratios, etc.
- **GRAPHICAL USER INTERFACES** will be developed to facilitate interpretation of complex brine/solid/gas interactions by geothermal community.
- **RELIABLE SUMMARY OF MANY GEOCHEMICAL DATA SETS FOR GEOTHERMAL BRINE/SOLID/GAS SPECIES:** Our chemical modeling methods include correlation of many data points for model parameterization and comprehensive model validation by comparison to both laboratory and field data.
- **NEW SIMULATION TECHNOLOGY:** Molecular dynamics methods will be used to develop models for predicting PVT behavior at the very high temperature and pressure conditions associated with reservoir formation and evolution which are prohibitive for experimental analysis.

The ability to rapidly and easily predict the chemical behavior of geothermal brine/solid/gas systems under a wide variety of conditions will markedly improve the efficiency of geothermal energy operations and thereby lower significantly the cost of both resource assessment and exploitation.

PROJECT BACKGROUND AND STATUS

Many of the most significant problems limiting the economical development of geothermal power are related to the chemical properties of the high-temperature and high-pressure brines from which the energy is extracted. The properties of these fluids and the dissolved gases which evolve from them are very difficult to predict. However, if the system is near equilibrium they can be calculated from the thermodynamic and physical properties of the system as summarized by the free energy, G . For brines, G is a complex function of the concentration of all the species in the phases present and the temperature. G is a weak function of the pressure for brines; however, for gas phases, G varies rapidly with the pressure. All these variations must be accounted for in a successful phenomenology. By minimizing G subject to mass and charge balance constraints, the distribution of solids, gases, and liquid phase species may be calculated.

We have developed highly accurate models incorporating phenomenological equations for the free energy of gas, liquid, and solid phases (*e.g.*, Harvie *et al.* (1984), Weare (1987), Møller (1988)). In 1980, Harvie and Weare (1980) showed that the Pitzer (1973, 1987) equations describing the thermodynamics of electrolyte solutions can be used to accurately predict the complex solubility relationships in multi-component brines, Na-K-Ca-Mg-Cl-SO₄-H₂O, to high concentration. These equations are soundly based on theoretical results but contain parameters that must be established from binary and ternary

experimental data. This is a difficult problem, but once the parameters have been evaluated the models can be applied to the much more complicated systems common in the energy production industry. The work of Harvie and Weare (1980) was supported primarily by grants from the National Science Foundation (NSF-EAR) and from the American Chemical Society-Petroleum Research Fund (ACS-PRF).

With funding from Department of Energy, contracts and grants from NSF-OCE, NSF/USA-FRANCE COOPERATIVE SCIENCE, and ACS-PRF, the modeling package based on the Pitzer equations was expanded to include additional species: carbonate, silica, borate, as well as acid-base reactions, pH and variable temperature ($T < 250^{\circ}\text{C}$). (See, for example, Harvie *et al.* (1984), Felmy and Weare (1986), Møller (1988), Greenberg and Møller (1989). Good agreement was found when these models were used to interpret geothermal field measurements. In order to achieve this agreement, it was necessary to develop extremely reliable methods of handling the massive data evaluation required by model parameterization and validation and of solving the complicated chemical equilibrium problem associated with simulating complex geothermal brine systems (Harvie *et al.* (1987)).

With support from the DOE Geothermal Program and ACS-PRF, highly significant breakthroughs were also made in developing new phenomenology for predicting the behavior of gases and liquid/vapor mixes containing species associated with geothermal reservoir formations as a function of temperature and pressure (Duan *et al.* (1992a), (1992b)). Using this phenomenology, we produced a gas model of the $\text{CH}_4\text{-CO}_2\text{-H}_2\text{O}$ system which accurately predicts the phase equilibria and PVT properties from 0 to 1200 bars and from 0 to 1000°C . This was the first model which could accurately simulate both the single and two phase behavior of gas mixtures. The new phenomenology allowed us to significantly improve our predictions of gas breakout in highly pressurized systems.

In June 1993, our chemical modeling group received funding under a five-year (1993-1997) DOE grant (DE-FG07-93ID13247: Renewable Energy Research and Development) to continue our research in the development of models of geothermal brine chemistry. The research projects proposed to undertake in this five-year program (see Table 2) are designed to add new species, important to geothermal energy operations, to our variable temperature ($T < 250^{\circ}\text{C}$) brine models as well as to extend the parameterization of the major species in these models to higher temperatures. The proposed research program also includes the development of new technology for expanding models into temperature ranges above the critical point of water and to high pressures. In addition, this program emphasizes close communication with the geothermal industry as well as other research groups in order to design the best models and the best user interfaces for facilitating the transfer of our technology to the geothermal community.

APPROACH

In order to have the predictability required for geothermal applications, highly accurate models of the chemical behavior and physical properties of the resource formation and working fluids and their interactions are necessary. Using recent developments in the chemistry of fluids and gases and with careful attention to parameterization, we have developed models that accurately reproduce the measured chemical behavior of brines (*e.g.*, scale formation), the solubility and liquid/vapor coexistence of gases, and other thermodynamic properties (*e.g.*, heat content). The models have been applied to well determined production situations with remarkable success. Our brine models handle the special problems of phase equilibrium prediction in complex mixtures, introduce a relatively low number of parameters and are highly accurate and flexible.

Our gas modeling approach utilizes our recently developed phenomenological equations which can reproduce PVT properties in both the liquid and gas phases, liquid/vapor coexistence, and other useful thermodynamic functions. Our research program includes a continuing effort to develop new phenomenologies by the first principles simulation of complex brines and gas phases and to incorporate these new phenomenologies in our models.

As the models are developed, they will be included in user-friendly application packages, called TEQUIL, GEOFLUID and GEOHEAT, which can be loaded from diskettes to PCs or Mackintosh computers. User-oriented graphical interfaces are developed and updated to facilitate the use of the software. Periodically, workshops are given in the use of these programs to treat problems of interest to the geothermal community (see Table 1). An instruction manual is updated as new technology is ready for application. Ideas for model improvement are generated at these workshops as well as from publications and invited lectures.

Our modeling technology is valuable not only for geothermal operations but also for other applications (see Table 3). For example, the present models and those we are developing are useful in other energy technologies (oil production, solar pond), industrial process chemistry and nuclear waste isolation. As a result, in addition to the support from the DOE-Geothermal Program, we have received ancillary support for our program over the years from: NSF-EAR, NSF-OCE, ACS-PRF, the DOE-Nuclear Waste Program, and the UC Water Research Institute as well as supplemental grants from industrial sources, e.g., UNOCAL, Potash Corporation of Saskatchewan, Canada.

RESEARCH RESULTS

For chemical models to be useful for geothermal applications, they must be both highly flexible (able to treat wide ranges of variables) and highly accurate as well as easy to use. We believe that the application packages we are developing are the only models presently available that meet these demanding criteria. We have demonstrated (see, for example, references cited below) that the model calculations compare well with both laboratory and field data. Typically, they retain the reliability of the experimental data on which they are based. With support from DOE, we have made considerable progress towards accomplishing our long-range research objectives. The capabilities of the geothermal brine models we have developed to date are summarized in Table 4. These models will predict saturation ratios, scaling behavior, pH, formation porosity changes, gas breakout in production wells, and liquid/vapor compositions throughout various brine flow and heat extraction systems and during reinjection procedures.

Parameterization of the Na-H-Ca-Cl-HCO₃-SO₄-CO₃-SiO₂-CO₂-H₂O system and of the seawater system, Na-K-Ca-Mg-Cl-SO₄-H₂O, is complete to high temperature (0-250°C) and to very high ionic strength. These models will treat all the major components of seawater-type brines in addition to the important calcium carbonate, calcium sulfate, and amorphous silica scale-forming minerals as well as CO₂ solubility.

Our equations of state (EOS) for the CH₄-CO₂-H₂O, the NH₃-H₂O and the NaCl-CO₂-H₂O systems can predict behavior from the two phase region to the homogeneous region. We consider this to be a breakthrough in thermodynamic modeling of natural processes.

In addition to model parameterization using very large sets of available thermodynamic data, model validation requires comparison with both laboratory and field data. For example, Table 5 illustrates the

type of data required to parameterize the $\text{CaCO}_3\text{-NaCl-CO}_2\text{-H}_2\text{O}$ system using the Pitzer equations, and Table 6 lists the PVT data used in constructing the EOS model for the $\text{CH}_4\text{-CO}_2\text{-H}_2\text{O}$ system. Our models, therefore, provide an effective means of summarizing, comparing, and validating the brine chemistry data presently available. They also provide a reliable standard of comparison for both field and laboratory measurements being collected in programs supported by DOE and other agencies.

As can be seen from a comparison of Tables 2 and 4, we have already achieved a number of the projected goals proposed in the recent five-year DOE grant. Not only have some grant projects already been completed and substantial progress made on long term grant projects, but several new projects not specified in the grant but requested by the geothermal community have been finished or started (see, for example, the $\text{NH}_3\text{-H}_2\text{O}$ system below). Other variances in the planned activities include alterations in the timeline for carrying out several of the yearly projected milestones in the five-year program. For example, our equation of state and molecular dynamics phenomenologies for modeling the chemical behavior of gas mixtures and liquid/vapor coexistence to supercritical temperatures and high pressures have proven so successful that we are significantly ahead of the timeline for these projects. Also, the development of user interfaces for our modeling programs has been highly successful, as evidenced from the very positive feedback from our recent (October, 1994) workshop conducted for the geothermal industry. Tutorials describing the development and use of our modeling programs and diskettes (for PC's and Macintoshes) with our current TEQUIL and GEOFLUID application packages have been distributed to workshop attendees and to many other academic and industrial research groups (see below).

Highlights Of Our Most Recent Results

The $\text{H}_2\text{O-CO}_2\text{-NaCl}$ System:

Fluids with major components in this system are by far the most commonly encountered in geothermal systems. The analysis of many problems associated with geothermal operations requires the ability to predict the properties of this system as a function of composition, temperature and pressure. We have a continuing program developing models of very complex brines at liquid densities (see below). This year we have begun to model the $\text{H}_2\text{O-CO}_2\text{-NaCl}$ system for a much wider range of temperatures and pressures. This requires a new approach similar to the equation of state method we used for the $\text{H}_2\text{O-CH}_4\text{-CO}_2$ system described in Duan, Møller and Weare (1992). The NaCl model is, however, more difficult since one of the end members is a solid. A new mixing model (the NHC model) had to be developed which takes in the unique properties of the subsystems. Our results are very positive, the predictions of the model being roughly within the experimental error. An example of two phase coexistence predictions is given in Figure 1. Note the large increase in the two phase region as the NaCl content of the brine is increased. Note that the NHC model has not been incorporated into the GEOFLUID package but is available upon request.

H_2S Solubility Model:

A model which predicts the solubility of H_2S in the $\text{NaCl-H}_2\text{S-H}_2\text{O}$ system up to 200°C has been developed. Using the data listed in Table 7 and the approach of Duan et al. (1992), we first determined an equation of state for H_2S which describes the chemical potential in the vapor phase. Then, we adjusted our brine model to give the chemical potential in the liquid phase. By equating the chemical potentials in the vapor phase and the liquid phase, the solubility of H_2S is calculated. The error of this model is about 10%, which is about the error of the experiments.

Enthalpy Calculations:

An important thermodynamic property of interest to the geothermal community is the enthalpy of the gas and liquid phases. Since in the brine models we calculate the free energy as a function of temperature, the enthalpy may be calculated from the derivative of G . We have shown that our model calculations of the enthalpy of the highly concentrated Salton Sea geothermal brine are within about 15% of that of pure water as a function of temperature. In our liquid density brine models, many of the mixing solution parameters and all of the parameters for the slightly soluble salts are determined from free energy data alone. Therefore, in complex, concentrated brine systems, such as the Salton Sea, when the free energy is differentiated, there may be an increased error. We will be testing enthalpy calculations for other systems against available data in the near future.

The situation for gas phase models is somewhat different. In the earlier version of GEOFLUID, our equation of state, which is a function of volume, was integrated to give the appropriate equation for the enthalpy. The error using this method can be over 15%. In the present version of GEOFLUID, we have calculated the enthalpy of pure water by directly fitting the data. The resulting errors are less than 1%. We are now developing a new program, GEOHEAT, which will include enthalpy models for gas-water mixtures as well as calculations of gas/liquid partitioning which take into account mixtures with noncondensibles, etc.

Silica Geothermometer:

We have incorporated the silica geothermometer model developed by Fournier (1977) into GEOFLUID. This model, which is based on the assumption that silica does not precipitate when a brine travels from the aquifer to the surface, allows the aquifer temperature to be calculated from the silica concentration sampled at the surface.

Liquid Density Brines to 250°C:

Our current efforts in solubility modeling of subcritical brines have focused primarily on completing the basic seawater (Na-K-Ca-Mg-Cl-SO₄-H₂O) system for the 0 to 250°C temperature range. Binary and ternary solubility data are used to establish temperature functions for the binary solution (e.g., NaCl-H₂O) parameters (β 's and C), the ternary mixing solution (e.g., NaCl-KCl-H₂O) parameters (θ and ψ) and for the chemical potentials of the various single and double salts stable in the seawater system from 0 to 250°C. The metastable behavior of many of these salts is also modeled. Except for the chemical potentials of complex salts, such as polyhalite (K₂SO₄•MgSO₄•2CaSO₄•2H₂O) and kainite (KCl•MgSO₄•H₂O), found in higher order systems, the temperature functions determined from binary and ternary systems are all that are necessary to complete the basic seawater model and to predict behavior in any brine within the basic seawater field. Comparisons with solubility data not used in the model parameterization (quaternary, quinary, and the full seawater systems) are used to validate this model. For example, recent predictions of sulphate scale (gypsum and anhydrite) solubilities in highly concentrated magnesium-containing brines at high temperature ($T > 200^\circ\text{C}$) are in very good agreement with the laboratory data. Preliminary temperature functions for polyhalite and kainite, both important in the analysis of formations derived from seawater, have been established from solubility data in the quaternary systems, K₂SO₄-CaSO₄-MgSO₄-H₂O and KCl-MgCl₂-MgSO₄-H₂O, respectively.

The Ammonia System:

Mixtures of ammonia and water have been suggested as working fluids in geothermal energy conversion systems. NH_3 also occurs as one of the major gases in geothermal reservoirs, such as The Geysers Geothermal Field. In order to predict the chemical behavior of NH_3 , we have produced an equation of state using the methods described in Duan, Møller and Weare (1992a,b).

The modeling process begins by parameterizing highly accurate phenomenological equations of state (EOS) for the end member gases, pure H_2O and NH_3 . The H_2O EOS for this system is the same as developed in our prior work. The NH_3 model was developed after carefully reviewing the existing literature to identify a complete and consistent data base. Extensive data for pure NH_3 are available (Duan, Møller and Weare, to be submitted). The resulting EOS predicts densities within 1-2% of the measured values for a range of temperatures from 0 to 400°C and pressures from 1 to 1200 bars. With the end member EOS established, an EOS for the mixed system is formed by a mixing rule roughly based on the virial expansion. Again, data are needed to evaluate ternary parameters. When this process is completed the predictions of the mixed system ($\text{NH}_3\text{-H}_2\text{O}$) EOS agree well with the experimental data. Typical examples of the results are given in Figure 2.

User-Friendly Graphical Interfaces:

An important objective of our program is to provide easy access for designers, engineers and scientists to accurate predictions of the chemical and thermodynamic properties of geothermal systems. In order to make our programs easier to use and to facilitate technology transfer, we have developed new graphical interfaces.

Previously, the user had to edit a file and input, in formatted columns, data such as the number of iterations, temperature, species concentration, and phases to withhold, as well as temperature and concentration change per iteration. This can be a tedious process. Our new interfaces are both easier to use and have increased functionality. For example, a user may more easily calculate mineral supersaturation.

Graphical User Interfaces (GUI) for TEQUIL and GEOFLUID have been designed for the Macintosh using SuperCard™ and for WINDOWS using Microsoft Visual Basic™. An X-window interface for TEQUIL using TeleUSE™ has also been written for the SUN. This represents the major effort of our software development this year. These user interfaces are designed to allow the user to efficiently build input files via input fields for data such as composition and temperature and, in the case of GEOFLUID, menus that allow the user to choose calculation options, such as fugacity, molar volume, or phase equilibria. The user may review the input file at any time by selecting phases or species from a scrolled list (in the case of TEQUIL) or by looking through a series of "cards," each representing one composition (in the case of GEOFLUID). A list showing all the input data also appears on the main window. When the user is ready to run the calculation, he/she chooses the "CALCULATE" button. When the job is finished, the user may look at the output by clicking with the mouse button on the "OUTPUT" or "EDIT" button. The use of the programs on the MAC and under WINDOWS is nearly identical. This program was introduced at the Geothermal Modeling Workshop (see below). It appears to be a great success. Users become familiar with the program options in a much shorter time allowing us to concentrate on the applications of the model to their problems and on increasing the ability to transfer the use of the models to others in their organization.

FUTURE PLANS

Our plans for the future include carrying out the research projects listed in the five-year DOE geothermal grant as well as amending this program with projects and tasks suggested by the geothermal community via workshops and personal communications. This process of interactive technology transfer (see below) has proven successful in the past and is expected to yield the best chemical modeling application packages for use in geothermal energy operations and in other technologies.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

A. Geothermal Modeling Workshop FY 94

We conducted at the University of California at San Diego Supercomputer Center on October 18th. a third DOE-UCSD Geothermal Modeling Workshop. The 1992 tutorial was revised and updated to include new improvements and additions to the TEQUIL and GEOFLUID models. A detailed description of the user interfaces for Macintosh and PC (running windows) users was also added to the 1994 tutorial. A complete set of problems to illustrate the use of the technology included in the TEQUIL and GEOFLUID programs was also developed for use in the workshop. This workshop was well attended by members of the geothermal industry. Among the companies and agencies represented were:

Idaho National Engineering Laboratory
University of Utah Research Institute
Geotherm Ex, Inc.
US Geological Survey
Magma Operating Company
UNOCAL(consultants)

Two-Phase Engineering and Research
California Energy Company
Lawrence Berkeley Laboratory
Goddard and Goddard Engineering
Oxbow Power Services
Los Alamos National Laboratory

We feel that this workshop was a highly effective means of both transferring our technology and of communicating with the geothermal industry. All participants received diskettes with TEQUIL and GEOFLUID application packages. Many of the comments we received at the workshop as well as those we will receive from attendees in the future will be incorporated as improvements in our technology.

B. Contacts, FY 94

The following is a list of personal contacts (phone calls, letters, visits, contributions) made over the last year. Note that these contacts were in addition to attendance at the October workshop.

BEN HOLT COMPANY: Workshop attendance, Request for new NH₃ program, Request for H₂S program.

BHP MINERALS: Visited UCSD to be briefly introduced to the TEQUIL package which is now successfully installed there.

DOE (Reed): Shipped a few months ago PC version of TEQUIL, also made available X11 version earlier this year.

GEOFORSCHUNGS ZENTRUM (Potsdam, GERMANY): requested TEQUIL.

INEL: Workshop attendance, we have made available special version of GEOFLUID in the form of a subroutine for possible incorporation in a mass transport model.

LAB. DE SCIENCE (Lyon, FRANCE): Request NHC* program.

LBL: Workshop attendance, shipped new MAC executable for Centris

LFC POWER SYSTEMS: Visited UCSD and requested copies of our software application packages.

MAGMA OPERATING COMPANY: Workshop attendance, have GEOFLUID, recommended improvements to User Interface.

POTASH CORPORATION OF SASKATCHEWAN, CANADA: Prepared a model for potash production, Gave a workshop in Canada for them, Received a \$30,000 (Canadian) grant to our group.

TECHNISCHE UNIVERSITAT (Berlin, GERMANY): Request NHC program.

UNIVERSITY OF NANJING (CHINA): Request GEOFLUID and NHC.

UNIVERSITY OF NEW MEXICO: Request NHC program.

UNOCAL: Workshop attendance, seminar invitation, \$5000. contribution to our group.

USGS: Workshop attendance, shipped new MAC executables (GEOFLUID, TEQUIL) for Centris operating system, requested NHC model.

UURI: Workshop attendance, request reprints of our papers.

VIRGINIA POLYTECHNICAL INSTITUTE: Requested NHC.

YANKEE/CAITHNESS: Requested GEOFLUID, collaboration on a paper.

*: EOS for NaCl-H₂O-CO₂ system

C. Pesentations at Technical Meetings, FY 94

April 25, 1994: DOE Geothermal Program Review, San Francisco, CA. "User Friendly Models for Chemical and Thermophysical Properties of Geothermal Fluids."

May 18-22, 1994: Pan-American Fluid Inclusion Study Meeting, Mexico City, Mexico. "An equation of state for the NaCl-H₂O-CO₂ system: Prediction of Immiscibility and volumetric properties".

August, 1994: Annual Calorimetric Conference, New Mexico.

Sept 22-23, 1994: UURI Geothermal Energy Meeting, Geochemistry Workshop, San Francisco.

Oct. 2-5, 1994: Geothermal Research Council Meeting, Salt Lake City, Utah.

Oct. 26, 1994: GSA Meeting, Seattle, Washington. "Computer Modeling of Geochemical Fluids - 1. Semiempirical Models; 2. MD Simulation."

D. Technical Papers, FY 94

Nancy Møller, John H. Weare, Zhenhao Duan and Jerry P. Greenberg. "User Friendly Models for Chemical and Thermophysical Properties of Geothermal Fluids." In: *DOE Proceedings of the Geothermal Program Review XII*, April, 1994.

Nancy Møller, John H. Weare, Zhenhao Duan and Jerry P. Greenberg "DOE Workshop on Chemical Models for Optimizing Geothermal Power Plant Performance." A Tutorial, pp. 57 (1994).

Zhenhao Duan, N. Møller and J.H. Weare. "Equation of State for the NaCl-H₂O-CO₂ System: Prediction of Phase Equilibria and Volumetric Properties." SUBMITTED TO: *Geochim. Cosmochim. Acta*, 1994.

Zhenhao Duan, N. Møller and J.H. Weare. "Molecular Dynamics Simulation of Water Properties using RWK2 Potential: From Clusters to Bulk Water." SUBMITTED TO: *Geochim. Cosmochim. Acta*, 1994.

Wenxuan Hu, Qijiang Ren, Zhenhao Duan, N. Møller and J. H. Weare. "Fluid Immiscibility and its Relation to Mineralization: Application of the Equation of State for the System NaCl-H₂O -CO₂ to the Shaxi Porphyry Cu(Au) Deposits, Eastern China." SUBMITTED to: *Geochim. Cosmochim. Acta*, 1994.

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Table 1. USES OF A BRINE SIMULATION MODEL

Exploration	<ul style="list-style-type: none">• <i>Predict Scale Formation</i>• <i>Predict Gas Behavior</i>• <i>Determine Formation Water Characteristics</i>• <i>Predict Recoverable Energy</i>• <i>Predict History and Evolution of Resource</i>
<i>Plant Design and Operation</i>	<ul style="list-style-type: none">• <i>Predict Scale Formation</i>• <i>Predict Phase Separation</i>• <i>Simulate Chemical Treatments</i>• <i>Test Energy Optimization Strategies</i>• <i>Test Ways to Minimize Operations Costs</i>• <i>Support Laboratory Simulations</i>
<i>Waste Treatment</i>	<ul style="list-style-type: none">• <i>Simulate Mineral Recovery Strategies</i>• <i>Predict Environmental Hazards</i>• <i>Simulate Reinjection Strategies</i>

Table 2. PROJECTED RESULTS, END OF FY 97

Task	Comment
Combine seawater plus carbonate model	complete (T, 0 - 250°C)
pH in brines	complete (T, 0 - 250°C)
H ₂ S and HS interactions in brines	initiate and continue (T, 100 - 250°C) T _{max} depending on data availability
Sulfide scale solubilities	initiate and continue (T, 100 - 250°C) T _{max} depending on data availability
Aluminum speciation in brines	initiate and continue (T, 0 - 250°C) T _{max} depending on data availability
Solubilities of solid silicates	initiate and continue (T, 0 - 250°C) T _{max} depending on data availability
Near critical behavior of brines for major ions	initiate and continue (T, 250 - 350°C)
Molecular dynamics simulation of high T brines	develop phenomenology
Supercritical properties of brines	(T, 350 -1000°C) develop phenomenology
High pressure effects on scale solubilities	initiate
Workshop	technology transfer (at least two sessions)
Reservoir research (fluid inclusion studies)	as funds are available
Test and apply the models to field problems	
Topical articles and presentations	

Table 3. TECHNOLOGY TRANSFER

- Mineral yields in mineral production processes
- Scaling potentials in industrial evaporation systems
- Solar pond thermodynamics
- Scale formation in oil wells
- Prediction of outcome of programs for scaling abatement
- Prediction of injection water incompatibilities in oil formations
- Site performance assessment in nuclear waste disposal programs
- Prediction of methane content in geopressured systems
- Yield and performance assessment of processes in the aluminum industry
- Atmospheric studies of CO₂ (e.g., global warming)
- Interpretation of natural and industrial geochemical processes
- Validation of laboratory data

Table 4. CAPABILITIES OF PRESENT MODELS

- Predict Behavior of Calcium Carbonate Scale Formation in NaCl and CaCl_2 Brines for $T = 0^\circ$ to 250°C
- Predict Solubility of CO_2 and CH_4 in NaCl Brines for $T = 0^\circ$ to 250°C
- Predict pH and Complete Carbonate Equilibria in Seawater Brines (Na-K-H-Ca-Cl- SO_4 - H_2O System) as a Function of CO_2 at 25°C
- Predict Solubility of Amorphous Silica Scale in Seawater-Type Brines for $T = 0^\circ$ to 250°C
- Predict Solubilities of Marine Scaling Minerals (e.g., NaCl, CaSO_4) to 250°C
- Predict Onset of Two Phase Behavior in NaCl Brines
- Predict Solubility of Hydrogen Sulfide (H_2O - H_2S - HS^-) System (0° to 200°C ; 0 to 100 atm)
- Predict Liquid-Gas Phase Equilibria in the NH_3 - H_2O System to 350°C and 200 bar
- Predict Partial Fugacity in Mixed Gas System (CO_2 - CH_4 - H_2O) $T = 0^\circ$ to 1000°C and $P = 0$ to 1000 bar
- Predict Enthalpies of Brines (0°C to 250°C) and Gases (0° - 1000°C)
- Predict Gas-Liquid Equilibrium in the CO_2 - CH_4 - H_2O System to 1000°C and 3000 bar -
- Predict Gas-Liquid Equilibrium in the NaCl- H_2O - CO_2 System to 1000°C and 5000 bar

**Table 5. DATA USED TO PARAMETERIZE
THE CaCO_3 - NaCl - CO_2 - H_2O SYSTEM**

Binary Interaction Parameters	
H^+, Cl^- Na^+, Cl^- $\text{Ca}^{2+}, \text{Cl}^-$ Na^+, OH^- $\text{Na}^+, \text{HCO}_3^-$ $\text{Na}^+, \text{CO}_3^{2-}$ $\text{CaHCO}_3^+, \text{Cl}^-$	<i>e.m.f. and osmotic data</i>
Ternary Interaction Parameters	
CO_2, Na^+ CO_2, Cl^- $\text{CO}_2, \text{HCO}_3^-$ $\text{CO}_2, \text{CO}_3^{2-}$	<i>solubility data as a function of composition</i>
H^+, Na^+ $\text{Na}^+, \text{Ca}^{2+}$ Cl^-, OH^- $\text{HCO}_3^-, \text{Cl}^-$ $\text{CO}_3^{2-}, \text{Cl}^-$	<i>e.m.f., osmotic and solubility data</i>
Speciation Constants	
$\text{H}^+ + \text{OH}^- = \text{H}_2\text{O} \quad K_w$ $\text{H}_2\text{O} + \text{CO}_2(\text{aq}) = \text{HCO}_3^- + \text{H}^+ \quad K_1$ $\text{HCO}_3^- = \text{H}^+ + \text{CO}_3^{2-} \quad K_2$	<i>e.m.f. and osmotic data</i>
$\text{Ca}^{2+} + \text{HCO}_3^- = \text{CaHCO}_3^+$ $\text{Ca}^{2+} + \text{CO}_3^{2-} = \text{CaCO}_3^0$	<i>e.m.f. and ternary solubility data</i>

Table 6. PTV DATA FOR CH₄, CO₂ and H₂O

System	Authors	Temperature (°C)	P(bar)	# of Measurements
CH ₄	Douslin et al.	0-350	16-400	240
	Olds et al.	20-250	0-700	294
	Deffet & Ficks	50-150	0-3000	156
	Michels & Nederbragt	0-150	400	68
	Keyes & Burks	0-200	30-250	40
	Schamp et al.	0-150	18-250	118
	Tsiklis & Linshits	50-400	8500	70
	Robertson & Babb	35-200	1000-2500	26
	Din	0-150	1-1000	55
	Kvalnes & Gaddy	0-200	1-1000	44
	Francesiconi	150-450	300-2800	89
CO ₂	Michels et al.	0-150	16-3000	329
	Vukalovich et al.	0-750	1-600	493
	Kennedy	0-1000	25-1400	2120
	Sass et al.	50-100	8-500	47
	MacCormack et al.	0-600	1-50	52
	Kirillin et al.	0-35	16-500	39
	Juza et al.	50-450	700-4000	82
	Greenwood	450-800	50-500	79
	Reamer et al.	38-238	14-700	142
H ₂ O	Burnham et al.	20-1000	100-8900	4280
	Greenwood	450-800	50-500	79
	Haar et al.	0-374.1	0-218.3	330
	D'Ans et al.	0-800	1-1000	580

Table 7. AQUEOUS H₂S SOLUBILITY MEASUREMENTS

Authors	Solution	T (°C)	P(atm)	# of pts
Barrett et al(1988)	NaCl(0-5m)	25-95	1.	172
Wright and Maass(1932a)	pure water	5-60	0.3-5	37
Wright and Maass(1932b)	pure water	5-60	0.3-5	26
Douabul et al(1979)	water	0-30	1.	49
Winkler(1906)	pure water	0-60	1.	7
McLauchlan(1903)	pure water	25	≈ 1.	5
Clarke et al(I 97 1)	pure water	0-50	0- 1.	36
Lee et al(1977)	pure water	60-180	1-65	121
Kiss et al(1937)	Urea(0-8m)	0-25	1.	14
Kendal et al(1921)	HCl(0-5m)	25	1.	11
Drummond(1981)	NaCl(0-6m)	30-380	6-30	474
Gamsjager et al(1969)	NaCl-HCl(0-3m)	25	1.	40

Figure 1. Coexisting liquid/vapor compositions in the NaCl-CO₂-H₂O system as a function of pressure for fixed temperature and salt concentration.

Figure 2. Coexisting liquid/vapor compositions in the NH_3 - H_2O system as a function of pressure for fixed temperatures.

HEAT AND MASS TRANSFER IN HYPER-SALINE GEOTHERMAL SYSTEMS

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KEY WORDS

Double-diffusive, convection, density, Salton Sea

PROJECT OBJECTIVES

The project objectives are to investigate the effects on fluid density of NaCl-CaCl₂ brines and the resulting natural convection patterns in liquid-dominated geothermal reservoirs with variable porosity. An understanding of convection in liquid-dominated systems such as the Salton Sea Geothermal System (SSGS) is important for explaining observed temperature and composition patterns and for successful exploitation of the resource.

Technical Objectives

- Determine the effects of heat and NaCl-CaCl₂ brine concentration on fluid density.
- Study the effects of variable porosity on double-diffusive convection.

Expected Outcomes

- Develop robust and efficient simulation capability for hypersaline geothermal systems.
- Better understand fluid flow and heat transfer in saline reservoirs.

PROJECT BACKGROUND AND STATUS

In a prior study, we investigated double-diffusive convection caused by heat and NaCl-brine in an idealized liquid-dominated geothermal system, representing a system like the Salton Sea Geothermal System (SSGS) (Oldenburg et al., 1994a). Because natural brines in the SSGS contain a significant fraction of CaCl₂, we have improved our density model in the current study by using a realistic brine density that is based on a CaCl₂-NaCl brine (Oldenburg et al., 1994b). The prior study investigated convection in a constant porosity reservoir in hydraulic connection with a constant-density aquifer. In the present study, we include a low-porosity layer and examine its effect on heat and mass transfer.

APPROACH

We have used numerical simulation with T2DM (Oldenburg and Pruess, 1993), the dispersion module for the TOUGH2 simulator (Pruess, 1991).

RESEARCH RESULTS

In Figure 1 we compare densities of a pure NaCl brine and a CaCl₂-NaCl brine such as that present in the SSGS. Plotted in Figure 1 are results of our simple mixing model using end-member densities from Pitzer et al. (1984) for NaCl brine and from Oakes et al. (1990) and Oakes (unpublished data) for CaCl₂-NaCl brine. In Figure 1, $X_b = 1.0$ corresponds to either (a) a 24.98 wt. % NaCl solution, or (b) a 24.6 wt. % CaCl₂-NaCl with Ca-Na in molar proportion .20/.80. Superimposed on the density isopleths are temperature and salinity (total dissolved solid [TDS]) of 45 fluid samples of low TDS brines, hypersaline brines, and mixed brines from the SSGS (Williams and McKibben, 1989).

We conclude that the addition of CaCl₂ in the amounts present in the SSGS has a very limited effect on brine density except at the highest brine concentrations. In Figure 2, we show that in forced convection, low porosity enhances brine transport relative to heat transport allowing the heat and brine fronts to separate.

Heat transfer alone is little affected by porosity due to the competing effects of thermal retardation and higher pore velocity. Figure 3 shows a double-diffusive convection scenario for a system with a low-porosity layer at a depth $-1500 < Z < -1000$ m.

The simulation indicates that in free convection, where buoyancy produced by temperature and brine concentration differences drive the flow, there is little enhanced transport of brine relative to heat. This occurs for two reasons:

- (1) In a low-porosity layer, heat transport is not greatly affected due to the competing effects of thermal retardation and increased pore velocity; and
- (2) The increased density at the top of the plume associated with the faster advance of the brine front causes fluid to resist moving upward and produces an effective lid on the plume.

FUTURE PLANS

Future work will include a more realistic reservoir description in terms of permeability structure and initial and boundary conditions. We also plan to examine the effects of porosity variation on downwelling heat and brine plumes.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The simulation program will be transferred to Department of Energy's Energy Science and Technology Software Center (ESTSC) for distribution to the public. Research results have been and will continue to be presented at conferences and in technical journals.

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Figure 1. (a) Density (kg m^{-3}) of NaCl brines and (b) of NaCl-CaCl₂ brines as a function of temperature and brine mass fraction. Superimposed are fluid temperature and TDS (total dissolved solids) data for the SSGS.

Figure 2. Effects of non-uniform porosity at $t=20$ days for heat and mass transfer in one dimensional forced convection.

Figure 3. Computed results at $t=30,000$ yrs. for system with a low-porosity layer ($\phi=.02$) at depth $-1500 < Z < -1000$ m. (a) Temperature field (C). (b) Brine mass fraction field. (c) Density field (kg m^{-3}). Results show the heat and brine plumes do not separate from one another but are instead coupled through their effects on fluid density.

CHARACTERIZATION OF FRACTURE-CONTROLLED POROSITY IN ACTIVE GEOTHERMAL SYSTEMS

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KEY WORDS

Fractures, porosity, image analysis, strike-slip faulting, core, brittle-ductile transformation

PROJECT OBJECTIVES

Fractures provide most of the porosity and permeability in high-temperature geothermal systems, yet in most such systems the origin, three-dimensional geometry and hydrothermal history of these important features are poorly understood. A variety of complex interactions between mechanical rock rupture and circulating thermal waters of diverse compositions can lead in some instances to creation of through-going, cavernous conduits flanked by porous rocks effective for thermal-fluid storage. In other cases, these fluid/fracture interactions foster tight sealing of pores and blockage of potential fluid-flow channels. The objectives of this research project are to improve knowledge of fracture-generated porosity in geothermal systems, to reduce the risk of failure, and to lower the cost of geothermal exploration and development.

Technical Objectives

The project employs a variety of geologic techniques at macroscopic to microscopic scales to:

- Map three-dimensional fracture configurations, sizes, and orientations;
- Characterize mineralogy and internal textures;
- Decipher the tectonic and hydrothermal evolution of fracturing; and
- Effectively transfer the technology to the geothermal industry through discussions, publications, and workshops.

Expected Outcomes

- Provide realistic constraints for numerical and conceptual geothermal reservoir models.
- Develop data on porosity, pore size and permeability of faults and fractures.
- Improve the success of geothermal wells by 5 percent.

PROJECT BACKGROUND AND STATUS

Fluid production in high-temperature geothermal systems is inevitably controlled by faults and fractures. However, failure to find sufficient permeability is the principal cause of failure of geothermal wells. This front-end risk of the failure of expensive wells significantly effects the economics of a geothermal project, and any improvements in the success rate of geothermal wells will benefit the entire geothermal industry. Review of published models of fracture porosity shows that these tend to be highly generalized, often because the only rock samples of the fractures are from drill cuttings rather than core.

Previous work investigated the *in situ* stress in geothermal systems and its application to exploration (Allison and Nielson, 1988; Nielson, 1989; Nielson and Brown, 1990). Allison and Nielson (1988) showed that the stress orientation, and therefore fracture orientation, could be different in different parts of a geothermal system and even within a single well. Nielson (1989) showed that an active system may be structurally decoupled from the regional stress environment leading to different fault orientations. Both of these papers relate directly to the siting and orienting of directionally drilled wells for geothermal production.

Fracturing is confined to the upper portions of the earth's crust. At depth, due to the increase in temperature, rocks undergo ductile deformation. It has long been known that the depth to the brittle-ductile transition zone is at shallower depths beneath active geothermal systems than for the continental crust in general. A review of published information shows that fluid circulates to a shallower depth in hotter than in cooler geothermal systems (Nielson, 1993, 1994). However, the hotter systems have higher volumes and, therefore, underlie larger areas. This study has defined the size of targets for exploration and also the depths beyond which drilling should not be planned. Based on models of porphyry copper system evolution and the natural evolution at The Geysers, the study suggests that fluid injection should be managed to grow fracture zones downward into the brittle-ductile zone.

The project is now emphasizing the character of fault zones and the details of permeability and porosity formation along faults. It is leading to a compilation of an atlas of faults with information on geometric and fluid flow characteristics, which is approximately three years from completion.

APPROACH

A fundamental focus of this project recently has been careful characterization of core from various portions of active, high-temperature geothermal systems, with emphasis on those recently made available from The Geysers steam field. Cores are the best samples of geothermal reservoirs available with direct evidence of the nature of subsurface fracturing, veining, brecciation, and the resulting porosity and permeability. Imaging techniques are under development as part of this project to study the geometries and internal textures of fractures and matrix pores in geothermal cores.

Our approach also includes field mapping over reservoirs to identify the character of the faults that are responsible for subsurface geothermal production. In this context, we have applied satellite image analysis to identify the larger-scale structural features. Subsequent field checks will more accurately identify the character of the fault and fracture zones. Often, satellite data was not available when initial geologic mapping of geothermal systems was done, and we have found that significant new information is available from this technique.

RESEARCH RESULTS

This year's efforts have concentrated on the procedures for accurately imaging core (Nielson et al., 1995). Due to the late start of The Geysers coring project, large-diameter core from a research hole in Utah was used in our methodology development. Problems that needed to be overcome were the standardization of light sources and piecing core images, collected on a foot by foot basis, together to form a continuous image. Automatic processing of the digital images of a short length of Geysers core was able to classify important lithologic and mineral constituents. From these results, the distributions of lithologies, veins, and fractures can be calculated.

Another product of image analysis is a Laser Scanning Confocal Microscopy (LSCM) image of a vein from well NEGU-17 in The Geysers. This image differentiates solid rock from pore space. The porosity decays to nil approximately four fracture widths from the center of the fracture. This sample illustrates our general concept of The Geysers reservoir; porosity is developed along fractures, but there is very little porosity within the "matrix" of the rock. Previous results of imaging analysis (Nielson et al., 1993) have shown that adsorption probably has little impact on fluid production from The Geysers, and that efforts to prolong reservoir life should be based on injection technology.

The core hole, sponsored by the Department of Energy (DOE), in The Geysers field (SB-15D) has provided a number of important results concerning the controls on fracture generation in the field. Many of the fractures observed in the core are related to strike-slip faulting. In the upper portion of the reservoir, the fault movement is concentrated along argillite zones, with the most extensive fracturing taking place in directly adjacent graywacke. With this evidence in hand, preliminary field work was done in The Geysers field. It became clear from that mapping that strike-slip faulting is present at the surface and under-represented on existing geologic maps.

An analysis of satellite images over The Geysers reservoir shows the presence of features that have not been previously reported. A major linear trend to the northeast from the Big Sulphur Creek fault to the south end of Clear Lake. Maps of both the top of the reservoir and the top of the felsite suggest that this feature does influence reservoir geometry. In addition, the images suggest that faults originally mapped as thrust faults have been reactivated as strike-slip zones. It is clear that the structure of The Geysers needs to be reinterpreted in the context of strike-slip tectonics.

Many other geothermal systems in the world are apparently associated with strike-slip faults. These would include some of the systems in Sumatra, such as Sarulla, and those associated with the Philippines fault. Unocal has offered to make the Tiwi field in the Philippines available for study. Included in this study would be an examination of 5500 feet of core from well Matalibong #25.

FUTURE PLANS

- Collect of a suite of samples from SB-15D for image analysis of porosity.
- Field map northeast trending structure that divides The Geysers reservoir into two parts, followed by incorporation of well information to evaluate the character of the structure and its importance to the reservoir.
- Conduct additional field analysis of strike-slip faults in The Geysers.
- Analyze satellite image of Tiwi geothermal field, Philippines, followed by field analysis and logging of corehole Malatibong #25.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	Permission to map in The Geysers field. Field support for mapping at Tiwi, Philippines.

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IMPROVED DUAL-POROSITY MODELS FOR SIMULATING THE BEHAVIOR OF FRACTURED GEOTHERMAL RESERVOIRS

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KEY WORDS

The Geysers, fractured reservoirs, reservoir simulation, dual-porosity

PROJECT OBJECTIVES

The objective of this research is to develop more accurate and efficient methods for numerical simulation of the behavior of fractured geothermal reservoirs, particularly The Geysers.

Technical Objectives

- Develop algorithms for more accurate and efficient simulation of flow processes in fractured geothermal reservoirs.
- Implement these algorithms in a geothermal reservoir simulator such as TOUGH.

Expected Outcomes

- The improved modeling capabilities that emerge from this project will be useful to field developers and operators in planning production schedules and finding remedies to pressure declines.

PROJECT BACKGROUND AND STATUS

Declines in reservoir pressure and steam rates of wells at The Geysers geothermal field have created the need for improved reservoir simulation capabilities. Over the next few years, numerical modeling of injection and other processes will clearly play an important role in finding remedies to reverse the production and pressure declines, and to decrease detrimental concentrations of non-condensable gases and chlorides. Numerical modeling of The Geysers field requires the use of dual-porosity models, in which the fractures and matrix blocks form two overlapping and interpenetrating continua. In dual-porosity systems, most of the global transport of mass and energy takes place in the relatively permeable fracture network, whereas most of the fluid is stored in the relatively impermeable matrix blocks.

Most simulations of processes occurring in fractured geothermal reservoirs are conducted using either the MINC approach (developed by Pruess and Narasimhan in 1985), in which the matrix blocks are represented by a nested set of gridblocks, or a lumped-parameter approach in which the matrix blocks

appear merely as source/sink terms for the fracture gridblocks. Simulations using the MINC method are capable of yielding accurate results, but at the expense of requiring a large number of matrix gridblocks. Lumped-parameter approaches typically utilize the Warren-Root equation to model flow between fractures and matrix blocks, which assumes the flow to be proportional to the difference in pressure between the fractures and matrix blocks. This approach is, for example, presently incorporated into the TETRAD simulator that was developed by Vinsome in 1991. This method is simpler and more efficient to use than MINC-type simulations, but can be very inaccurate during early stages of production.

In this project, we have been developing methods for conducting simulations of fractured reservoir behavior that are more accurate than those that utilize the Warren-Root approach, but which do not require discretization of the matrix blocks. We began in FY 92 by developing a more accurate, nonlinear version of the Warren-Root equation for single-phase flow, and incorporating it into the TOUGH code. In the next two years, this method was extended to cover production from two-phase matrix blocks in which the liquid was at irreducible saturation, and to include thermal conduction effects. The last remaining part of this work is to extend the method to treat cases where both fluid phases are mobile.

APPROACH

The approach taken is to model heat and fluid flow between the fractures and matrix blocks using a nonlinear version of the Warren-Root equation. This equation has been verified as being more accurate than the Warren-Root equation, over all time scales (Zimmerman et al., 1993a). This equation is used as a source/sink term for the fracture gridblocks, eliminating the need for the five to ten matrix gridblocks (for each fracture gridblock) that would otherwise be needed. Hence, the new method allows either: (a) a large increase in computational speed, if the number of fracture gridblocks is kept constant; or (b) a five- to ten-fold increase in the number of fracture gridblocks that can be included in a simulation, thus allowing much more accurate predictions of reservoir behavior.

RESEARCH RESULTS

Our new nonlinear fracture/matrix interaction equation was first incorporated as a modification of the TOUGH simulator, which was developed by Pruess in 1987. This modified version of TOUGH was used to simulate one-dimensional flow of a single-phase fluid into a fractured formation (Zimmerman et al., 1993a).

The results were compared to those obtained using the Warren-Root method or the MINC approach, and were found to be more accurate than the Warren-Root results, while requiring about ten times less computational time than did the MINC method.

We then adapted the method to treat conduction of heat from the matrix blocks into the fracture system. This is possible because both heat conduction and single-phase fluid flow are governed by analogous diffusion equations. Our new nonlinear equation was then incorporated into TOUGH to serve as a source/sink term for heat conduction from matrix blocks into the fracture network, with the temperature difference as the driving force (analogous to the pressure difference), and energy as the flux (analogous to mass flux). This version was verified against the results found by Pruess and Wu in 1989 for the problem of the injection of cold water into a single well in an infinite, fractured reservoir.

The method was then extended to treat situations such as fluid production from a fractured geothermal reservoir in which the liquid in the matrix blocks is initially at irreducible saturation. This type of flow

can be modeled by a single diffusion equation by using the equivalent two-phase compressibility that was defined by Grant and Sorey and others (see Zimmerman et al., 1993b).

Figures 1 to 4 show the results of a simulation of a sample problem of injection and production in a three-dimensional, liquid-dominated reservoir whose properties are similar to those of The Geysers. In the simulations, the matrix permeability is $1.0 \text{ E-}19 \text{ m}^2$, the matrix porosity is 0.04, the rock density is 2468 kg/m^3 and the heat capacity of the matrix rock is 1 kJ/kg K .

The fracture network has a porosity of 0.01, and a permeability of $2.0 \times \text{E-}14 \text{ m}^2$. The irreducible liquid saturation is 0.25 in the matrix blocks, and 0.0 in the fractures. For comparison, the problem was simulated using the modified version of TOUGH, as well as using TOUGH with a MINC-type grid. The results, shown in Figures 2 to 4, indicate that the new method gives very accurate results, with a savings in computational time of about a factor of ten.

FUTURE PLANS

Remaining work includes extension of our approach to cases where both fluid phases are mobile in the matrix blocks. Finally, each of the various modules we have developed must be combined into a single module that will allow simulation of single-phase isothermal, single-phase non-isothermal, or two-phase flow, as required by the problem at hand.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This work is currently being pursued in cooperation with UNOCAL, which is interested in incorporating the algorithms developed in this project into the TETRAD simulator.

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Figure 1. Schematic diagram of grid used in the sample problem.

Figure 2. Pressure in the fractures of the production gridblock.

Figure 3. Pressures in the fractures of the injection gridblock.

Figure 4. Vapor saturation in the fractures of the injection gridblock.

COUPLING OF A RESERVOIR SIMULATOR AND A WELLBORE SIMULATOR FOR GEOTHERMAL APPLICATIONS

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KEY WORDS

Geothermal reservoirs, modeling, wellbore flow

PROJECT OBJECTIVE

The objective of this work is to develop the capability of performing simultaneous simulation of reservoir and wellbore flow, for the purpose of allowing more accurate modeling of geothermal reservoir behavior.

Technical Objectives

- The objective of this project is to develop a subroutine, COUPLE, that will provide coupling between the reservoir simulator TOUGH and the wellbore simulator WFSa.

Expected Outcomes

- The subroutine COUPLE will allow simultaneous simulation of wellbore and reservoir flow, which will permit more accurate modeling of geothermal reservoir behavior.

PROJECT BACKGROUND AND STATUS

Currently, reservoir simulation and wellbore simulation are typically performed separately, in an uncoupled manner. Although many reservoir simulators exist that model flow processes in the subsurface, they typically ignore the details of flow in the wellbore, and treat the well in a very simplified manner. Likewise, several simulators exist which model the internal flow in the wellbore; these codes usually take as their input parameters such as flowrates and enthalpies that would typically be found as output of a reservoir simulator. Hence, simulation of the total reservoir/wellbore system is usually done sequentially, in a time-consuming iterative manner. The purpose of this project is to provide an interface between the wellbore simulator WFSa and the reservoir simulator TOUGH, so that wellbore and reservoir flow can be simulated in a coupled, integrated manner.

The main part of this project, which is the development of the subroutine COUPLE, has been completed in FY 94. The subroutine has been tested on various idealized reservoir problems. The remaining work consists of the following stages: to write a user's manual for COUPLE, and to validate the new coupled simulation procedure against actual field data.

APPROACH

We have developed a computational module called COUPLE that serves as an interface between the reservoir simulator TOUGH and the wellbore simulator WFSa. This allows WFSa to function as a subroutine of TOUGH, calculating production rates from wells that serve as source/sink terms for the gridblocks that contain the well. Simulations no longer require the frequently inaccurate assumption that the bottomhole pressure remains constant, and therefore more accurately reflect the physical processes that occur in the reservoir and wellbore.

TOUGH (Pruess, 1987) is a numerical code designed to simulate the coupled transport of fluid, heat and chemical species for multi-phase flow in porous as well as fractured media. TOUGH is a member of the MULKOM family of codes developed by Karsten Pruess at LBL, which are widely used in geothermal applications. TOUGH is a three-dimensional code which solves the equations of motion by discretizing them in space using the "integral finite difference" method. Time is discretized in a fully implicit manner, as a first-order finite difference. At each time step, TOUGH solves mass balance and an energy balance equations for each computational gridblock. TOUGH has options for describing fluid/heat injection or withdrawal from the reservoir, treated as source/sink terms. The code also has a deliverability option to evaluate well output based on a specified bottomhole pressure and productivity index. According to the deliverability option, the mass flowrate is proportional to the difference in pressure between the fluid in the wellblock, and the bottomhole pressure, which is assumed to be fixed.

The simulator WFSa was developed at Auckland University, New Zealand (Hadgu, 1989; Hadgu and Freeston, 1990). The WFSa computations apply mass, momentum and energy conservation at each selected depth interval along the well. WFSa can account for the presence of dissolved solids, heat exchange with the surrounding rock, variations in pipe diameter with depth, pipe roughness, and multiple feedpoints. Calculations can begin at either the wellhead or at bottomhole.

The new program COUPLE functions as a subroutine that is called by TOUGH during its calculations. An iterative procedure is utilized between COUPLE and WFSa to evaluate mass flowrates and wellbore pressures at each feedzone. For a fixed wellhead pressure, the wellbore flowrate computed by WFSa will depend on the bottomhole pressure. The flowrate computed by TOUGH from the wellblock to the wellbore will also depend on the bottomhole pressure. Hence, the calculations are iterated until a bottomhole pressure is found such that both TOUGH and WFSa calculate the same wellbore flowrate, thus assuring conservation of mass.

RESEARCH RESULTS

The new subroutine COUPLE has been used to solve various idealized geothermal reservoir problems. To test the performance of the coupled simulation procedure, the results were compared to those obtained using the deliverability option of TOUGH. The results showed that the coupled simulators produce much more accurate output than the deliverability method, except in some limited cases such as when the reservoir permeability is very high, so that changes in bottomhole pressure are minimal. The problems demonstrated that reservoir-wellbore simulation in general is needed in order to obtain accurate predictions of reservoir behavior.

Following is a sample problem to demonstrate possible applications of the coupled simulation procedure. One of the most useful applications of the coupled simulators is to study various energy and power output

scenarios. In this problem we used the coupled simulators to demonstrate power output prediction of a well operating under different wellhead pressures over a period of five years.

In the problem a single well is located at the center of an infinite radial grid. Reservoir and caprock thicknesses are 1000m and 500m, respectively. The reservoir permeability is taken to be 0.5 darcy, the porosity is 0.10, the rock density is 2600 kg/m³, the specific heat is 1.0 kJ/kg°C, the initial reservoir pressure is 60 bars, the initial temperature is 275.6°C, and the initial vapor saturation is 0.2. A radial mesh was used, with the radius of the wellblock taken to be 100m, and each successive gridblock radius increasing by a factor of 1.29. The simulations were conducted using different values of wellhead pressure.

The results of the simulations are given in Figures 1-4. Figure 1 shows prediction of mass flowrate at different wellhead pressures. The curves indicate an increase in mass flowrate with a decrease in wellhead pressure, which agrees with typical output curves of large-diameter production wells (note that higher wellhead pressures can cause higher resistance to flow). Predicted flowing enthalpies consistently show a rise, with enthalpy decreasing slightly as wellhead pressure increases (Figure 2). Figure 3 gives the variation of mass flowrate and enthalpy with wellhead pressure after a production period of five years. As pointed out above, where as the mass flowrates change significantly with wellhead pressure, the changes in enthalpy are not as substantial.

Electrical power output and steam consumption predictions were made using the computed mass flowrates, enthalpies, and wellhead pressures, assuming that the wellhead pressure represents the turbine inlet pressure. A turbine exhaust pressure of 0.8 bar was selected. The results are shown in Figure 4. At low wellhead pressures, the mass flowrates are high, but the change in enthalpy between turbine inlet and exhaust is low. At high wellhead pressures, the reverse occurs. As a result, the curve for electrical power output shows a peak at intermediate pressures.

FUTURE PLANS

The code COUPLE has been written, and a paper describing its development and use has been accepted for publication in *Geothermics* (Hadgu et al., 1995). Some additional work is required to develop a user's manual that will illustrate how the code can be used to simulate geothermal reservoir/wellbore behavior. We are also attempting to locate data sets that will allow the coupled simulation procedure to be verified against actual field data.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The coupled reservoir-wellbore simulator will greatly help in the management of exploratory and producing geothermal fields by generating more reliable predictions. Because of the interest in the industry's researchers this simulator will be made available to industry through the Energy Science and Technology Software Center, P.O. Box 1020, Oak Ridge, TN 37831.

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Figure 1. Prediction of well discharge flowrate using the coupled simulators at different wellhead pressures.

Figure 2. Prediction of well flowing enthalpy using the coupled simulators at different wellhead pressures.

Figure 3. Well discharge flowrate and flowing enthalpy at different wellhead pressures.

Figure 4. Well power output and steam consumption at different wellhead pressures.

DEVELOPMENT OF A PC VERSION OF TOUGH2

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KEY WORDS

Personal computers (PCs), large-scale geothermal reservoir simulations, conjugate gradient solvers, computer platforms comparison

PROJECT OBJECTIVE

Take advantage of the computing power of present PCs, and provide the geothermal industry with a cost-effective solution to conduct production forecast and field development simulations on these type of machines.

Technical Objectives

- Adapt the TOUGH2 simulator [Pruess, 1991] to run on PC platforms.
- Make transparent to the user the transportability of numerical models between platforms, and keep the PC version of TOUGH2 compatible with the mainframe and work station versions.

Expected Outcomes

- Facilitate the use of DOE-funded software like LBL's simulator TOUGH2 by making it more accesible to the geothermal community, especially to small companies and individuals which in many cases do not have access to workstations and mainframes.

PROJECT BACKGROUND AND STATUS

The TOUGH2 numerical simulation program has been widely applied in geothermal reservoir engineering, and other geoscientific fields. The code has been used mainly on mainframes and high-end workstations, which are expensive, and in many cases not accessible to individuals or small organizations. With the objective of reaching a broader range of users, TOUGH2 was modified to operate on PC-type machines. A parallel study being conducted by Moridis and Pruess at LBL since 1992 on the use of preconditioned conjugate gradient (CG) solvers allowed to define three different CGs that are adequate for solving the type of matrices produced by TOUGH2 in geothermal applications.

The CG solvers significantly increase the size of problems tractable on personal computers. CG solvers also significantly decrease the execution time and memory requirements, making possible the simulation of much larger (in terms of number of equations) systems when compared to what was possible to execute using TOUGH2 and its standard direct solver MA28 [Duff, 1977].

The CG package was derived from the Sparse Linear Algebra Package (SLAP) Version 2.0 [Seager, 1988] developed for the solution of large sparse linear systems and contains the TOUGH2 standard direct solver MA28, a Bi-Conjugate Gradient (BCG) proposed by Fletcher [1976], a Lanczos-type Bi-Conjugate Gradient Squared (BCGS) developed by Sonneveld [1989], and the Generalized Minimum Residual (GMRES) method of Saad and Schultz [1986].

TOUGH2 with the CG package of solvers was tested with: a) Cartesian simulation models of up to 10,000 grid elements for single-phase and two-phase cases and b) an irregular grid simulation model of the Cerro Prieto geothermal field [Antúnez and Lippmann, 1993; Antúnez et al., 1994] using single-porosity approach and a double-porosity approach using the Multiple Interactive Continua (MINC) technique [Pruess, 1983]. Antúnez et al. (1995) conducted tests using TOUGH2 and the Cerro Prieto model on different machines, three PCs (486-33, 486-66, Pentium-90), a MacIntosh Quadra 800, and a workstation IBM RISC 6000. This study reinforces that PCs are a very cost-effective platform to conduct geothermal reservoir simulations.

TOUGH2-PC was revised to conform to a mainframe/workstation update of the code recently released (November 1994) to the Energy Science and Technology Software Center (ESTSC) for general public distribution. This new version (Ver. 1.11) of TOUGH2 and TOUGH2-PC, includes the CG solvers package and some minor internal changes required to assure compatibility with TOUGH2 modules to be released in the near future. TOUGH2-PC will be released in the first quarter of 1995.

APPROACH

The TOUGH2 code requires 64-bit arithmetic. When using a 32-bit machine (i.e., machines with 386 and 486 processor), it is necessary to modify the code to declare all variables REAL*8 (or DOUBLE PRECISION), and to comply with the FORTRAN77 ANSI X-3.9-1978 standards, also all floating point constants must be converted from E##.# to D##.# format.

RESEARCH RESULTS

The TOUGH2 code with the CG solvers package was transported to the PC environment and thoroughly tested using the sample problems provided in the standard TOUGH2 package and an existing computational grid [Antúnez et al., 1994]. TOUGH2 is set to be compiled and linked using the Lahey Fortran Compiler for 32-bit machines Ver. 5.0 or better. Minor changes are required if TOUGH2 is used in combination with any other 32-bit Fortran compiler.

The TOUGH2-PC code was beta-tested by selected research associates. There have been no reports of errors. From the testing conducted on TOUGH2-PC with the CG solvers package, it was concluded that conjugate gradient solvers significantly reduced the execution time and storage requirements making possible the execution of considerably larger problems (10,000+ grid blocks) on PCs [Antúnez et al., 1994].

The Lanczos-type Bi-Conjugate Gradient Squared was found to be the fastest of all tested solvers. Therefore, it was set to be the default solver for TOUGH2 and TOUGH2-PC version 1.11. Users have now the option of selecting the direct solver MA28 or any of the three precondition CG solvers included in the package. The CG solvers have the advantage that the computation time and memory requirements increased with problem size only slightly faster than linear. Memory requirements for TOUGH2-PC with

the conjugate gradient solvers are approximately linear. Therefore, the amount of random access memory required by a grid can be easily interpolated or extrapolated [Antúnez et al., 1994].

To help the potential users of TOUGH2-PC to make an informed decision about migrating from other platforms to PCs. It is necessary to have an idea about the efficiency of running the code on the PC and compare execution times with other platforms. A study conducted by Antúnez et al. (1995) shows TOUGH2 performance, using a Cerro Prieto model as the input file, on different machines, three PCs (486-33, 486-66, Pentium-90), a MacIntosh Quadra 800, and a workstation IBM RISC 6000.

Time comparisons for the different machines presented in Figures 1 and 2 indicate that the three PCs showed performances very similar to the high-end workstation IBM RISC 6000 and one of them, the PC Pentium 90, gave 50% faster performance than the workstation. At current prices, a well equipped Pentium 90 costs approximately a fourth of a comparably equipped RISC 6000.

The MacIntosh developed some roundup errors that did not allow the simulation to advance in time. The problem was solved by tightening the closure criteria for the conjugate gradient (from 1×10^{-6} to 1×10^{-8}). This way the roundup errors did not continue increasing and the Mac was able to attain the same total simulation time as the other machines. The overall simulation on the Mac took a higher number of Newtonian iterations to converge. The results for the MacIntosh presented in Figures 1 and 2 correspond to the run conducted with the same closure criteria for the CG solver (1×10^{-6}) as for the other machines to keep a comparative basis.

It is worth noticing that the results presented in Figures 1 and 2 reflect not only the performance of the machine but also the efficiency of the executable code produced by their respective Fortran compiler.

This study reinforces the conclusion that PCs are a very cost-effective platform to conduct large-scale three-dimensional geothermal reservoir simulations, and that they compare or surpass the performance of some of the most popular high end workstations.

PCs Setup and Requirements

The processing speed of the code will depend on the machine being used. The maximum size of computational grids will depend on the amount of extended memory (XMS) available on the machine. A minimum configuration to run TOUGH2-PC would be a 386 PC equipped with 4 MB of RAM, an 80 MB hard drive and an optional (but recommended) numerical coprocessor (387). This configuration will allow to perform three-dimensional³ simulations with grids of approximately 800 elements and 2,400 connections when using the CG solvers; or approximately 500 elements and 1,500 connections using the standard version of TOUGH2-PC with the direct matrix solver (MA28).

FUTURE PLANS

Information about the general availability of the TOUGH2-PC code will be released on the first quarter of 1995. Other LBL developed TOUGH2 compatible modules relevant to the geothermal industry like the wellbore simulator module [Hadgu et al., 1995] are planned to be modified and made available on PC version.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

There has been significant interest on TOUGH2-PC and copies have been distributed to registered owners of the mainframe and workstations versions of the code that requested it. This procedure will be valid until TOUGH2-PC is released to the ESTSC.

At the request of the California Department of Conservation, Division of Oil Gas and Geothermal Resources (DOGGR), LBL is training two DOGGR engineers on the use of TOUGH2-PC. With this, DOE-LBL are helping DOGGR to: (1) decrease its dependency on interpretative data provided by field operators; (2) develop in-house reservoir simulation capabilities increasing its forecasting confidence; and (3) enhance its supervision of fields under production.

-
1. Conjugate Gradient solvers are algorithms for the iterative solution of large sets of linear equations.
 2. Extended memory (XMS) is additional memory beyond the first MByte (MB) of random access memory (RAM). The first MB of RAM is usually occupied by the Disk Operating System (DOS), the 640 KB of DOS conventional memory and the Terminate and Stay Resident applications (TSR).
 3. Three-dimensional simulations are the most memory demanding. 1-D and 2-D problems result in arrays of smaller size.

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Figure 1. Timing of Newtonian iterations for different machines using the Cerro Prieto model, the simulation code TOUGH2 and a Lanczos type biconjugate Gradient Squared solver

Figure 2. Comparative performance ratio, taking the timing of Newtonian iterations of a PC 486-33 machine as the basis for the comparison.

RECENT TETRAD MODIFICATIONS

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KEY WORDS

TETRAD, numerical simulation, decay, adsorption, vapor-pressure lowering

PROJECT OBJECTIVES

The intent of this project is to continue enhancement of a numerical simulator used in the geothermal community by incorporating additional physical phenomena affecting transport of geothermal fluids. By allowing for more complex physics to be modeled, a better understanding of the processes of interest in a geothermal reservoir can be attained. Improved predictive capabilities are also required for optimal resource management.

Technical Objectives

- Improve the ability to simulate the processes of injection, including adsorption/desorption, capillary condensation, dispersion and diffusion, and thermal and radioactive decay. Such simulation capabilities require the code modifications noted below.
- Make and validate modifications to the geothermal simulator TETRAD. Modifications include molecular diffusion and dispersion, adsorption, thermal and radioactive decay, generalization of vapor-pressure lowering, and incorporation of parametric expressions for capillary pressure functions.

Expected Outcomes

- An improved numerical simulator has been developed and is being validated. The additional features allow for a variety of enhanced reservoir engineering studies, including simulation of tracer injection experiments and adsorption studies. TETRAD is a dynamic code, and additional enhancements and upgrades occur frequently in response to industry needs.

PROJECT BACKGROUND AND STATUS

Numerical simulation studies for geothermal reservoir management have been used increasingly over the last decade. Models used in the simulation studies have evolved from transport of a single component (water) in a porous medium to complex simulations including water, salts, and noncondensable gases with adsorption/desorption in fractured media. Tracer use to characterize flow paths has also increased appreciably. Complex transport and storage mechanisms must be accounted for in order to accurately predict movement of the injectate under these conditions. Because of the complexity of the processes, numerical simulations are useful in interpreting results.

The geothermal numerical simulator, TETRAD, has undergone a series of modifications over the last year. Modifications were made specifically to improve simulation of injection problems. Models were implemented to treat dispersion/diffusion, adsorption, vapor-pressure lowering, decay, and thermal degradation. Additional enhancements can and will be made as they become important to the geothermal community.

APPROACH

Expressions for each of the new phenomena were extracted from the literature, and incorporated in TETRAD. Each of the models has been validated by comparing against analytical or experimental results.

RESEARCH RESULTS

Over the last year, several additional features have been added to TETRAD. A generalization for vapor-pressure lowering was presented by Shook (1993), and this has recently been added to the general release version of the code. Mechanical dispersion and molecular diffusion have also been added and validated, as has an option for thermal, radioactive, and biological decay. Finally, an adsorption package was added. Some of these modifications have been discussed in conference papers (e.g., Shook, 1994), and a validation report is in progress (Shook, 1995). The new modifications have been tested satisfactorily and all are available in the current general release of TETRAD.

FUTURE PLANS

No modifications are currently being planned; however, as research identifies processes of interest in transport of geothermal fluids, enhancements to TETRAD will be undertaken. A validation report discussing the most recent modifications is in progress.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

TETRAD is used by approximately 12 geothermal operators, both domestically and in international studies. Several of the operators - most notably UNOCAL Geothermal and California Energy Co. - have been instrumental in suggesting enhancements to the code as well. In addition, nearly one dozen universities use TETRAD in classroom instruction, both for geothermal and oil & gas topics.

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ROOSEVELT HOT SPRINGS - BASIN AND RANGE RESERVOIR CASE STUDY

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KEY WORDS

Roosevelt Hot Springs, reservoir evaluation, exploration, case study, long-term flow test

PROJECT OBJECTIVE

The objective of the project is to conduct a reservoir case study of the Roosevelt Hot Springs geothermal system that: provides an evaluation of the utility of reservoir engineering techniques in detection, early assessment, and sustainability of the geothermal system; evaluates the exploitation response of the reservoir; and results in a conceptual model of the geothermal system consistent with the reinterpreted geologic and engineering data.

Technical Objectives

- Examine the available data, evaluate reliability, and assess existing interpretations.
- Generate new data critical for the case study.
- Perform an integrated, interdisciplinary analysis and interpretation of the data.
- Assess the usefulness of the types of data and techniques used in their application to geothermal exploration and resource assessment.
- Prepare a concise case study with documentation of the results obtained.

Expected Outcomes

- Obtain an enhanced understanding of the long term deliverability of a fractured granitic reservoir.
- Obtain an improved understanding of the long-term behavior of water influx into the Basin and Range geothermal reservoir.
- Determine improved reservoir testing and analysis tools.
- Refine the conceptual model of the Basin and Range liquid-dominated hydrothermal system.

PROJECT BACKGROUND AND STATUS

This is a new project that was initiated in 1994 with the cooperation and support of California Energy Company, Inc. (CECI), the operator of the field, and the University of Utah Research Institute (UURI). CECI has made available extensive data sets from Roosevelt Hot Springs, including the raw data from three long-term flow tests conducted prior to the start of exploitation, the complete exploitation production history, and a calibrated numerical reservoir model. Thus, almost 20 years of high quality data are available for this effort.

APPROACH

The reservoir testing and evaluation of Roosevelt Hot Springs spans a time period of almost 20 years. Various reservoir testing and evaluation programs were performed over this time period. The reservoir analysis will be broken down into specific tasks corresponding to these events.

PROJECT BACKGROUND AND STATUS**Pre-Exploitation Deliverability Testing**

The early reservoir assessment work consisted of many single wells, short-term deliverability tests and extensive pressure and temperature surveys of the wells. This early testing phase and data collection will be reviewed first. This early testing provided a great deal of pre-exploitation reservoir engineering data about the reservoir permeability and the role of water influx into the reservoir. CECI has provided the data set on an in-kind basis.

Long-Term Flow Testing

Three long-term flow tests were conducted in the time period 1977 to 1983 with a single production well and five to six observation wells at distances of 600 feet to two and half miles. These flow tests had durations ranging from 90 to 180 days with shut-in periods of up to 90 days. The long-term flow tests were essentially reservoir deliverability and reservoir limits tests and the volume of the reservoir influenced by each test will be determined. The testing series will be summarized based on proprietary operator's reports. During this test series, there was evidence of recharge into the reservoir and this will be reviewed and quantified. At the conclusion of the third long-term flow test, sufficient temperature, pressure, and pressure transient data had been collected to prepare pre-exploitation reservoir temperature and pressure maps. A conceptual model will be developed based on the information available at the conclusion of this testing episode.

Reservoir Response to Exploitation

Production started in 1984 with the operation of a 20 MWe single flash power plant. Plant operation has been very stable with an annual capacity factor nearly 100%. A steam cap evolved in the reservoir in response to exploitation. Production, injection, and observation pressure data will be summarized and reservoir pressure trends in response to production will be presented. An extended field shut-down in response to production will be presented. An extended field shut down occurred in 1993 in which the reservoir pressure increased about 60 psi.

Pressure Transient Testing of the Reservoir Undergoing Exploitation

A series of single-well and interference pressure transient tests were conducted to supplement information about the reservoir permeability structure and verify the pre-exploitation data. This data will be reviewed and compared the pressure transient data.

Reservoir Simulation Studies

Several reservoir simulation studies have been performed at different times in the development of the reservoir. These studies will be reviewed in light of the data presented, reviewed and analyzed. The most recent reservoir model has been provided by the operator and calibrated against an extended field shut-down that occurred in 1993. This model matches the exploitation response, however the model under-predicts reservoir pressure recovery to field shut-downs. Specific topics to review with the simulation model are the native state of the reservoir, long term sustainability of the resource, the rate of natural recharge into the reservoir, and the development of a reservoir management plan.

Synthesis of Data and a Reservoir Description

The results from the above sections will be synthesized with the geologic, geophysical, geochemical, and reservoir engineering data into an internally consistent reservoir description. A final conceptual model will be developed for integration with the geologic studies undertaken at UURI as part of this reservoir case study.

Chronology of Events

A chronology of events will be prepared outlining the timing and duration of the various reservoir tests, data collection, and studies undertaken. This chronology will be crucial in understanding the field testing events that occurred.

RESEARCH RESULTS

The first long-term flow test has been analyzed and the results have been published. This long-term flow test provided insight into the role of water influx into the reservoir in response to the flow test and resulted in a downward revision of the estimated reservoir volume. The estimated reservoir volume is in much better agreement with the calibrated reservoir model, developed by CECI.

FUTURE PLANS

The preparation of the case study will involve the several interrelated disciplines, as briefly outlined: 1) geologic studies; 2) geochemical studies; 3) geophysical studies; 4) reservoir engineering studies; 5) integration of the study results; and 6) reporting. Items 1), 2), and 3) will be performed by UURI, item 4) will be performed by INEL, and items 5) and 6) will be performed jointly.

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DEVELOPMENT OF A GEOTHERMAL RESOURCE IN A FRACTURED VOLCANIC FORMATION: CASE STUDY OF THE SUMIKAWA GEOTHERMAL FIELD, JAPAN

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S-Cubed

KEY WORDS

Sumikawa Geothermal Field, fractured volcanic formation, pressure transient data, acidic fluids, computerized data base, downhole logs, slimholes

PROJECT OBJECTIVES

The next major geothermal area in the United States to be developed is likely to be the Cascade volcanic zone in the Pacific Northwest region. At present, detailed practical information pertinent to the development of geothermal resources in fractured volcanic rocks is scarce in the United States. Geothermal resources in Japan, however, are located in fractured volcanic zones and the development of the Cascade region would likely be expedited by the availability of information concerning the Japanese experience in geothermal exploration and reservoir assessment.

Technical Objectives

- Document and evaluate the use of drilling logs, surface and downhole geophysical measurements, chemical analyses and pressure transient data for reservoir assessment purposes.
- Evaluate the feasibility of predicting the discharge characteristics of large-diameter production wells on the basis of test data from slim holes.
- Demonstrate the usefulness of a map-oriented geothermal database for interpretation of exploration data and analysis of exploration strategies and reservoir information.

Expected Outcomes

- A conceptual model of the natural state of the Sumikawa Geothermal Field will be developed based on the complete exploration and production data.

PROJECT BACKGROUND AND STATUS

The Sumikawa Geothermal Field is located in the Hachimantai volcanic area in northern Honshu, Japan, about 1.5 kilometers to the west of the Ohnuma geothermal power station operated by Mitsubishi Materials Corporation (MMC). The Hachimantai area also includes the Matsukawa and Kakkonda

Geothermal Fields. An extensive well drilling and testing program was initiated in the Sumikawa area in 1981 with the spudding of boreholes S-1 and S-2 by MMC and the Mitsubishi Gas Chemical Corporation (MGC). The New Energy and Industrial Technology Development Organization (NEDO) became involved in the field characterization effort with the drilling of borehole N59-SN-5 in 1984-1985.

During the years 1986-1990, under NEDO sponsorship, S-Cubed carried out reservoir engineering studies of the Sumikawa Geothermal Field. The field characterization program at Sumikawa was successfully concluded in 1990 with a decision to build a 50 MWe power plant. The Sumikawa geothermal power plant is expected to be commissioned some time in 1995.

In 1993, S-Cubed under a contract with the U.S. Department of Energy (DOE)/Sandia National Laboratories (Sandia)—approached Mitsubishi Materials Corporation (MMC) for release of their proprietary data from the Sumikawa Geothermal Field for use in a case study of a high-temperature, fractured, volcanic field. As a result of these negotiations, MMC gave permission to S-Cubed to use pertinent Sumikawa data obtained prior to 1990. MMC has also indicated its willingness to release more recent data at a future date.

Because of DOE's budget constraints, the Sumikawa case study will be conducted over several years. A report (Garg et al., 1994) describing work performed during FY 93 was approved by MMC for publication in December 1994. The report is now being reviewed by Sandia. DOE decided to fund the second year (FY 94) of this project through the Idaho National Engineering Laboratory.

APPROACH

The principal purpose of the present work is to document and evaluate the use of drilling logs, surface and downhole geophysical measurements, chemical analyses and pressure transient data for reservoir assessment purposes at the Sumikawa Geothermal Field. To provide convenient access to the Sumikawa data base, the pertinent Sumikawa data are being incorporated into S-Cubed's Geothermal Reservoir Data Management System (GEOSYS).

GEOSYS (Stevens et al., 1992) is an interactive, graphical, map-oriented computer system used to store, display and analyze large volumes of geothermal reservoir engineering data. The design requirements for GEOSYS were defined by S-Cubed scientists experienced in the integration/synthesis of geothermal data. GEOSYS consists of a set of independent, integrated modules that analyze and display geographical data, subsurface cross sections, well structure, well logs, and chemical and production data. GEOSYS runs on Unix workstations using the X Window System. More information about GEOSYS is available on the World Wide Web at <http://www.scubed.com:8001/products/GEOSYS.html>

To date, the following data have been entered (and checked for errors) into GEOSYS:

- Surface tectonic and topographic maps;
- Well drilling (circulation loss, deviation, stratigraphy) and completion data;
- Well histories; and
- Downhole logs (pressure, temperature, spinner) in shutin and flowing wells.

With very few exceptions, the above data sets (for the period prior to mid-1990) are now available as part of GEOSYS. These data are also available in paper copy form (Garg et al., 1994).

Work is presently (FY 94) continuing on incorporating (and verifying) geochemical data from analyses of well fluids and hot springs into GEOSYS. Surface geophysical/geological data, core test data, well testing and pressure transient data will be entered into GEOSYS at a later date. As already mentioned, MMC has expressed its willingness to supply some post-1989/1990 data for this study; these data will also need to be incorporated into GEOSYS.

Under its drilling research program, the U.S. Department of Energy through Sandia National Laboratories (Sandia) has initiated a research effort to demonstrate that slim holes can be used (1) to provide reliable geothermal reservoir parameter estimates comparable to those obtained from large-diameter wells, and (2) to predict the behavior of large-diameter wells. During FY 93, S-Cubed was tasked to examine the existing production and injection data for both small-diameter boreholes and large-diameter wells at the Sumikawa Geothermal Field. The major thrust of this work was to evaluate the feasibility of predicting the discharge characteristics of large-diameter production wells on the basis of test data from slim holes. Mitsubishi Materials Corporation (MMC) has carried out a series of pressure transient (both single well drawdown/buildup and multiple well pressure interference tests) tests at the Sumikawa Geothermal Field. These test data are invaluable for determining the permeability structure at Sumikawa. During FY 94, work was initiated on analyzing some of the pressure interference tests. Analyses of pressure transient data will be continued in the future years within the available budget constraints.

The reservoir fluids at Sumikawa are mainly of the Na-Cl type with a near neutral pH. Acidic fluids have been encountered only infrequently at Sumikawa. Drilling along the flanks of young volcanoes (e.g., Mt. Yake at Sumikawa) can be expected to result in encounters with acidic zones. An examination of geochemical data for the Sumikawa Geothermal Field should be useful in deriving a better understanding of acidic zones in high-temperature, fractured, volcanic geothermal fields.

RESEARCH RESULTS

The work accomplished during FY 93 is described in a report by Garg, et al. (1994). A brief overview of the Sumikawa Geothermal Field is given. The drilling information and downhole pressure, temperature, and spinner surveys are used to determine feed zone locations, pressures, and temperatures. Production and injection data from slim holes and large-diameter wells at the Sumikawa Geothermal Field, Japan, are analyzed to determine the effect of wellbore diameter on: 1) the productivity/injectivity index, and 2) on the discharge rate. The injectivity indices for Sumikawa boreholes do not depend on borehole diameter in any systematic manner; furthermore, the productivity indices (for boreholes with liquid feeds) are more or less equal to the injectivity indices. For boreholes with liquid feed zones, discharge rates scale with diameter according to a relationship previously presented by Pritchett (1993). Pritchett's scaling rule does not appear to apply to discharge data from boreholes with two-phase feed zones; however, discharge characteristics of slim holes with two-phase feed zones can be used to infer production rates from large-diameter wells. A paper (Garg and Combs, 1995) describing slim hole aspects of work performed during FY 93 has been accepted for presentation at the 1995 Stanford Geothermal Reservoir Engineering Workshop.

FUTURE PLANS

Because of DOE's budget constraints, it appears that it will be necessary to perform the Sumikawa case study over several years. During FY 95, we will continue to enter all the data released by MMC into the computerized database system GEOSYS. While no large-scale numerical simulations of the Sumikawa reservoir will be performed under this case study, we plan to analyze available geochemical and pressure

transient data. A conceptual model of the natural state of the Sumikawa Geothermal Field will be developed based on the complete exploration and production data.

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THE GEYSERS FELSITE STUDY

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KEY WORDS

The Geysers, felsite, pluton, magmatic, vein mineralization, hydrothermal alteration, fracturing, brecciation, porosity, permeability

PROJECT OBJECTIVES

The Geysers vapor-dominated geothermal reservoir has recently been undergoing dramatic pressure declines and local generation of corrosive, acidic steam. In response to these problems, the Department of Energy's Geothermal Division (DOE-GD) has been sponsoring an industry-supported scientific investigation aimed at improving knowledge of the field's reservoir controls and hydrothermal history. One portion of this multidisciplinary investigation centers on The Geysers felsite, a large (at least 100 km³), composite felsic pluton which underlies and partially hosts the steam field (Figure 1), and was instrumental in the field's formation. The new information gained from this work should help Geysers steamfield operators improve forecasts of steam supply and quality for the field's remaining productive life, while furnishing useful new information for extending that life by maximizing deep injection strategies and hopefully targeting deep new felsite-hosted steam reserves.

The Geysers felsite study is focused on characterization of presently unknown steam-reservoir controls in this igneous intrusive body and its contact-metamorphic halo. Key components of the pluton that may influence these controls are being investigated in detail. Deep steam-reservoir controls in the felsite are at present very little understood. Improving knowledge of these controls should help Geysers steam-field operating companies.

Technical Objectives

- Lithology: what intrusive rock types constitute the felsite; what are the compositions and textures of each; in what sequence were they emplaced?
- Determine hydrothermal alteration.
- Determine vein mineralization.
- Determine origins (e.g. tectonic vs hydrothermal), extents, textures, and lithologic influences of fracturing and brecciation.
- Hydrothermal history, as deduced, for example, from vein-mineral paragenesis and geothermometry.

Expected Outcomes

- Exploit existing felsite-hosted steam reserves more efficiently and cost-effectively.
- Devise optimum water-injection programs for this generally deeper portion of the reservoir.
- Target new reserves in the felsite at depth or beyond the field's presently known lateral limits.

PROJECT BACKGROUND AND STATUS

The felsite is a composite felsic pluton which appears to be the intrusive equivalent of the overlying but much more laterally extensive Pliocene to Holocene Clear Lake Volcanics (Hearn et al., 1981; Donnelly-Nolan et al., 1981, 1993; Schriener and Suemnicht, 1982; Hulen and Nielson, 1993; Hulen and Walters, 1993). The felsite was clearly the heat source for a vast, high-temperature (up to at least 400°C; Moore, 1992), liquid-dominated hydrothermal system which immediately preceded the modern steam reservoir, and may continue to supply heat at present. Not only is the felsite a paleo- and probable modern heat source, it is also the host for a significant portion of the deeper Geysers steam reservoir (Thompson, 1992). In spite of this obvious felsite/geothermal connection, prior to this investigation little was known about the nature of reservoir controls in and immediately above the pluton. This lack of information was largely due to the fact that most samples of the felsite are extremely small-diameter (<50 micron) air-drilled cuttings. "Mud logs" of wells penetrating into the felsite-hosted portion of the steam reservoir show very little "character," though we have since demonstrated that the igneous body is locally intensely hydrothermally altered and mineralized in patterns systematically tied to steam-entry distribution and quality.

The Geysers felsite study is approximately 80% complete at this writing. Cuttings from selected felsite-penetrating geothermal wells throughout the field -- more than 1000 samples representing several tens of kilometers of drilled depth -- have been logged in detail and analyzed by various means (see below) to provide a database from which to construct a series of detailed cross-sections and level maps for comparison with field-wide steam production characteristics. Finalization of the maps and cross sections was delayed this year due to scheduling conflicts with The Geysers Coring Project (this report), but these instruments and their interpretation will be published during FY 95.

APPROACH

To accomplish the objectives outlined above, we have applied an array of geological and geochemical techniques of proven value in characterizing plutonic and metamorphic rocks as well as high-temperature hydrothermal systems. In addition to the 1000 representative cuttings samples, we have also acquired short air-drilled cores from four felsite-penetrating geothermal wells from Unocal and Calpine Corporations. These borehole samples have been logged in detail, with emphasis on lithology, nature of fracturing and brecciation, hydrothermal alteration and vein mineralization, with support as appropriate from petrographic, XRD, SEM, geochemical, and electron-microprobe analysis. G.B. Dalrymple (formerly of the U.S. Geological Survey) has age-dated selected felsite samples utilizing high-precision argon-argon methods (Dalrymple, 1992). We are also collaborating with J. Stimac of Los Alamos National Laboratory, an igneous petrologist who has studied extensively the felsite-contemporaneous Clear Lake Volcanics. Stimac has been studying micro-textural relationships in the felsite cores and completing microprobe geochemical analyses of felsite orthopyroxenes for contrast and comparison with immediately

overlying and compositionally similar Clear Lake Volcanic rhyolites and dacites. As mentioned above, we are preparing a series of field-wide felsite maps and cross sections for correlation with reservoir parameters such as steam-entry frequency and quality, injection characteristics, and reservoir-fluid geochemistry.

RESEARCH RESULTS

The felsite is a composite pluton with at least three major intrusive phases -- a relatively shallow rhyolite or microgranite porphyry, a deeper and possibly coeval biotite orthopyroxene granite, and the youngest phase, a biotite-hornblende-orthopyroxene granodiorite (Hulen and Nielson, 1993). The granodiorite is by far the most extensive of the three main felsite phases, and appears to have been responsible, through generation of an associated high-temperature hydrothermal system, for the wholesale oxygen-18 depletion noted in overlying hornfelsic steam-reservoir rocks by Gunderson and Moore (1993). The granite and microgranite porphyry apparently occur principally as "scabs" at the top of the intrusive body, and as probable large xenoliths or roof pendants deeper in the pluton (Figure 1). In addition, there are extensive volumes of the felsite which appear to hybrid intrusive rock types intermediate in composition and texture between the granites and granodiorites (Figure 1). One of the cores available for this study, from well GDC-21 (Figure 1), was retrieved from such a composite intrusive. We believe these hybrid igneous rocks arose from mixing of fresh granodioritic magma with still partially molten granitic intrusives.

The entire felsite pluton is more or less hydrothermally altered and mineralized, with much of the alteration and mineralization apparently genetically and spatially related to emplacement of the granodiorite (Hulen and Nielson, 1993). In many geothermal wells, productive steam entries are closely associated with zones of intense borosilicate mineralization and alteration. NCPA well Q-9, in the southern portion of The Geysers, provides a good example of this phenomenon (Figures 1 and 2). Note that the upper portion of the felsite as penetrated by this well is relatively barren of such mineralization and alteration as well as productive steam entries. By contrast, the deeper portion of the well intersects numerous steam entries, and two-thirds of these are directly associated with dramatic enrichments in ferroaxinite, a calcium borosilicate, with or without associated epidote. The cuttings are too small in general to establish with certainty whether or not these secondary minerals are derived from veins or are replacements of the original rock feldspar, but whatever their origin, they serve as excellent indicators of steam-entry proximity. Several of these steam entries are also located around the contacts of granodiorite with older, probably xenolithic granites (Figure 2), suggesting that these interfaces throughout the pluton might serve to localize productive fluid channels.

FUTURE PLANS

Completion of The Geysers felsite study was delayed this year due to scheduling conflicts with The Geysers Coring Project (GCP; see summary elsewhere in this report). The drilling phase of the GCP has now been accomplished, and the full set of felsite maps, cross sections, and corresponding interpretive text will be made available in 1995. At least two papers on the intrusive body and its key role in formation of The Geysers steam field will be submitted to scholarly journal such as, but not limited to Geothermics, the Journal of Geophysical Research, and Economic Geology.

INDUSTRY RESEARCH AND TECHNOLOGY TRANSFER

This project could not have been undertaken without the support and encouragement of Geysers steamfield operating companies, including Unocal Corporation, Calpine Corporation, NCPA, CCPA, and Santa Fe Geothermal. Results of the felsite study should be useful not only for more effective geothermal exploitation and exploration at The Geysers but in the search for and development of high-temperature geothermal systems worldwide.

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Figure 1. (Top) - Map of the central and the southern Geysers steam field, showing locations* of wells penetrating The Geysers felsite and utilized for this study.

(Bottom) - Simplified geologic section of A-A' through the southern portion of the felsite.

* (at top of pluton)

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Figure 2. Simplified downhole lithology and selected mineralogy distributions for the portion of NCPA Well Q-9 penetrating The Geysers felsite. Note concentrations of steam entries at zones of intense borosilicate mineralization.

THE GEYSERS CORING PROJECT

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KEY WORDS

The Geysers, core drilling, porosity, permeability, fluid saturation, fractures, hydrothermal alteration, vein mineralization, caprock formation

PROJECT OBJECTIVES

This project is a cost-shared undertaking involving the Department of Energy's Geothermal Division (DOE-GD), Unocal Corporation and other Geysers steamfield operating companies, and a team of collaborating scientists from universities, national laboratories, and various governmental agencies such as the U.S. Geological Survey. The governing goal of the project is provision, through continuous coring, of critical and otherwise unobtainable new information for near- and long-term prediction of steam availability and quality at The Geysers vapor-dominated geothermal system, California (Figure 1).

Technical Objectives

The Geysers Coring Project (GCP) seeks to improve understanding of the following crucial steam-reservoir parameters:

- Porosity and permeability controls;
- Nature, amount, and availability of remaining, indigenous, liquid water reserves; and
- Potential sources of chloride and non-condensable gases in produced steam.

Expected Outcomes

- Characterize and quantify the porosity and permeability in a significant length of continuous core retrieved from the Franciscan graywacke- and argillite-hosted portion of the main Geysers steam reservoir.
- Determine the amount and configuration of the reservoir's remaining indigenous liquid water reserves.
- Improve insight into sources of non-condensable gases and corrosive acids in produced steam.

Expected Outcomes (continued)

- Obtain a clearer understanding of the evolution of The Geysers hydrothermal system, particularly:
 - The mechanisms by which the modern vapor-dominated geothermal system evolved from its high-temperature, liquid-dominated precursor;
 - Physical and chemical controls on the development of reservoir porosity; and
 - Formation of the reservoir's relatively impermeable caprock.

PROJECT BACKGROUND AND STATUS

Effective near- and long-term prediction of reservoir performance and longevity as well as steam quality at The Geysers steam field require detailed information on a wide range of specific reservoir parameters. Existing reservoir models (e.g. Williamson, 1992) incorporating current field information simulate closely The Geysers' production history for the past several decades, but optimum accuracy in forecasting the field's future behavior requires certain data still not available. These data can only be measured in cores, which prior the GCP were extremely rare from The Geysers; most borehole samples from the field are small-diameter (< 50 micron), air-drilled cuttings. Although The Geysers occupies a volume of at least 600 km³ (Williamson, 1992), only about 100 m of core had been collected from the resource before this project was undertaken. Moreover, this early core consists of broken, milled, and highly fragmented pieces from 24 separate geothermal wells. Continuous core was completely lacking. Small-scale porosities and permeabilities have been obtained for 1" and 4" plugs taken from these cores (Gunderson, 1992), but broad-scale porosity and permeability characteristics were unknown. The composition, abundance, and availability of liquid-in-place in the reservoir rock are even more poorly constrained, but especially important for longer-term predictions of reservoir performance (Williamson, 1992). Another unknown has been the combination of factors favoring evolution of the corrosive, acidic, non-condensable gas-rich steam commonly produced by wells in the field's northwestern sector (Walters et al., 1992).

The GCP was designed to address the lack of information outlined above by providing a long, continuous reservoir core from a representative section of the field hosted by the dominant reservoir rock -- hydrothermally altered and mineralized Franciscan (Late Mesozoic) metagraywacke and argillite. The retrieved core would be carefully documented on site, subjected to a broad range of baseline geologic studies to ensure uniform characterization, then made available for a variety of detailed, multidisciplinary studies proposed to address project objectives by the project's collaborating investigators.

The coring phase of the GCP was completed from late August to early September 1994. Baseline geologic studies as well as a number of the more focused complementary investigations are in progress. Initial results were reported at the 1994 Geothermal Resources Council Annual Meeting in Salt Lake City. More detailed accounts of the GCP to date will be provided at the January 1995 Stanford University Reservoir Engineering Conference and the April 1995 World Geothermal Congress in Florence, Italy. The core is being archived at University of Utah Research Institute's Geothermal Sample Library, where a longitudinal half-split will remain available for judicious sampling in support of legitimate research projects.

APPROACH

As initially designed, the GCP called for retrieval of 300-500 m of continuous core from the so-called "normal" Geysers steam reservoir hosted by Franciscan (late Mesozoic) metagraywacke, beginning at a depth of 1260 m at the bottom of an existing Unocal Corporation steam well, SB-15, in the northwest-central portion of the field (Figures 1 and 2; Hulen et al., 1994). Extensive caving and bridging of the penetrated graywackes and argillites prevented implementation of this plan. The desired core was therefore obtained from a newly created sidetrack to the original steam well, beginning at a depth of 251 m and ending at a total corehole depth of 488 m. This sidetrack (SB-15-D) penetrated the never-before-cored transition between The Geysers' steam reservoir and its caprock, furnishing material which will permit a much better understanding of just how this critical reservoir top-seal was formed. SB-15-D also penetrated the slightly deeper transition between that portion of the reservoir devoid of hydrothermal epidote (a key indicator of reservoir rock throughout the field) and the underlying portion of the reservoir in which this calc-silicate was extensively deposited.

Coring operations for the GCP were accomplished by Tonto Drilling Services utilizing a Universal 5000 coring rig utilizing a triple-tube wireline coring and core retrieval system. This system permits recovery of delicate features like fault gouges, slickensides, and fracture stockworks in a condition approximating *in situ* — features which would otherwise be obscured or obliterated by the drilling process. The triple-tube system also allows sealing of selected cores in thin-walled aluminum liners immediately upon retrieval to the surface, thereby minimizing the escape of any indigenous reservoir fluids initially present, and preserving such fluid-bearing cores for later short-range remote-sensing analysis for investigation of fluid quantities and distribution. This coring system also permitted recovery, by Unocal Corporation, of selected cores which were retrieved and frozen under simulated reservoir pressures, thereby potentially ensuring not only optimum preservation of the contained fluids but also immobilization of these fluids in their presumably original configurations in the reservoir rocks.

Following careful on-site documentation and description of the retrieved cores, a broad range of detailed investigations addressing project objectives will be carried out the GCP's collaborating investigators. These studies, with a combined, projected budget of about 1.6 million dollars, include the short-range remote-sensing investigations (X-ray CT scanning, MRI scanning) mentioned above as well as others aimed at deciphering The Geysers' hydrothermal history and quantifying porosities and permeabilities of the penetrated Franciscan rocks. These focused investigations are projected to span one to three years.

RESEARCH RESULTS

Once the initial drilling problems were overcome, coring in the new GCP sidetrack, SB-15-D, proceeded without significant difficulty. 251 meters in length of continuous core were obtained, nearly quadrupling the amount of core now available for the entire Geysers reservoir. The corehole penetrated a fractured and veined, Franciscan (late Mesozoic) graywacke-argillite sequence clearly of turbiditic origin. Older veins in the core consist of milky quartz and calcite. These older veins are locally leached of calcite to form large, irregular vugs, which enhance the field's overall reservoir porosity; some of these vuggy Franciscan veins appear to be major steam conduits. Younger veins in the cores, some with sericite or K-feldspar selvages, are dominantly high-angle (60-90° relative to a plane normal to the core axis) and consist of quartz, bladed calcite, sericite, pyrite, K-feldspar (adularia) and wairakite in various combinations for the most part, with epidote below a depth of 436 m. This assemblage and its texture indicate that the veins were formed from at least intermittently boiling hot water at a minimum temperature of about 220°C. The sericite consists of mixed-layer illite/smectite with minor mixed-layer

chlorite/smectite in the upper 100 m of the corehole, with illite and subordinate chlorite in the lower 150 m. There is strong evidence that the mixed-layer clays in the higher-level veins are a major factor in the formation of The Geysers caprock. Fractures in the core are also high-angle, and where slickensided typically record strike-slip displacement. The GCP has convincingly demonstrated the viability and value of continuous wireline coring in high-temperature, vapor-dominated geothermal systems.

FUTURE PLANS

The SB-15-D core has been shipped to the UURI Geothermal Sample Library in Salt Lake City, Utah, where its baseline geologic characterization is currently being refined. This baseline characterization consists of detailed geologic logging with emphasis on fractures, breccias, veins, dissolution voids, and other potential porosity elements. The work is being supplemented with petrographic study, X-ray diffraction, whole-rock geochemical analysis, and limited-scale organic-geochemical study of representative carbonaceous argillites. This work should be complete by the end of FY 95. Complementary detailed core studies underway by the GCP science team are anticipated to span one to three years.

INDUSTRY RESEARCH AND TECHNOLOGY TRANSFER

The GCP corehole was completed from an existing steam-production well made available for the project by Unocal Corporation, which since completion of the corehole has completed it for large-scale water injection to replenish partially this sector of the reservoir's depleted reserves.

New information on porosity and permeability controls, fluid saturation, and hydrothermal history already available and being uncovered by more detailed investigations of the SB-15-D core will benefit not only Unocal but also the following Geysers steamfield operating companies: Northern California Power Agency, Calpine Corporation, Santa Fe Geothermal, and Central California Power Agency.

In addition, the information from SB-15-D should be of general use to companies working not only with vapor-dominated geothermal systems but also their liquid-dominated counterparts anywhere in the world.

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*Hulen and Nielson**The Geysers Coring Project*

Figure 1. Location of Unocal well SB-15 for The Geysers Coring Project relative to the steam field and coaxial, underlying felsite pluton.

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The Geysers Coring Project

Figure 2A. SB-15-D: Original design

Figure 2B. SB-15-D: Modified configuration and completion.

Figure 3. Summary field geologic log for Corehole SB-15-D.

GEYSERS GEOCHEMISTRY

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KEY WORDS

The Geysers, fluid inclusions, isotopes, gas analyses

PROJECT OBJECTIVES

Despite recent declines in the pressures and productivities of The Geysers wells, the field remains a significant geothermal resource. According to the field developers, continued high levels of production can be expected from a combination of increased injection of water into the reservoir and the development of previously untapped portions of the field.

Technical Objectives

- Develop a model of the system that describes the chemical, thermal, and permeability changes that have occurred over time.
- Develop geochemical methods that can be used to help target regions for future production or injection.

Expected Outcomes

- Allow prediction of permeability variations within different parts of the field and thus, improve the future siting of production and injection wells.
- Allow the operators to predict the occurrence of the high-temperature reservoir and the presence of corrosive steam.
- Provide constraints on numerical simulations and laboratory experiments being conducted at national laboratories and universities.

PROJECT BACKGROUND AND STATUS

The Geysers is the largest geothermal system in the world and one of the few that produce only dry steam. Recent drilling has demonstrated that The Geysers consists of two distinct reservoirs: an upper reservoir where temperatures are nearly constant at 240°C; and a lower, higher-temperature reservoir where temperatures range from 240° to 345°C. This deeper reservoir produces corrosive, HCl-bearing steam.

Electrical production at The Geysers first began in 1960 but did not peak until the late 1980's when fieldwide declines in the reservoir pressure occurred. In 1990, a committee composed of representatives

from the four major companies operating the field recommended that the Department of Energy (DOE) sponsor fundamental geochemical research to designed to characterize the reservoir rocks and their evolution. Among the research topics included by the operators were, among others, the origin of the corrosive HCl-bearing steam, the characteristics of the high-temperature reservoir which produced this steam, and the permeability distributions within the reservoir. The geothermal companies provided samples of cuttings and cores, surface and downhole locations, supporting production and chemical data, and oxygen isotope analyses for study. As described in detail below, these companies have expressed continued interest and support of the work through cost-shared research.

Geochemical investigations of these samples provided significant new insight into the questions raised by the operators and into the evolution of the thermal system. A preliminary report on the fluid inclusion systematics was published by Moore (1992) and in 1992, Moore and Hulen developed an initial evolutionary model of the system based on fluid inclusion and mineralogic data. In FY 93, Unocal provided more than 550 whole-rock oxygen isotope analyses to UURI for study. A more detailed conceptual model of The Geysers, which combined fluid inclusion and isotopic data was developed in FY 94 (Moore and Gunderson, 1994a, b). The key points of this model are discussed below.

The wide range of salinities recorded by the inclusion fluids (0-43 weight percent NaCl equivalent) demonstrated that multiple fluids were involved in the formation of this steam resource. In order to characterize these fluid sources, investigations into the gas compositions of the inclusions by quadrupole mass spectrometry were initiated. Some of the data is being obtained on samples from SB-15, a recently drilled core hole jointly funded by Unocal and DOE. This drill hole, which penetrated the steam reservoir, will provide important new information on the transition between the cap rock and underlying steam zone. We are collaborating with several investigators from UURI and elsewhere on the characterization of this important drill hole.

In addition, our studies have shown that there are no obvious mineralogic differences between the rocks that host the normal and high-temperature reservoirs. Other, more subtle differences may, however, exist. During FY 94 discussions were initiated with Central California Power Agency (CCPA) to obtain isotopic and geologic data from the high-temperature reservoir in the northwestern part of the field. Additional isotopic data was obtained on samples from two hot wells drilled on the margins of the geothermal system. The results of these wells will be compared to those from the productive portions of the field to establish the characteristics of productive and non-productive rocks.

Investigations initiated in FY 94 are approximately 25% completed. It is anticipated that two years will be required to complete these studies.

APPROACH

Our approach to obtaining chemical and thermal data on The Geysers has been to combine geologic data from carefully described and documented samples with the results of geochemical and petrologic analyses. The application of quadrupole mass spectrometry for the characterization of fluid inclusion gases is in its infancy. Thus, part of our approach involves the testing of this technique to insure its future applicability to other hydrothermal systems. The following steps are being taken to achieve the goals of our project.

1. Collect and describe samples of existing core and cuttings from different environments within the thermal system at The Geysers. Core samples are preferable for this work because paragenetic relationships among the vein minerals and the depth of the samples can be documented.

2. Establish the paragenetic relationships among the minerals being studied. We are collaborating with J. Hulen and D. Nielson (UURI) on the petrographic relationships and geologic characteristics of core hole SB-15.
3. Conduct fluid inclusion analyses on the samples to determine homogenization temperatures, apparent salinities, and gas contents.
4. Determine the gas contents by mass spectrometry of well characterized samples utilizing both crushing and thermal decrepitation. This work is being done in collaboration with Dr. D. Norman at New Mexico Tech, Socorro, New Mexico.
5. Determine the isotopic compositions of the secondary minerals and whole rock samples in order to calculate the composition of the thermal fluids that were responsible for their deposition and the extent of water rock interaction. If possible, the oxygen isotope data from the high-temperature and normal reservoir in the northwestern part of The Geysers will be investigated.
6. Compare the gas compositions of the fluid inclusions with that of the reservoir steam. Data on the reservoir compositions has been provided by Calpine.
7. Integrate the results geochemical data to determine the origins, compositions, and timing of the fluids that have circulated through the thermal system, and possible areas and sources of natural recharge, and the extent of water-rock interactions in various parts of the field. The latter provides a measure of permeability.

RESEARCH RESULTS

Petrographic, fluid inclusion, and isotope data have been used to develop an evolutionary model of the system (Moore and Gunderson, 1994a,b). The data show that The Geysers is host to a long lived hydrothermal system that initially developed in response to shallow plutonic intrusions 1.5 to 2 Ma. Although wells drilled into The Geysers produce only dry steam, fluid inclusion, isotopic, and mineralogic data demonstrate that the present vapor-dominated conditions evolved from an earlier and more extensive, liquid-dominated regime.

Fluid inclusion data record steep gradients in the temperatures and salinities of the early hydrothermal system. Pressure corrected homogenization temperatures ranged from 441°C at a distance of 282 m from the intrusion to 324°C at a distance of approximately 1500 m. The initial pore fluids had salinities that ranged from near 7 weight percent NaCl equivalent at distances of more than 600 m from the pluton to 43 weight percent NaCl equivalent in the pluton and the biotite hornfels that formed adjacent to the intrusive contact. Nitrogen, argon, helium, and methane analyses of fluid inclusions and the salinity data indicate that fluids within the present reservoir were connate in origin but that the gases were derived from magmatic and crustal sources (Norman and Moore, 1994). Both the liquid and gas components of the fluid in the hornfels and pluton were dominantly magmatic in origin. In contrast, gases in inclusions from the cap rock are enriched in argon, helium and methane relative to other samples. These enrichments suggest the inclusions contain a large component of crustal and/or meteoric gases. As the temperatures around the pluton declined, the hydrothermal system collapsed upon itself, allowing the downward migration of waters from the marginal parts of the system and a reduction in rock permeabilities due to the deposition of calcite.

Whole-rock $\delta^{18}\text{O}$ values of metagraywackes related to The Geysers hydrothermal system display systematic variations with respect to depth, location within the field, and grade of alteration (Gunderson and Moore, 1994). At depths below +610 m relative to mean sea level, the $\delta^{18}\text{O}$ values of the metagraywacke are strongly zoned around a northwest-southeast trending low located near the center of the steam reservoir. As the pluton beneath The Geysers is approached, the $\delta^{18}\text{O}$ values of the metagraywacke decrease from approximately 15 per mil near the surface to 4 to 7 per mil within the biotite hornfels. The $\delta^{18}\text{O}$ values then increase to 8 to 10 per mil at the intrusive contact, and thereafter, remain nearly constant with depth. Calculated rock-water fractionation factors suggest that temperature was the dominant control on the vertical decrease in the isotopic values of the reservoir rocks. In contrast, the increase in the $\delta^{18}\text{O}$ values within the hornfels suggest equilibration with an isotopically heavy fluid and/or decreasing water:rock ratios.

The present vapor-dominated regime is a recent feature of the geothermal system that resulted from the boiling off of the waters that circulated through the reservoir. Within the main, vapor-dominated reservoir widespread boiling, perhaps initiated by tectonic activity, is documented by the presence of low salinity inclusion fluids that record temperatures between about 240° and 265°C. We have tested the possibility that downward percolating acidic steam condensate may be actively leaching and transporting gold and other metals by measuring their concentrations in rocks near the transition from the normal to high-temperature steam reservoirs (Fournier and Moore, 1994a, 1994b). No anomalous concentrations of gold were observed.

FUTURE PLANS

Our initial studies of the gas compositions of the fluid inclusions have indicated that this technique holds significant potential as a means of determining the origins of the gases trapped within secondary minerals. Samples from different environments within the thermal system (cap rock, normal and high-temperature reservoirs, non-reservoir rocks) will be analyzed. We plan to obtain isotopic data from the northwestern part of the field, and interpret existing data from wells on the periphery of the system. Petrographic analyses of these wells will be conducted. Fluid inclusion and isotope analyses of core samples from SB-15 will also be conducted.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal Calpine CCPA	Application of results to field development Cost-shared studies
NEDO (National Energy Development Organization of Japan)	Application of models to the Kakonda geothermal system in Japan
Japanese Geological Survey	Application to Japanese systems
ENEL (Italian National Electrical Utility)	Application of models to Larderello

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STUDY OF NONCONDENSABLE GASES AT THE GEYSERS FOR THE GEOTHERMAL TECHNOLOGY ORGANIZATION

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KEY WORDS

The Geysers, vapor-dominated, gases, HCl, magmatic, high-temperature reservoir, modeling

PROJECT OBJECTIVES

The concentration of non-condensable gases in Geysers steam is one of the most important factors in power plant design and one of the least predictable. Through better understanding of the origin of these gases it may be possible to improve predictions of their changes in concentration with time and well location. Recent changes in the flow and pressure of Geysers steam have been accompanied by large increases in gas concentrations in several areas of the field. This increase in gas may result from movement of high-gas steam from reservoir margins into lower-pressure central areas or from decrease in liquid vaporization, lowering the supply of low-gas steam to dilute gas in existing steam. Other possibilities include entry of higher-gas steam from deep high-temperature zones or production of gas from mineral reactions (buffers).

Technical Objectives

- Understand better the origin of The Geysers reservoir and the pre-exploitation chemical and isotopic characteristics through geochemical studies.
- Document the changes in distribution of isotopes and gases in The Geysers reservoir resulting from exploitation.
- Apply the methods of phase and reaction equilibrium to explain (and predict) changes in chemical and physical character of Geysers steam resulting from exploitation.
- Identify sources of steam that may extend the life of the field and predict the appearance of high gas, high HCl steam that could increase production costs.

Expected Outcomes

- Steam producers may be able to more confidently predict the rate of decline in steam flow, the future concentrations of non-condensable gases, and the possible appearance of corrosive HCl.

PROJECT BACKGROUND AND STATUS

A nearly field-wide accelerated decline in pressure and steam production occurred at The Geysers in the late 1980s. As a result of this crisis, the Department of Energy (DOE) has begun a program to examine

the reservoir processes at The Geysers in order to better understand the sources of steam and noncondensable gas, and predict changes in pressure, steam flow and gas content. As part of that program the Lawrence Berkeley Laboratory started a study of the chemical compositions of steam at The Geysers, conceptual modeling, and mathematical modeling of the evolution of the thermodynamic structure, temperature, pressure, and steam compositions of The Geysers reservoir. This program has been continued, in part, through funding by the Geothermal Technology Organization.

In this study, the aspect of greatest near-term importance is the prediction of changes in noncondensable gas concentrations in steam. Removal of gas is necessary to achieve low pressures at the turbine exhaust and higher conversion efficiency. It is of great concern to the producers whether existing gas-handling equipment will be adequate for future gas concentrations. Inadequate capacity may cause plant shutdown. For a 100 MW geothermal power plant, each percent of gas increase costs about a million dollars in gas-handling equipment. The appearance of HCl gas in future steam is also of concern. Prevention of corrosion from this gas requires wellhead or downhole injection of caustic solution and adds to production costs. Both high gas and high HCl characterize steam from most of the high-temperature reservoir (HTR) of the NW Geysers. The possible existence of this reservoir under areas of the central and southern Geysers is of great concern.

APPROACH

The approach to the problem has involved: 1) compilation and interpretation of chemical and isotopic analyses of steam provided by field operators including NCPA, CCPA and Calpine (see complete names below); 2) construction of a conceptual model for the origin and present state of The Geysers reservoir; 3) Numerical modeling of critical parts of the conceptual model; and 4) The analysis of steam from typical wells throughout The Geysers for isotopes of noble gases and other elements that can trace steam origins and indicate the presence of a deep HTR (this part of the project is collaborative with Mack Kennedy of Lawrence Berkeley Laboratory (LBL) and is described elsewhere in this volume).

RESEARCH RESULTS

Extensive study was made of steam compositions from the Northern California Power Agency (NCPA) field of the SE Geysers. In this field, near the southern margin of The Geysers reservoir, a relatively rapid decrease of reservoir pressure occurred in the period between 1985 and 1990. Initial gas concentrations were low in the middle of the field but increased sharply to the east and south. Gas concentrations in steam not affected by condensate injection had generally decreased from the start of production to 1987, but increased sharply in 1988 and have continued to increase. Gas remained low only in areas of strong injection. Initially ^{18}O and D in steam were fairly uniform across the field except for a decrease of ^{18}O in the east toward a condensation boundary. After 1987 both isotopes increased sharply in the center of the field in response to increased total injection of evaporated condensate. These observations are interpreted to indicate that most liquid water (except that adsorbed or held in small pores far from fractures) was depleted by 1987. The loss of liquid caused the rapid decline in pressure in the central part of the reservoir. The increase in gas also resulted from loss of liquid because dilution of existing steam with low-gas steam from vaporized liquid ceased and, possibly more important, high gas steam from undrilled reservoir margins was drawn into the wells. The changes in gas and isotopes after 1987 indicate that an increasing fraction of steam production is from vaporized injectate and margin steam.

The Geysers conceptual model (abbreviated in Truesdell et al., 1993) lead to an examination of the conditions under which a two-phase vapor-dominated reservoir can lie above and be in pressure continuity with a high-temperature steam-only reservoir. The model (Figure 1) and earlier studies (Truesdell, 1991) indicate that all parts of The Geysers reservoir were formed by downward penetration of the vapor-dominated reservoir into hot, fractured, vapor-saturated rock formed by igneous intrusion ("heat mining"). In the NW Geysers the interface between normal and high-temperature reservoirs occurs at relatively shallow, drillable depths because of limited recharge of liquid. Numerical modeling (Lai et al., 1994) showed that the balance of heat input and overall liquid saturation was critical to the reservoir structure and that with 75% or greater steam saturation, two-phase conditions overlie high-temperature superheated vapor. These conditions would be expected if limited amounts of liquid water were introduced into a high-temperature, dry reservoir. Although this cooling process is probably common adjacent to igneous intrusions, the unusually low intrinsic permeability of the Franciscan greywacke and the presence of open fractures from earlier intrusions created the extraordinary Geysers reservoir.

Ongoing studies collaborative with Mack Kennedy of LBL (Kennedy and Truesdell, 1994 and this volume) have confirmed several other parts of the conceptual model. The high total gas and the nearly pure magmatic noble gases in the HTR of the NW Geysers indicate that the heat mining process hypothesized in the model is more probable than the boildown of a liquid-dominated reservoir. A boildown process would necessarily produce low-gas steam with an atmospheric noble gas signature related to the source of recharge. In addition the observed sharp gradients in gas compositions within the HTR suggest that large scale convection does not occur. This results from the lack of an underlying liquid zone. The patterns of gases and isotopes found in the central and southern Geysers (but not in the NW) indicated that partial condensation of laterally flowing steam must have occurred with condensate returning to central boiling zones in a liquid saturated layer (Figure 1).

FUTURE PLANS

The joint project with LBL involving collection and analysis of steam samples for isotopes of noble gases will be extended throughout The Geysers. This study is contingent on enough funding to keep the isotope laboratory operating. The next phase of this study will be crucial to discovering if high-temperature reservoirs similar to that of the NW Geysers extend under central and southern areas. This study will also be extended to include analyses of carbon isotopes in CO_2 and CH_4 which provide durable indications of gas formation temperatures. The methods applied to the NCPA reservoir are now being applied to the larger and more central Calpine area (Figure 2). Collaboration with Franco D'Amore (IIRG, Pisa) will involve applying new gas reaction models to Geysers Gases. Work with Jill Haizlip to interpret gas compositions at inlets to PG&E power plants will continue. As the present GTO grant is nearly finished, an extension or other funding will be sought. Extension of this project would complement ongoing noble gas isotope studies (Kennedy and Truesdell, this volume).

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Northern California Power Agency	Interpretation of gas analyses; location of HTR
Central California Power Agency	Prediction of gas changes in NW Geysers
Calpine Corp	Detection of HTR gases; prediction of gas changes
Pacific Gas and Electric Co.	Interpretation of gas at plant inlets

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Figure 1. Conceptual model of The Geysers reservoir showing the relation of the central and SE, where the vapor-dominated reservoir was developed earlier by heat mining from high-temperature fractured rock and supports large-scale convection, and the NW, where the more recently developed reservoir is thinner, major convection is absent, and wells penetrate the underlying hot, vapor-saturated rock.

Figure 2. Changes in well flow and reservoir gas/steam, y values and liquid saturation for Calpine well DV-3 from start of production to 1993. This well produced initially from the central two-phase reservoir then increasingly from high-gas margins of the field. Note accelerated changes in 1987.

MAGMATIC ORIGIN OF SOME RESERVOIR GASES AT THE GEYSERS

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KEY WORDS

The Geysers, high-temperature reservoir, magmatic gas, isotopes

PROJECT OBJECTIVES

Many wells in the Northwest Geysers produce corrosive gas-rich steam from a high-temperature reservoir (HTR) inhibiting future development. The objectives of this study are to use the elemental and isotopic compositions of noble gases to identify the origin of gases in the HTR, to examine the influence these gases may have on the overlying normal-temperature reservoir (NTR), and determine if the HTR extends under the normal Geysers reservoir further south.

Technical Objectives

- Identify the origin of the HTR gases associated with corrosive steam produced in the NW Geysers.
- Identify a characteristic or unique chemical-isotopic signature of the HTR gas to evaluate the occurrence and distribution of the HTR throughout The Geysers geothermal field.
- Evaluate the implications of the origin, distribution, and influence to genetic models of The Geysers.

Expected Outcomes

- Minimize or alleviate the uncertainty as to the origin, persistence, and influence of the high gas component in the HTR which has made exploitation difficult.
- Identify areas where the HTR may contribute gas-rich corrosive steam to production as pressures are depleted.
- Provide a new natural and conservative tracer for early detection of HTR steam intrusion.

PROJECT BACKGROUND AND STATUS

The Geysers vapor-dominated geothermal reservoir is known to have a wide range of gas concentrations in steam (< 100 to > 75,000 ppmw), but the variations in gas compositions and the origin of the gases

have been little studied. Low gas concentrations and steam isotopes similar to meteoric waters are found in the SE Geysers, but a corrosive steam high in gas and HCl from a high temperature reservoir ($T > 350\text{ }^{\circ}\text{C}$) in the NW Geysers has been thought to be related to metamorphic or magmatic brine. The high gas and HCl, and the uncertainties as to origin, persistence, and influence of the high gas component in the HTR have made exploitation difficult because the high gas (and HCl) cannot be used in some power plants without expensive modifications.

APPROACH

In vapor-dominated systems such as The Geysers, wells produce only steam without liquid so the isotopes of water and the chemical and isotopic composition of the accompanying gases provide the only geochemical indications of reservoir processes and fluid origins. The stable noble gases (He, Ne, Ar, Kr, and Xe) and their isotopes are excellent natural tracers for fluid source and migration in the Earth's crust. Due to their inert chemical character, they retain information and provide long lasting tracers. Therefore, fluids originating in the mantle (characterized by large ^3He enrichments) as well as shallower fluids of crustal (enriched in radiogenic ^4He , ^{40}Ar , and nucleogenic components) and atmospheric origin can be readily identified (eg. Lupton, 1983, Kennedy et al., 1985, Hiyagon and Kennedy, 1992).

Volatiles degassed from the upper mantle through magmatic processes are enriched in total helium ($^4\text{He}/^{36}\text{Ar} \sim 7400$, Javoy and Pinneau, 1991) and ^3He ($^3\text{He}/^4\text{He} = 1.12\text{--}1.26 \times 10^{-5}$) and have coherent $^3\text{He}/\text{CO}_2$ ($\sim 5 \times 10^{-10}$, Marty and Jambon, 1987) and radiogenic $^{40}\text{Ar}/^4\text{He}$ (~ 0.27), the latter reflecting in growth of radiogenic gases in accordance with the average mantle K/(U+Th) ratio (Jochum et al., 1983). Geothermal fluids hosted in continental crust but in regions influenced either by recent or active magmatic processes will be enriched in magmatic volatiles. The degree of enrichment, as measured by the above parameters, will depend strongly on the intensity and/or time since magma intrusion or eruption and the present rate of magma chamber recharge by fresh mantle material (cf DePaolo et al., 1992). For example, recent anomalous seismic events attributed to dike intrusion beneath Mammoth Mountain, Long Valley Caldera, California were accompanied by a factor of two increase in the $^3\text{He}/^4\text{He}$ ratio (3.8 to 6.7 Ra, Ra is the ratio in air, 1.4×10^{-6}) and a seven fold increase in total helium (relative to air gases) in surface fumarolic vapors (Sorey et al., 1993). Similar changes in the mantle enrichment of geothermal volatiles due to increased magmatic activity have been observed in hydrothermal plumes over the Juan de Fuca Ridge (Lupton et al., 1989) and in produced steam from the Icelandic Geothermal system (Poreda and Arnorsson, 1992).

Fluids circulating through continental crust, far removed from magmatic influence, will be enriched in crustal volatiles acquired from rock/water interaction, diffusive loss enhanced by the natural geothermal gradient, and/or tectonic processes. Such fluids may also be enriched in total helium relative to air gases, but the helium will have a radiogenic origin and therefore depleted in ^3He ($^3\text{He}/^4\text{He} < 10^{-7}$) while enriched in other radiogenic and nucleogenic noble gases (eg. radiogenic ^{40}Ar).

Crustal fluids influenced by meteoric water will also contain noble gases with an atmospheric isotopic composition and elemental abundances determined by their respective solubilities in water. Solubilities are known as a function of temperature (up to the critical point) and salt (NaCl) concentration.

RESEARCH RESULTS

Eleven non-condensable gas samples for noble gas studies were collected and analyzed from selected production wells and one total fluid sample from an injection well of the Coldwater Creek Steam field

owned and operated by the Central California Power Agency No. 1 (CCPA). The sampled production wells were selected to insure representation from a wide range in total gas and HCl content so as to characterize the NW Geysers HTR and the transition between the HTR and the overlying NTR. Five of the sampled wells are believed to produce steam entirely or in large part from the HTR and the remainder are thought not to contain a significant HTR component (personal communication, M.A. Walters, 1994). The samples were analyzed in the noble gas laboratory, Center for Isotope Geochemistry, Lawrence Berkeley Laboratory.

Elevated helium isotopic compositions providing evidence for a magmatic component in The Geysers steam were first reported by Torgersen and Jenkins (1982). Confirming this earlier report, all production wells sampled in this study are enriched in ^3He with helium isotopic compositions ranging from 6.6 to 8.3 Ra. We have also found that in the NW Geysers Field (1) the highest $^3\text{He}/^4\text{He}$ ratios occur in fluids produced from the HTR, (2) the helium isotopic compositions are correlated with the radiogenic $^{40}\text{Ar}/^4\text{He}$ ratio, total helium to non-condensable gas ratios, ^{36}Ar concentrations, and the ratio of total helium to the atmospheric noble gas inventory, and (3) the correlations require three distinct fluid components influencing the gas composition of produced steam in the NW Geysers.

The data are summarized in Figure 1 showing the helium isotopic composition (R/Ra) plotted against the radiogenic $^{40}\text{Ar}/^4\text{He}$ ratio and Figure 2 showing the $^4\text{He}/^{36}\text{Ar}$ ratio normalized to the ratio in air [$F(^4\text{He})$] verses the non-condensable gas to ^{36}Ar ratio (NCG/ ^{36}Ar). In these plots the linear relationships imply two component mixing. In Figure 1, the end members are a ^3He -enriched magmatic fluid characterized by $R/Ra > 8.3$ and $^{40}\text{Ar}/^4\text{He} < 0.05$, similar to mid-ocean ridge basalts, and a second fluid enriched in radiogenic ^4He and ^{40}Ar ($R/Ra < 6.5$ and $^{40}\text{Ar}/^4\text{He} > 0.25$) consistent with dilution of the magmatic component by a crustal source. The highest $^3\text{He}/^4\text{He}$ ratio is for steam from well Pratti 37 (P37). This steam also has the lowest value of ^{36}Ar (Figure 2) showing that there is almost no atmospheric influence. Steam samples from Pratti 37 have also had the highest total non-condensable gas and highest HCl of the production field (data from CCPA). On the basis of these analyses, steam from this well has almost exclusively magmatic noble gases and possibly other magmatic gases as well, although these probably have been modified by reaction with rock minerals. None-the-less, the Pratti 37 steam has a $^3\text{He}/\text{CO}_2$ ratio of $\sim 4 \times 10^{-10}$, slightly less but comparable to the best estimate for the source of mid-ocean ridge basalts (Marty and Jambon, 1987). Nearby Pratti 38 (P38) has lower R/Ra, much higher $^{40}\text{Ar}/^4\text{He}$, and higher ^{36}Ar . This well has had maximum NCG about one fifth and HCl about one tenth of Pratti 37, suggesting that the lateral gradient of the magmatic gas is very sharp. It is also evident from Figure 2 that the dilution of the HTR magmatic component with the second fluid enriched in crustal gas cannot be accomplished simply by mixing HTR and NTR fluids as implied by Figure 1.

The sharp boundary between strongly magmatic steam from Pratti 37 and more ordinary steam and the lack of direct mixing of HTR with NTR fluids is a consequence of the lack of large scale convection in the high-temperature reservoir and between the HTR and overlying NTR reservoirs. This confirms the hypothesis of Truesdell et al. (1993) that there could be no saturated liquid layer at the bottom of the high-temperature reservoir and that without such a layer lateral steam flow within the reservoir could not occur. In addition, the persistence of the near-magmatic gas and its similarity in composition with mid-ocean ridge basalts in the high-temperature reservoir supports models for the formation of the high-temperature reservoir which invoke heating by recent massive emplacement of magma (Truesdell, 1991; Truesdell et al., 1993; Williams et al., 1993).

This study also suggests that on the basis of the total helium to non-condensable gas ratio (Figure 2) wells containing the high-temperature reservoir gas component can be distinguished from gases derived from

the normal temperature reservoir, like that produced in the SE Geysers. Our preliminary results indicate that wells with an HTR component have He/non-condensable gas ratios ~ 2.5 times greater than that in NTR steam. More data, however, are needed to extend and confirm this observation.

Surprisingly, despite the wide variation in helium content, isotopic composition, and ^{36}Ar abundance, the composition of the atmospheric noble gas component, as measured by the Ne/Ar, Kr/Ar, and Xe/Ar ratios and which trace meteoric influence, appears invariant. This implies that the HTR magmatic component and the NTR He-rich component are decoupled from meteoric waters. In addition, the relative abundances of the atmospheric noble gases do not match that expected for natural meteoric recharge, i.e. water previously in equilibrium with air at recharge temperatures of 0-20 °C and are more like the composition of the one analyzed sample of injectate fluid. More work is needed in this area as it bears directly on the question of the origin of the steam being produced in the NW Geysers.

FUTURE PLANS

Expand our sampling and analysis of steam wells in the Northwest Geysers and extend sampling and analyses to include the Southeast Geysers and the transition region between the NW and SE reservoirs. This would benefit several Geysers operators by identifying the source of production gases and the potential for future production of corrosive steam from certain wells in the field. We would also like to initiate a monitoring program for wells that from our initial survey of gas compositions show a high potential for production of corrosive steam.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Central California Power Agency	Origin of production in NW Geysers.
Calpine Corporation Northern California Power Agency	Origin of production gas in NW Geysers and potential for production of corrosive steam in SE Geysers.

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Figure 1. Coldwater Creek wells sampled (filled circles). Area with high-temperature reservoir (HTR) is cross hatched. Well Prati 4 (P4) does not penetrate the HTR.

Figure 2. R/Ra plotted against $^{40}\text{Ar}/^{4}\text{He}$, an indicator of crustal influence. Wells not in the HTR are shown as open circles.

Figure 3a. $F(4\text{He})$ plotted against $\text{NCG}/[^{36}\text{Ar}]$, an indicator of atmospheric influence. Symbols as in Figure 1.

Figure 3b. Detail of Figure 3a near the origin. Symbols as in Figure 3a.

GEYSERS TRACERS

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KEY WORDS

Tracers, vapor-phase tracers, tracer tests, halogenated alkanes, The Geysers

PROJECT OBJECTIVES

Chemical tracers provide the best and most rapid method of evaluating the efficiency of injection into geothermal fields. Prior to this project, none were available for vapor-phase reservoirs such as The Geysers. The overall objective of this research project is to identify and test compounds for use as geothermal tracers that are nontoxic and are thermally stable or have easily quantified rates of decay under geothermal conditions, have minimal rock-tracer interactions, are detectable at very low concentrations, and are relatively inexpensive.

Several of these compounds should be identified to allow simultaneous tracing from several injection wells and to avoid raising the reservoir background level of any one compound. Some of the tracers will fractionate between the liquid and vapor phases in the reservoir, so that they can be used to examine the rate and direction of boiling of the liquid plume in the reservoir. Others will have similar concentrations in both the liquid and vapor phases. Theory and methodology for planning and interpreting a vapor-phase tracer test are also being developed. The theory will account for boiling parameters in the injectate plume and the solubility of the tracers.

Technical Objectives

- Prove the stability of several compounds with a range of volatilities that can be used as tracers in vapor-dominated geothermal systems, using both laboratory and field tests.
- Evaluate the effects of solubility on the transport of highly soluble, or two-phase, tracers.

Expected Outcomes

- Develop a variety of tracers (minimum of six) suitable for conditions at The Geysers. Some tracers will fractionate between the liquid and vapor phases, so that they can be used to examine the rate and direction of boiling of the liquid plume in the reservoir.
- Develop theory and methodology for planning and interpreting vapor-phase tracer tests. The theory will account for boiling parameters in the injectate plume and solubility of the tracers.

PROJECT BACKGROUND AND STATUS

The Geysers is the largest geothermal electricity-producing field in the World. Recently, production from The Geysers has significantly declined, due in part to a lack of injected water. In 1989, the Department of Energy (DOE) responded to urgent requests from industry by creating a Geysers cooperative research program. One of the items requested by industry was the development of tracers that will work in the unique geothermal environment of The Geysers. The need for compounds that will trace the injected fluid through the reservoir has been emphasized by the recent evidence that injection has beneficial effect on production.

Prior to our research, successful tracer tests at The Geysers used either deuterium or tritiated water to trace the flow of injected fluids. Although both of these tracers provided useful information, they also have certain limitations. Repeated use of tritiated water, which is radioactive and soluble in both water and steam, can saturate the reservoir after several tests. Deuterium can be problematic because its signature in the injected fluid varies somewhat with time due to factors such as the rate of cooling tower evaporation. Furthermore, changes in operating procedures at some power plants at The Geysers have eliminated the use of deuterium as a tracer in several units. Recently, a method for using ammonia was developed by J. Beall to replace deuterium as a natural tracer. However, like deuterium, the NH_3 method requires a buildup of injectate in the reservoir before it is useful as a tracer and is subject to the uncertainties of all natural tracers. Consequently, the need for other tracers still exists.

We have pursued the development of tracers for use at The Geysers on two fronts. The first approach has been to test halogenated alkanes, most of which fractionate completely to the steam phase under geothermal conditions (Adams et al. 1991a). These compounds, which are known for their high stability and low toxicity are available in a wide variety of species. Thus, multiple injection wells can be tagged simultaneously.

The second approach is to search for compounds that will fractionate to both the liquid and steam phases. These compounds must have sufficient polarity to be soluble in the liquid phase but have a low enough acidity to fractionate to the steam phase from a high-pH boiling liquid.

At the present time the Geysers Tracers Project is approximately 40% complete.

APPROACH

Our approach to developing tracers for vapor-phase geothermal systems has been to test compounds that are commonly used in industry, preferably those that are used in close proximity to personnel. This provides a pre-existing health and safety evaluation for use of the compound, and generally provides some toxicity data. Toxicity studies are generally too expensive for us to undertake on our own budget.

The second step is to choose compounds used in other elevated-temperature applications. These applications are not always obvious. For example, we tested ethanol for use as a tracer because it is commonly distilled, indicating that it can survive exposure to moderately high temperatures without producing poisonous byproducts.

Preliminary tests for thermal stability are then conducted in our laboratory. These tests are difficult for those compounds that are extremely volatile, but relatively trivial for two-phase compounds. Once we are satisfied that the compound is safe and appears to be stable, a field test is performed in cooperation

with industry. If the compound performs satisfactorily, it is tested further in the laboratory to further refine our knowledge of its properties.

All of our field tests are designed to maximize the return of reservoir information as well as data on tracer stability. Because of this balance between research and application, industry is always willing to cost-share our field tests. To date we have cost-shared two tests with Unocal Geothermal, Calpine Corp., and Northern California Power Agency (NCPA).

RESEARCH RESULTS

A category of compounds that appears to be suitable as strictly vapor-phase tracers was identified in 1990 by Adams et al. (1991a). Several compounds from this category, which consists of volatile halogenated chemicals, were tested in the laboratory and in the field. The first field test was performed in 1991 in The Southeast Geysers by Calpine, NCPA, Unocal, and the Geothermal Technology Organization (Adams et al., 1991b). Although one of the compounds, R-12, displayed excessive decay, the other, R-13, did not appear to decay. Another fluorinated compound suggested by our research, SF₆, has also been recently used as a tracer at The Geysers.

Several tracer tests using R-13 have been performed at The Geysers since the joint DOE-industry test in 1991, two of which are described in Beall et al. (1994). These tests were conducted in portions of the reservoir that ranged from highly water-depleted, with low reservoir pressure and liquid saturation, to significantly less depleted, with high reservoir pressure and liquid saturation. Tracer returns from the highly water-depleted portions of the reservoir displayed sharp peaks, rapid transit times, and high recoveries, while those from less depleted portions exhibited broad peaks, slower transit times, and extremely low recoveries. These characteristics indicate that the volatile tracers spend a significant amount of time in the liquid phase in tests conducted in moderately depleted portions of The Geysers reservoir. In these areas the distribution pattern displayed by the vapor-phase tracers is nearly identical to that of the bulk of the injectate. In contrast, the pattern of the vapor-phase tracers deviates from that of the bulk of the injectate in highly depleted regions of The Geysers reservoir. This was illustrated in the latest DOE-industry joint injection test, as described below.

The 1994 cooperative venture of DOE and industry was an extensive examination of the effects of injection in The Southeast Geysers (Voge et al., 1994). A tracer test into Unocal injection well DV-11 was included in the DOE-industry test as part of the research agreement. In this test three tracers were used, R-13, SF₆, and tritiated water. The purpose of the test was to evaluate the performance of SF₆ with respect to R-13, and to compare the behavior of these two volatile tracers to that of tritium, whose volatility is nearly identical to that of the water injected at The Geysers.

The three tracers were injected as a five-hour slug in which the tracer ratios were held constant. In the production fluid, however, the ratios of the tracers varied by up to five orders of magnitude. The change in ratio of the tracers was caused by their differing solubilities in water, which affects the timing and rate at which they are released into steam from the boiling injectate plume. The use of tritiated water and two vapor-phase tracers allowed for three boiling variables to be solved (Adams, 1995). In the case of the DV-11 test, these variables were dilution and two boiling parameters.

Two boiling parameters were required to fit the data of the DV-11 test because the data best fit a multi-stage boiling model, which requires both steam fraction and the number of boiling stages. This necessitated estimating the boiling temperature. If the data had fit a single-stage or continuous boiling

model, temperature could have been solved for in addition to dilution and steam fraction. Single-stage and continuous boiling can be considered as boiling mechanism end-members, where single-stage boiling is a static, equilibrium relationship between the steam and the liquid, and continuous boiling occurs where the steam is immediately removed from the liquid as it forms, and only instantaneous equilibrium is achieved. Multiple-stage boiling is an intermediate case, where the steam is modeled as being removed in discrete batches of specified size.

Computations based on single-stage and continuous boiling failed to match the concentration range and ratios of the vapor-phase tracers. Multiple-stage boiling provided a splendid match, in which both the concentration range and ratios were easily fitted (Figure 1). The relationship used to fit y , the steam fraction per boiling stage, was:

$$k_i = (1 + y(B_i - 1))^{(\log k_i / (\log(1 + y(B_i - 1))))} \quad (1)$$

where $k_i = \frac{C_{i,v}}{C_i^\circ \cdot B_i}$, $C_{i,v}$ = the concentration of tracer in steam, corrected for dilution,

C_i° = the initial concentration of species i , and B_i = the liquid-vapor distribution coefficient for species i . The steam fraction was then used to solve for n , the number of stages, using the relationship:

$$\frac{C_{i,j}}{C_i^\circ} = 1 + y(B_i - 1)^n \quad (2)$$

where $C_{i,j}$ = the concentration of species i in the liquid.

The calculated boiling parameters showed a very rough correlation with the velocity of the steam through the reservoir. In general, n and y increased with increasing velocity, approaching continuous boiling at very high velocities. Very low velocities would presumably produce low n , or approach single stage boiling.

The results of the DV-11 test show that care should be taken in the use of vapor-phase tracers in highly depleted regions of The Geysers. The use of caution should be extended to any simulation of geochemical mass transfer from a boiling region. These simulations are frequently performed by geochemists to predict gas ratios arising from a boiling fluid. As shown by the DV-11 test, these ratios can be significantly affected by the velocity of the steam leaving the boiling zone.

We have also continued our research into two-phase tracers. We have tested alcohols at temperatures of up to 320°C and they continue to look stable enough for use at The Geysers. However, they need a low detection limit in order to be used as tracers. We have recently looked at pre-analysis fluorescent derivitization as an analytic technique, but have unfortunately not found any water-stable reagents. We will continue to look for other analytic methods for these tracers.

FUTURE PLANS

Our plans for the coming year are finish our interpretation of the data from the DV- I I tracer test at The Geysers, and to produce an open-file report of the data as well as a professional publication of the

interpretation. We are currently planning a test in which we will piggyback SF6 onto an industry R-13 tracer test in a moderately depleted region of The Geysers. We will also continue to search for sensitive analytical methods for the alcohol two-phase tracers.

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Figure 1. Multi-stage boiling parameters calculated from the tracer data of a recent injection test performed at The Geysers (Voge et al., 1994). The concentrations shown have been corrected for dilution using tritium tracer concentrations. The steam fractions (y) for each stage and the number of stages (n) are shown in the insert.

MODERN APPROACHES TO PROBLEMS IN MAGMATIC VAPOR EVOLUTION

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KEY WORDS

Texture, magma, volatiles, apatite, volcanic

PROJECT OBJECTIVE

The aim of this research is to develop a model to explain the behavior of volatile species (such as H_2O , HCl and HF) and other magmatically derived chloride-complexed species (such as $NaCl$, KCl , $CuCl_2$, and $FeCl_2$) in silicic volcanic and plutonic systems. These magmatic fluids contribute to the acidity, and to the total dissolved solids, of fluids in geothermal systems, and are often present in alteration products associated with these systems. This research is important to the geothermal industry, because as magmatic fluids cool and become corrosive, surface equipment life is reduced, increasing operation and maintenance costs. The results of this research can be used to calculate the concentration of HCl in the magmatic component of a geothermal fluid as a function of the depth of the magma chamber, the estimated Cl /water ratio, and bulk composition of the melt in the regional magma system.

APPROACH

We are estimating the magmatic contribution to geothermal fluids in silicic systems through: 1) detailed field analysis of magmatic textures in fossil geothermal systems of the High Sierra and interpretation of these textures in light of halogen-bearing accessory phases; 2) experimental investigations in systems with a magmatic volatile phase and high silica rhyolite, and systems with a low-salinity vapor, a brine, and high silica rhyolite; and 3) chemical and physical modeling of exsolution processes in subvolcanic and plutonic environments. Understanding the behavior of magmatic fluids and their contribution to geothermal fluids is dependent upon the successful integration of these components.

PROJECT BACKGROUND AND STATUS

Many geothermal systems appear to have a fluid component of magmatic-hydrothermal origin. Application of experimental studies and modeling efforts to magmatic processes requires detailed field observations. Recognition of magmatic, subsolidus, and hydrothermal textures in the field is imperative. Textures of magmatic volatile-phase exsolution in fossil geothermal systems have been recognized in several areas. Determining if a volatile phase has been liberated from a particular high-silica melt (especially plutonic systems) can be difficult, but can be approached using apatite chemistry ($Ca_5(PO_4)_3(F,Cl,OH)$) in conjunction with rock textures. To this end, several shallow plutons (subvolcanic conduits), which almost certainly exsolved a magmatic fluid phase (one- or two-phase) are being studied to relate textural features with geochemical changes in halogen-bearing accessory phases.

To accomplish this the following three-part approach is being utilized:

1. **Field Investigations:** We are investigating igneous apatite chemistry as a function of magmatic textures in the fossil remains of several localized, shallow magmatic-geothermal systems of the high Sierra of California, all about 100 million years old, including the Billy Lake-Rush Creek Complex, Shellenbarger Lake Complex, and the granites of Hogan Mountain, Lost Peak and Big Sandy Bluff.
2. **Experimental Investigations:** We are performing experiments on the partitioning of HCl and other substances (*e.g.* Cu) between silicate melts and two phase mixtures of chloride-bearing aqueous fluids, and between silicate melts and crystalline phases.
3. **Physical and Chemical Modeling:** We are modeling aspects of the chemistry (in the systems high silica melt-aqueous phase and high silica melt-aqueous brine-low salinity vapor) and the physics of aqueous phase exsolution in plutonic systems.

The combination of these three approaches will yield important information about the time integrated effects of magmatically derived components of geothermal fluids associated with low-pressure silicic systems.

RESEARCH RESULTS

A. Field Investigations and Physical Models of Geothermal Fluid Exsolution from Magmas.

The region that is presently represented by the High Sierra of California has been subject to intense plutonism from late Triassic (*ca.* 225 Ma (million years old)) through the middle Cretaceous (*ca.* 85 Ma). At *ca.* 100 Ma, low volume shallow plutonism and coeval, cogenetic volcanism occurred sporadically throughout the central Sierras. Shallow intrusions provide a unique opportunity for research because: 1) they almost certainly exsolved a magmatic volatile phase in the early stages of their evolution and the associated textures should be well developed; 2) exsolved magmatic fluids probably interact with externally derived geothermal fluids, throughout the crystallization history of the pluton; 3) the physical mechanism of magmatic fluid phase exsolution in low pressure systems is unique; and 4) at low pressures, immiscible low salinity vapor and brine can be in equilibrium with the melt.

Textural features identified in these shallow intrusions, thought, by various workers, to be related to magmatic volatile phase exsolution, include: 1) simple aplite and pegmatite dikes which are rarely exhibited in a stockwork pattern; 2) simple aplite dikes (dominantly feldspar-quartz) which grade laterally into pyrite-bearing quartz-rich hydrothermal veins with minimal amounts of alteration; 3) variably sized miarolitic cavities (dominantly of feldspar-quartz mineralogy) with assorted degrees of connectivity; and 4) hydrothermal veins in which little secondary material has been deposited which are identified by calcic/potassic alteration in the host rock.

As part of our previous research efforts (*e.g.* Piccoli and Candela, 1994; 1993; Piccoli, 1992) we have described a model in which the chloride concentration (*e.g.* HCl, Cl) in the magmatic volatile phase associated with silicic plutons can be estimated. Utilization of this model requires that the Cl and F concentrations in the mineral apatite be known. We have previously described how halogen concentrations in apatite vary in several of the cases described above (*e.g.* aplites in the Tuolumne Intrusive Suite; Piccoli, 1992).

Our observations at Courtright Reservoir show the importance of proximity of contact, rather than prodigious magmatic volatile phase flow, in the production of zones of variable texture (pegmatites, granophyre, etc.) in granitic rocks. There are numerous near-contact pegmatites, and miarolitic granophyre. Miarolitic cavities here, and in the Big Sandy Bluff granite show only minor interconnection, although more interconnection can be seen at Courtright Reservoir. This is consistent with the Big Sandy Bluff granite being deeper and drier. Biotite schlieren is closely associated with pegmatite, but not always. As pegmatites result from low nucleation densities (not necessarily volatile saturation), then schlieren may also be a result of nucleation phenomena. The granophyric granite is obviously quench (as opposed to the equivocal "aplite" texture) by evidence of micrographic granite and quartz densities. This suggests that miarolitic cavities are produced by rising (and therefore quenching) plumes of water-saturated melt. These plumes probably represent Rayleigh-Taylor instabilities produced along the side wall during crystallization.

B. Experimental Investigations

A series of experiments were performed at 1 kbar, 800°C and 1/2 kbar, 850°C in the system felsic silicate melt + HCl + NaCl + KCl to investigate the partitioning systematics of HCl between felsic silicate melts and mixtures of low-salinity aqueous vapors and high-salinity brines (Williams, Candela and Piccoli, 1995). Under room temperatures and pressures, the aqueous vapor and brine remix to form an aqueous mixture [$Aq = V(apor) + B(rine)$]. Changes in the bulk Cl/water ratio will shift the proportions of vapor to brine at high pressure and temperature. To monitor the changes in the partitioning systematics of HCl with changes in the bulk Cl/water ratio we formulated an apparent equilibrium constant expression, $K^{Aq/M}$, for hydrogen and sodium exchange between the silicate melt and the aqueous mixture. We have developed an algorithm for modeling hydrogen and sodium exchange in the vapor and the brine by assuming a model two-phase field. Our data show that, at 1 kbar (800°C), as the mass proportion of vapor to brine increases (*i.e.* at low Cl/water ratios), the $K^{Aq/M}(H,Na)$ increases indicating that HCl favors the low-salinity vapor over brine. One implication of these results is that if a chloride-bearing aqueous fluid is associated with a felsic silicate melt at pressures of approximately 1 kbar it will stratify into a low-density, high-HCl/(NaCl + KCl) vapor and a denser low-HCl/(NaCl + KCl) brine. As the low-density vapor rises and cools, ahead of the denser brine, it will form a plume of very acidic (low pH) fluid. More aluminous melts yield aqueous fluids with higher HCl/(NaCl + KCl).

FUTURE PLANS

Our previous modeling of apatite - melt systems allow us, using indirect methods, to make estimates of both melt and magmatic volatile phase halogen concentrations during magmatic-geothermal processes. Our future plans are to expand the scope of the modeling, to include transition and high field strength elements, to obtain information about temporal relationships between these elements in both the melt and magmatic volatile phase. We plan to model these chemical trends as a function of: 1) depth of emplacement and/or water solubility in silicic melts, 2) initial melt composition, 3) the physical process which generates exsolution of the magmatic volatile phase (*i.e.* crystallization, or rise of a magma to the surface), 4) fractional or batch removal of the magmatic volatile phase from silicate magma, and 5) chemical constraints on partitioning behavior of elements between the magmatic volatile phase, crystalline phases and silicate melt (*i.e.* do elements partition with Nernstian-type behavior, or is their behavior dominated by mass-balance action). This, in conjunction with successful integration of field and experimental investigations, will lead to important understanding of the magmatic contribution to fossil and active geothermal systems.

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VOLATILITY OF HCl DURING BRINE DRYOUT

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KEY WORDS

Hydrochloric acid, volatility, corrosion, The Geysers, modeling, thermodynamics, acidity, chloride, brine, steam

PROJECT OBJECTIVES

The goals of this project are to determine the likely source of highly corrosive steam from high-temperature geothermal wells and to suggest likely procedures for mitigation of corrosion problems resulting from the production of corrosive steam based on the thermodynamics of liquid-vapor partitioning of corrosive solutes. This research is of particular importance to the control of hydrogen chloride in the produced steam from the vapor-dominated reservoir at The Geysers geothermal field in California. However, the fundamental approach taken makes the results of this program generally applicable to a variety of geothermal-plant operating problems arising from partitioning of solutes between brine and steam.

Technical Objectives

- Carry out high-precision laboratory measurements of the partitioning of corrosive solutes, including acids and chloride salts, over ranges of temperature and brine composition encountered in the development of geothermal resources.
- Represent the experimental data with a high level of accuracy using fundamentally sound thermodynamic models, in order to provide the means for quantitative calculation of the composition of coexisting brine and steam under both geothermal-reservoir and surface-equipment (e.g., piping and turbine) conditions.
- Propose and validate methods for mitigation of the production of corrosive steam from geothermal reservoirs based on the experimental and modeling results.

Expected Outcomes

- The primary products of this research will be new experimental information on the partitioning of potentially corrosive solutes between brine and steam over wide ranges of temperature and composition characteristic of various geothermal systems, and a method for the quantitative calculation of the composition of coexisting phases at various points in the geothermal steam cycle.
- In collaboration with technical and plant-operations personnel from companies operating geothermal power plants, these experimental results will be used to develop methods for the mitigation of problems (corrosion; solids deposition) encountered in energy production from geothermal resources.

PROJECT BACKGROUND AND STATUS

The generation of acidic, corrosive steam has been cited as an increasingly serious problem limiting the production of steam, particularly at The Geysers geothermal reservoir. Wells drilled recently in the northwest Geysers have produced steam at higher temperatures ($> 300^{\circ}\text{C}$) than usually found in the main body of the reservoir ($\approx 240^{\circ}\text{C}$). Often these wells produce high levels of chloride at the wellhead, with observed levels greater than 100 ppm in some cases. Owing to its high volatility and the nonstoichiometry of observed chloride with cations in steam (e.g., Na), the observed chloride has been assumed to be due to hydrochloric acid. This acid-chloride-bearing steam is extremely corrosive to piping and well casings, leading in severe cases to loss of production within a few days. In addition to the current problem, the question of potential production of acidic steam in older wells at The Geysers as the reservoir dries out with continued production is of great long-term significance in the operation of the resource. A laboratory study of the partitioning of acid chlorides over both single electrolyte solutions and over brines likely to be encountered in the reservoir was undertaken to address the current problem of acidic steam production in deeper, hotter wells and the projected behavior of the reservoir with further production. The project began in FY 1990, and to date has yielded both significant new experimental results and a new modeling approach for the calculation of the composition of coexisting brine and steam phases, giving important indications of potential problems in geothermal power plants due to corrosion by acidic brines.

APPROACH

The problem is addressed through laboratory measurements of liquid-vapor partitioning equilibria. The partitioning of hydrochloric acid to the vapor phase has been measured at temperatures to 350°C over pure $\text{HCl}(\text{aq})$ and from aqueous mixed brines including $\{\text{HCl} + \text{NaCl}\}$, MgCl_2 , $\{\text{MgCl}_2 + \text{NaCl}\}$, and CaCl_2 . Experiments are currently in progress to measure the partitioning of chlorides (HCl and NaCl) from brine to steam during the process of evaporation of brine through the three-phase system (brine + steam + halite) to (steam + halite) at high temperatures. These experiments serve both as model systems for the mixed electrolyte brines encountered in geothermal reservoirs, and as a method for measurement of the high-temperature pH imposed in mixed electrolyte brines by the hydrolysis of metal ions (i.e., Ca and Mg) in solution.

This project is part of the program "Physical Chemistry of Geothermal Systems" at ORNL. Significant contributions to the general objectives of this program are provided by other closely-related programs in progress at ORNL, including research in fundamental aqueous chemistry at high temperatures and measurements of solute volatilities important in fossil-fired and nuclear steam cycle chemistry.

RESEARCH RESULTS

The conditions necessary for generation of corrosive steam are being investigated by static measurements of the partitioning of chloride between liquid and vapor phases, and its relation to temperature and source brine composition. A special apparatus has been constructed for these measurements, using a thin platinum liner within a stainless-steel pressure vessel to permit studies to high temperatures on these very corrosive solutions. The apparatus is filled to approximately one-third of its total volume with an appropriate chloride brine, and maintained at the desired constant temperature ($\pm 0.01^{\circ}\text{C}$). Samples of both the liquid and vapor phases are obtained at temperature through chemically-inert tubing and valves, with condensed vapor-phase samples withdrawn at a precisely controlled rate in order to prevent disturbing equilibrium conditions and to minimize sample contamination by entrained liquid droplets.

Liquid-phase samples are obtained before and after each vapor sample in order to monitor and account for the changes in solution composition due to the withdrawal of condensed vapor from the high-temperature vessel. Sample compositions are determined by acidimetric titration and/or ion chromatography as appropriate for the particular solute concentrations observed. Where practical, experiments are carried out over wide ranges of ionic strength and acidity/salinity ratios at each temperature, to insure that the correct thermodynamic equilibrium constant is obtained from the analysis of the results. In addition to the measurement of partitioning of HCl over brines, vapor-phase samples are analyzed quantitatively to determine the concentrations of other cations from the brines present in the vapor phase, giving the volatility at high temperatures of the sparingly-volatile brine components (e.g., NaCl). A second apparatus, consisting of a titanium pressure vessel equipped with a glass liner and fitted with inert tubing and valves, was also used in measurements of HCl partitioning over HCl(aq) and {HCl + NaCl}(aq) to 100°C by an inert-gas (nitrogen) transpiration technique.

In analyzing the results, it has been assumed that chlorides are present as associated molecules (e.g., HCl or NaCl) in the vapor phase, and significantly dissociated to ions in the liquid phase. The thermodynamic equilibrium constant for the partitioning reaction may then be written as $K = m_v(\text{MCl}) / \{m_l(\text{M})m_l(\text{Cl})\gamma_{\pm}^2(\text{MCl})\}$, where m_v and m_l are molalities of the components in the vapor and liquid phases and $\gamma_{\pm}$ is the stoichiometric mean ionic activity coefficient for MCl in the liquid phase. These activity coefficients, which are significantly different from unity at the conditions investigated, are known or can be estimated reliably from previous studies in this Laboratory; the activity coefficient for the neutral MCl molecule in the vapor phase is assumed to be unity. The invariance of K with observed liquid and vapor phase compositions and sampling rates serves as a check for the presence of mechanical carryover of solute, and of the accuracy of the activity coefficients.

The values of K for HCl have been represented as a simple function of temperature and solvent (water) density for purposes of interpolation and extrapolation of the results to the solvent critical temperature (374°C); these results have been published recently. The observed partitioning of NaCl is somewhat more complex: at constant temperature, values of K decrease with increasing liquid-phase molality. This behavior has been modeled quantitatively by incorporating the density of steam, which decreases with increasing molality at constant temperature due to the vapor-pressure lowering of NaCl, into the overall fit equation. Using these new data, we have shown that for $t \geq 300^\circ\text{C}$, $\text{pH} \geq 3$, and relatively high salinities, the predominant means for transport of chloride to the vapor phase from NaCl(aq) brines should be as NaCl, rather than as HCl. The known partitioning behavior of HCl makes it possible to use measured concentrations of HCl in the vapor phase as an indicator of the pH at high temperatures of solutions containing hydrolyzable cations (e.g., Mg or Ca). Measurements of the compositions of coexisting phases have been made to 350°C for aqueous brines containing MgCl_2 , $\text{MgCl}_2 + \text{NaCl}$, and CaCl_2 . It is clear from these experiments that while significant levels of HCl are produced by hydrolysis in these solutions, and may be used as an indicator of the extent of hydrolysis in the liquid phase, the total amounts of HCl generated are too small to account for the high levels of chloride observed in steam from the high-temperature reservoir at The Geysers.

The production of corrosive, high-chloride steam at The Geysers is often accompanied by enhanced production of noncondensable gases, including relatively high levels of ammonia (to ~1000 ppm). We have combined these field observations with our laboratory measurements on volatilities of HCl carried out in this program and our measurements of NH_4Cl partitioning supported by the Electric Power Research Institute to outline a possible mechanism for the formation of corrosive steam having high levels of both chloride and ammonia. In a mixed brine containing HCl, NH_3 , NH_4Cl and NaCl, all four solutes partition from the brine to steam. However, as the temperature and pressure decrease during production

of steam, the steam becomes supersaturated with respect to halite, and sodium can be stripped from steam through deposition as $\text{NaCl}(\text{cr})$. The resulting steam, containing relatively high levels of both chloride (as $\text{NH}_4\text{Cl} + \text{HCl}$) and ammonia gives compositions consistent with the analyses obtained from wellhead samples. The pH within the reservoir of a brine (predominantly NaCl) which is in equilibrium with steam having the observed wellhead concentrations of chloride and ammonia can be calculated from the partitioning results. This dependence is illustrated in Figure 1. While this mechanism is not the only one which could lead to high levels of HCl and NH_3 , the application of the liquid-vapor partitioning results for this system remains of primary importance in evaluating possible corrosion mechanisms due to possible enhancement of these solutes in "early condensate" liquids as compared with their concentrations in steam.

FUTURE PLANS

The partitioning of solutes between 'brines' adsorbed on solid surfaces and the vapor phase may be significantly different from that observed for bulk liquids. Initial experiments with solids present include (brine + steam + halite) and (steam + halite) studies. Further experiments are anticipated on the partitioning of solutes to steam with both well-characterized 'inert' solids (e.g., amorphous silica) and rock samples from The Geysers reservoir in contact with the equilibrating fluids.

The experimental techniques and modeling approaches developed in this program have applications to geothermal systems beyond the original problem of corrosive-steam production at The Geysers. It is anticipated that this work will be extended to similar problems encountered in other geothermal systems (e.g., corrosion in process units at Magma Power Company sites in California), including liquid-dominated as well as vapor-dominated resources.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Technology transfer has been an integral component of this program from its inception. Results have been communicated frequently to the geothermal industry through both periodic, focused update meetings and participation in geothermal conferences of broader scope. Direct contact and consultation on the application of these results to problems arising from volatility of solutes are continuing with the organizations listed below.

Organization(s)	Type and Extent of Interest
UNOCAL and other Geysers operators	Geysers geothermal field applications
Magma Power Company	Salton Sea geothermal field process applications
Electric Power Research Institute	Fossil-fired and nuclear steam cycle applications

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Figure 1. Predicted pH of a brine [predominantly NaCl(aq)] at 350°C as a function of the chloride and ammonia concentrations in wellhead condensate samples.

SEISMIC IMAGING AT THE GEYSERS USING MICROEARTHQUAKES

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KEY WORDS

Seismic imaging, P-wave, S-wave, attenuation, fluid content

PROJECT OBJECTIVES

We are attempting to determine the in-situ liquid/vapor content of The Geysers reservoir rocks using seismic imaging techniques with microearthquakes as sources.

Technical Objectives

- Carry out seismic imaging of the southeast Geysers using P- and S- wave velocity and attenuation data extracted from the microearthquakes being collected by the Lawrence Berkeley Laboratory's digital, high-frequency network currently deployed over the injection test region in the southeast Geysers.
- Use Geysers reservoir physical property measurements being made from The Geysers corehole to constrain the interpretation of the seismic images in terms of liquid/vapor content of the reservoir rock pore spaces.
- Attempt to see time-varying saturation changes due to injection in the southeast Geysers with the seismic images.

Expected Outcomes

- Develop seismic images for P- and S-wave velocity and attenuation from the southeast Geysers for several time segments.
- Interpret the images in terms of The Geysers reservoir rock's fluid content and liquid saturation.

PROJECT BACKGROUND AND STATUS

Several studies have suggested that seismic velocity and attenuation information can be used to infer saturation conditions in the reservoir (Evans and Zucca, 1988; Zucca and Evans, 1992; Zucca et al., 1994). We are applying these techniques using higher resolution seismic data than was available in these earlier studies in an attempt to improve their resolution so that they can be used as tools to monitor the effects of steam production and the migration of injected fluids at The Geysers. We are using data collected by Lawrence Berkeley Laboratory's digital network deployed in the southeast Geysers. The

network consists of 13 three-component surface stations that telemeter their data to a central site using a sample rate of 500 Hz per channel which provides usable data over 100 Hz.

Inference of the reservoir parameters using seismic information depends on our knowledge how Geysers reservoir rocks behave under the temperature and pressure conditions found in the reservoir. This kind of laboratory data is relatively sparse and has not been done on rocks that are even a close analog to Geysers rocks. Therefore, we are dependent on the results of the measurements being carried out in The Geysers corehole and on the core itself. Our project has been inactive for most of the year while work is proceeding on the corehole.

APPROACH

We are continuing to test our hypothesis that seismic velocity and attenuation images of geothermal fields can be jointly interpreted to give the degree of the liquid saturation in the matrix of the reservoir rock. Subsurface mapping of liquid saturation is critical in understanding the movement of water that is injected into the reservoir to slow the decline of steam production. Our seismic images are calculated from recordings of earthquake generated seismic waves that pass through the region of interest, in this case the geothermal field. We use variations in the patterns of arrival time and frequency content of the P- and S-waves to calculate velocity and attenuation structure respectively. Both P-wave velocity and attenuation are sensitive to changes in saturation, but have different responses. To date we have used mostly P-waves in our analyses. However, we are beginning to include S-waves in our analysis which should increase the reliability of our saturation estimates. This is because S-waves are not as sensitive to changes in saturation as are the P-waves. Therefore, including shear wave information should make it easier to determine if a given change in velocity is due to saturation variations or a change in lithology. In the southeast Geysers we hope to be able to map the movement of injected liquids since they should make a contrast with the low-pressure depleted parts of the reservoir.

RESEARCH RESULTS

Our project has been on hold most of the year while the effort with The Geysers corehole proceeds. As mentioned above, the results of the corehole are needed to thoroughly interpret the results of the seismic images that we plan to calculate. Before our work was stopped in the early part of the year, we did begin some calculation of parameters from Geysers microearthquake waveforms for inclusion in the computer routines that calculate the seismic images. In addition, we completed work on a previous project (Zucca et al., 1994) to calculate images for the central Geysers using data collected by the UNOCAL Corporation. The primary result of that work was the inference that the liquid saturation of The Geysers reservoir rock increases with depth.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Geysers operators	If this R&D is successful, reservoir fluid conditions could be determined from the surface without drilling. That would allow tracking of injected fluids and aid in characterizing new geothermal fields.

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GEYSERS MICROEARTHQUAKE MONITORING

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KEY WORDS

Seismology, microearthquake monitoring, resource management

PROJECT OBJECTIVES

The objective of the project is to evaluate the usefulness of high-frequency, high-resolution microearthquake (MEQ) monitoring as a geothermal resource management tool. It is hoped that MEQ studies at The Geysers can provide information to better understand reservoir dynamics and to delineate the structures controlling heat and fluid flow.

Technical Objectives

- Obtain a three-dimensional model of the P- and S-wave velocity structure of the reservoir.
- Use the velocity model to obtain high-precision hypocenters of microearthquakes.

Expected Outcomes

- Locate high-permeability paths in the reservoir.
- Determine a general three-dimensional structural model of the reservoir.
- Monitor of the effects of condensate injection in real time.
- Aid in location of in-fill well drilling.

PROJECT BACKGROUND AND STATUS

Northwest Geysers:

In March of 1990, LBL undertook the collection, processing, analysis, and interpretation of the data from the 16-station MEQ network in the NW Geysers owned by the Coldwater Creek Operator Company. Two phases of data collection have occurred. The first phase began just before production and injection activities started in the northwest Geysers (late 1987), and ended about one year later. During this time period injection occurred at Prati 8. Processing of the data revealed a strong correlation between injection and seismicity. The injection seismicity, however, is superimposed on a more general pattern related to such factors as natural seismicity and the effects of steam withdrawal. In addition, the 3-D, P- and S-wave velocity and attenuation structures determined from the data have been related to geologic structure and other properties of the steam reservoir.

In the fall of 1993, the network was upgraded with current data-collection hardware and software, and was brought back online in October 1993. Data collection continued until September 1994. During this time a data set associated with injection around Prati-9 was acquired. Analysis of this data has been ongoing during the past year, and is being coordinated with A. Truesdell (consultant to LBL), and with D. Faulder (of Idaho National Engineering Laboratory), who is modeling the reservoir performance.

Southeast Geysers:

For several years, Unocal Geothermal has operated an analog array of MEQ stations over a large area of The Geysers. While the information obtained from this array has been useful, results from the NW Geysers network encouraged several operators in the SE Geysers (Unocal, NCPA, and Calpine) to undertake a cooperative effort with LBL to obtain higher-precision data from a high-resolution network. In 1991, a two-part array consisting of 8 stations operated by LBL and 5 stations operated by Lawrence Livermore (LLNL) was installed in the SE Geysers in the Unocal-NCPA-Calpine lease areas in order to monitor MEQ activity associated with upcoming injection operations and to provide a 3-D seismic velocity and attenuation model of the area. The split-array configuration did not provide reliable data, however, so in late 1993 the LLNL stations were replaced with components compatible with LBL's electronics, and the collection and processing of the data was centralized. The array was also slightly reconfigured to better monitor the anticipated seismicity associated with the DV-11 injection test which commenced in mid-December 1993. This upgrade of the network solved the processing problems and eliminated the concerns regarding data precision and accuracy that were hindering progress on the objectives. The data collected during the past year has been processed and analyzed for 3-D seismic velocity structure and high-quality locations of MEQ hypocenters.

APPROACH

The approach taken in this project is the inversion of MEQ travel-time data for 3-D P- and S-wave velocity structure. The obtained velocity model is then used to invert additional travel-time data for the hypocentral coordinates of the MEQs of interest. The data are recorded on arrays of high-frequency, high-resolution, three-component, digital seismic stations, which provides higher precision MEQ locations than have previously been obtained in the monitoring of geothermal systems. The seismograms are also used to obtain moment tensors, which yield a measure of the size of the event, as well as information about source mechanisms, such as the rate and manner of energy release.

LBL operates two arrays at The Geysers. The first array is located in the northwest region, in the Central California Power Agency (CCPA) No. 1 lease area, and consists of 16 three-component bore-hole seismometers. The area is representative of a high-temperature, deep reservoir environment. A similar 13-station array, with the seismometers deployed at ground surface level, is installed in the southeast region of The Geysers, in the area occupied by Unocal, Northern California Power Agency (NCPA), and Calpine leases. The arrays are unique in their dense coverage (approximately 1 km between stations) and in their low magnitude-threshold monitoring ability.

The results are communicated regularly to representatives of CCPA No. 1, Unocal, NCPA, and Calpine. A collaborative effort is then made to interpret the results in terms of the reservoir conditions of interest to these operators.

RESEARCH RESULTS

Northwest Geysers:

In 1994, 3-D velocity and attenuation models were obtained for the NW Geysers region. Most of the work done focused on interpreting these models to help characterize the steam reservoir beneath the area (Romero et al., 1994a and b). Results of the study indicate that the velocity and attenuation variations correlate with the known geology of the field. High-velocity near-surface anomalies correspond to mapped sections of Franciscan metagraywacke and greenstone, while low-velocity anomalies appear to represent sections of Franciscan melange. High V_p/V_s anomalies at depth suggest a recharge region or a condensation zone. The steam producing zone is marked by low V_p/V_s values suggesting partial liquid saturation of the reservoir rocks.

Analysis of the spatial and temporal patterns of the 1994 seismicity exhibit compelling correlation with geothermal exploitation. Hypocenters lie between depths of 1.5 and 2.5 km and appear to be associated with the steam production zone. A deeper cluster of events is located beneath the active injection well Prati-9. This cluster appears to shift with changing injection activities. High resolution MEQ locations hold promise for tracking injectate.

In 1994, we developed a procedure for determining the moment tensor of a MEQ event. In order to understand the nature of geothermally-induced seismicity, this method was applied to a subset of the injection-related events. The resulting mechanisms revealed a change in the mode of failure with depth. Shallow events (depths less than 1.5 km) exhibit both normal and right-lateral mechanisms, with stress axes consistent with the regional trend. Deeper events (depths greater than 1.5 km), however, show mostly normal-type motion. This change in mechanism suggests a realignment in the direction of the principal stress axis with depth, perhaps reflecting the effects of exploitation. Further work will be done in 1995 to understand fully this intriguing observation.

Southeast Geysers:

During the past year, travel-time data from selected 1994 events have been inverted for a 3-dimensional P- and S-wave velocity model of the SE Geysers area. Interpretation of these results in terms of geology and reservoir structure and geometry is ongoing.

The velocity model has been used to locate approximately 1100 events from January through July 1994. These results are shown in Figure 1. The cluster of events around the injection well DV-11 are shown in more detail in Figure 2. Events in this area first occurred in February 1994, one to two months after injection began. Further analysis of the spatial and temporal aspects of this group of events, and their relation to the injection in DV-11, and the extraction in nearby wells, is ongoing, as is investigation of seismicity surrounding other injectors.

The moment tensor inversion method has been applied to selected events. The results are still preliminary; however, they appear to show that the principal stress axes of events comprising some clusters of MEQs are similar, while the principal stress axes of events comprising other clusters are variable. These axes do not necessarily correspond to the regional stress axes, which could mean that local stress regimes dominate in SE Geysers induced seismicity.

FUTURE PLANS

Monitoring of the NW Geysers network ceased in September 1994 and there are no current plans to reinitiate it. We will continue collecting data from the SE Geysers network indefinitely. With the development of a reliable 3-D velocity model, we can now concentrate on location of hypocenters and their correlation with injection and withdrawal activities and their relation to high-permeability pathways. More work will also be done with source mechanism studies. Interpretation of all the results into a comprehensive structural model of the SE Geysers reservoir will also continue.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal Geothermal Division Northern California Power Agency Calpine Corporation Central California Power Agency No. 1	Detection of high permeability pathways and delineation of steam

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Figure 1. Microearthquake hypocenters (+) for January-July 1994 in the Southeast Geysers. Stations are denoted by triangles. (a) Plan view. (b) East-west cross-section.

Figure 2. Microearthquake hypocenters around the injection well DV-11 for January-July 1994. Large circle denotes well head, hatched line course of well projected onto (a) surface, and (b) east-west plane.

MECHANICAL PROPERTIES OF GEYSERS ROCKS

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KEY WORDS

Fluid content, Geysers core, SB-15, wave velocity and attenuation, seismic interpretation, fluid migration

PROJECT OBJECTIVES

A principle objective of this project is to determine fluid content (water saturation) at The Geysers using direct measurements on recovered core and calibrated field seismic measurements. Basic rock properties data must be known in order to recover maximum information from seismic images currently being produced at The Geysers.

Technical Objectives

- Develop new methods to determine water content of geothermal reservoir rocks to provide data core to span the range from reservoir scales.
- Determine water content and distribution for Geysers rocks, using a combination of methods including gravimetry and x-ray scanning.
- Calibrate geophysical methods used for tracking fluid movements on the reservoir scale including elastic modulus and attenuation and electrical conductivity.

Expected Outcomes

- Observe directly from x-ray scans fluid distribution in recovered core.
- Obtain evidence for or against mud infiltration during drilling.
- Measure seismic velocity and attenuation for comparison with field measurements.

PROJECT BACKGROUND AND STATUS

Reliable water saturation estimates are of fundamental importance for managing and predicting the long-term performance of The Geysers reservoir. The conventional practice of determining water content by measuring weight loss upon drying of core gives scattered results which are inconsistent with steam production data. Earlier measurements failed to account for mud infiltration and water loss from the sample during core recovery. Reservoir heterogeneity also raises fundamental questions about sampling methods and measurement technique. Nondestructive methods, based on extensions of medical imaging technology, show promise for rapidly determining water content and distribution for relatively large volumes of core while keeping core disturbance to a minimum.

Determining liquid movement and content at the reservoir scale is possible in principle through detailed mapping of seismic velocities in the reservoir using microearthquake sources. Laboratory velocity measurements for generic crustal rocks suggest that changes in velocity and attenuation for compressional and shear waves may be used to diagnose water saturation. Although this result can be applied to the field in a qualitative way, the measurements were made for rocks that are very different from the graywackes and felsites present at The Geysers. Therefore, basic calibration data must be extended to geothermal rocks. These early studies also ignored the potential effects of velocity dispersion on extrapolating laboratory results obtained at ultrasonic frequencies to field interpretations based on measurements taken in the seismic frequency range. Recent improvements in laboratory capabilities make velocity and attenuation measurements possible at seismic frequencies.

APPROACH

X-ray computed tomography may provide a means of imaging open porosity, lithology variations, and water content. Although computed tomography has been used with success in following fluid movements in oil reservoir rocks, modified methods are now being applied for the first time to low porosity rocks from The Geysers. Laboratory mechanical properties are measured with a combination of traditional ultrasonic methods for determining elastic properties and new low frequency methods. High frequency measurements are based on propagation of ultrasonic waves and are being done both by Lawrence Livermore National Laboratory (LLNL) and by a Department of Energy (DOE) contractor, New England Research (NER). The low frequency measurements are being done at LLNL using a torsional oscillator which operates at seismic frequencies.

RESEARCH RESULTS

During the first part of the fiscal year, measurements were made for a half core of Franciscan graywacke recovered from reservoir depth (2599m) from well NEGU-17. At the time, this was the only core available for detailed experiments, and surrogate materials were also used to test and calibrate x-ray methods. The entire graywacke sample was scanned with high energy x-rays to produce a series of tomograms which clearly show filled and partially filled veins. The NEGU-17 core was then divided to produce appropriate samples for ultrasonic (NER) and low frequency measurements (LLNL). Details of measurement technique and procedures are given by Boitnott and Bonner (1994); results are summarized below. Ultrasonic compressional and shear velocities show an unusually weak pressure dependence for both the dry and saturated cases. Apparently, little damage was done to the NEGU-17 matrix in the drilling and recovery process, because fresh microfractures would close easily with increasing pressure, producing the characteristic rapid increase in velocity typically seen in low porosity rocks. Both the ultrasonic and low frequency shear measurements show that the shear modulus decreases with saturation, consistent with frame weakening caused by chemical interaction between pore fluid and rock at the grain contacts. In-situ seismic velocities are low compared to laboratory results, suggesting that the matrix sampled by NEGU-17 is not representative of seismic velocity as measured at the field scale. Clearly, fractures and large scale porosity in the reservoir would tend to lower the velocity.

Small cores of NEGU-17 graywacke were dried, evacuated, and backfilled in the laboratory to study imbibition and storage of pore fluid. High-resolution computed tomographs were reconstructed from multiple x-ray measurements for the same sample, dry and nominally saturated. Veins and associated selvage are easily resolved. Although increases in x-ray attenuation could be detected in the saturated case, it was necessary to increase the x-ray ray contrast of the pore fluid by adding 1% potassium iodide

so that changes in attenuation caused by the pore fluid could be separated from variations caused by grain heterogeneity. These results are referenced below as Bonner, Roberts and Schneberk, 1994.

Additional core samples were received in September from the corehole on the SB-15 sidetrack. Preserved cores, alternating in length at 1.5 and 5 ft., were transported to LLNL and radiographed within 36 hours of drilling. Selected intervals were then scanned to produce three dimensional tomographs with resolution of ~ 120 micrometers. An example is shown in Figure 1. Radiographs of the deepest 5 ft core recovered for x-ray inspection, run 81, revealed a vuggy section near 1531 ft. The radial tomograph, on the right, shows a slice through this structure, a complicated partially mineralized vein. Note also the fresh fracture near the bottom of the slice. Vertical slices through the central region of the core were examined to investigate the three dimensional character of the vuggy region. The vertical slices are ~0.7 in high, extending upward into the core from the radial slice. The slices are taken across the core progressing from the top to bottom of the radial section according to the indexes shown on the figure. The slices show that this feature is not planar, but extends upward and to the left as a system of partially connected stringers. The brighter regions near the outer edges indicate higher local x-ray attenuation, which we suspect is caused by infiltration of drilling mud.

FUTURE PLANS

Future work will be aimed at obtaining reliable estimates of fluid saturation and of processes controlling water storage in Geysers rocks. Baseline x-ray tomographs of the recovered core from SB-15 are now being analyzed to detect gradients in x-ray attenuation that might be related to mud infiltration, loss of fluid during core recovery or previous steam production in SB-15. Measurements will be coordinated with Withjacks's NMR estimates of water content. Further laboratory measurements of the 'seismic' properties of Geysers rock recovered from the core hole will be made to determine the generality of results already obtained for NEGU-17. These tasks will again be shared between LLNL and NER.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Geysers operators	Water content, distribution measurements
New England Research	Seismic, transport properties

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Figure 1. X-ray tomographs of coring run 81, 1531 ft depth in SB-15 D, showing both vertical and radial sections. This was the deepest core preserved for x-ray examination. a) Reconstructed vertical slices, ~0.7 in. high extending upward from the radial slice at the right, taken east-west through the ~3.4 in. core. The outermost vertical features are slices through the aluminum coring tube. b) Radial tomograph showing a partially mineralized vein, open fracture, and parallel filled veinlets. The numerals indicate locations where the vertical tomographs were reconstructed.

LABORATORY MEASUREMENTS ON RESERVOIR ROCKS FROM THE GEYSERS GEOTHERMAL FIELD

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KEY WORDS:

The Geysers, laboratory measurements, physical properties, velocities, permeability, partial saturation, reservoir properties

PROJECT OBJECTIVES

A wide variety of laboratory measurements are being performed in order to aid in the assessment and prediction of reservoir performance at The Geysers Geothermal Field. The measurements address issues concerning the coupling between water storage in the matrix and physical properties of rocks within the reservoir. The main focus of the project is to understand the relationship between pore structure, degree of saturation, and physical properties such as seismic velocities which are used for constraining reservoir simulations and/or geophysical exploration and monitoring.

Technical Objectives

- Measure ultrasonic velocities, quasi-static elastic deformation, permeability, porosity, and electrical resistivity of reservoir matrix material.
- Develop and constrain models relating measured transport and mechanical properties to the underlying pore structure of the matrix material.

Expected Outcomes

- Develop the necessary physical understanding, specific to The Geysers rocks, of the effect of saturation on mechanical and transport properties, which is required to extrapolate laboratory measurements to field conditions.
- Critically examine field-seismic observations and interpretations of reservoir properties in the context of the laboratory measurements.

PROJECT BACKGROUND AND STATUS

Field seismic experiments by O'Connell and Johnson, [1991] and Zucca et al., [1994] have interpreted anomalies to reflect variations in the degree of fluid saturation associated with the water/steam transition. However, these interpretations have been based on laboratory data on other rock-types and field data from other geologic settings. The purpose of this project is to provide direct measurements on reservoir material from The Geysers to assess and constrain these interpretations.

Over the last 18 months, a suite of measurements have been conducted on Geysers rocks recovered from reservoir depths in NEGU-17. The tests have been focused on understanding the physical properties of the matrix and their relationship to the degree of saturation. Ultrasonic velocity data has demonstrated that the V_p/V_s signature of saturation is quantitatively similar to anomalies observed in field data. However, the interpretation is complicated by a number of factors concerning the extrapolation of laboratory scale velocity measurements to field scales, since velocities at the field scale are considerably lower than the matrix velocities measured in the laboratory.

In this work, we are emphasizing measurements required to enable the extrapolation of laboratory data to field scales. Models are being developed to better understand the importance of matrix properties in influencing field scale observations. In order to have confidence in extrapolating from laboratory measurements to field observations, a physical understanding of influence of partial saturation on matrix properties is required.

APPROACH

A variety of measurements are being conducted on matrix material recovered from NEGU-17. Samples received from The Geysers Coring Project in SB-15 will be tested when available. The available material has been selected to sample the various lithologies as well as to examine variations within the dominant metagraywacke material. The experiments are designed to characterize the variations in mechanical and transport properties within the matrix, identify physical phenomena controlling rock properties, and to constrain models of field-scale processes.

The measurements include bulk and grain density, porosity, ultrasonic velocities, permeability, specific storage, electrical resistivity, and quasi-static elastic moduli. The measurements are being used to develop and test models which integrate pore structure with mechanical and transport properties. The measurement program has been designed to develop the necessary physical understanding of the influence of partial saturation on mechanical and transport properties, specific to The Geysers matrix material. It is through this physical understanding of the rock properties that we can then develop and constrain models to predict field scale phenomena and interpret field scale observations.

RESEARCH RESULTS

Seismic Properties

A variety of ultrasonic pulse propagation experiments have been conducted on samples of core from reservoir depths in NEGU-17. Metagraywackes, metasilstones, and metashales have been tested. The results indicate that the matrix is very tight, yielding high velocities and low acoustic attenuation. The lack of a strong pressure effect on the velocities even at low effective confining pressures indicates that the matrix porosity is confined to relatively stiff pores and/or mineralized grain contacts and micro-fractures.

The dominant effect of saturation on the compressional velocities is quantitatively consistent with Biot-Gassmann poroelastic theory. However, many samples exhibit a shear velocity reduction with saturation which is far in excess of what can be explained by the theory. An example of the effect of saturation on ultrasonic velocities is shown in Figure 1. In the example, we see that saturation causes a moderate increase in compressional velocity and a slight decrease in shear velocity. The decrease in shear velocity with saturation commonly appears to increase with increasing effective confining pressure.

This behavior, which is rather uncommon in low porosity rocks, is thought to reflect the presence of chemo-mechanical weakening of the matrix material. In the simplest case, the shear weakening effect can be modeled by assuming that the weakening inhibits the increase in shear modulus with increasing effective stress. As seen in Figure 1, both the reduction in shear velocity as well as second order effects of saturation on compressional velocities can be modeled by modifying Biot-Gassmann theory to include a chemo-mechanical weakening of the shear modulus. The modified Biot-Gassman theory provides us with a theoretical foundation upon which to interpret field observations, develop models of wave propagation in partially saturated rock, and identify physical processes and phenomena which may be important to reservoir performance.

Interpretation of Field-Scale Anomalies

Field seismic imaging experiments at The Geysers have indicated velocity, V_p/V_s , and attenuation anomalies associated with the dry steam reservoir [O'Connell and Johnson, 1991; Zucca et al., 1994]. The observed anomalies have been interpreted as reflecting changes in the degree of saturation associated with the water/steam transition. It has been observed that the measured difference between V_p/V_s for dry and saturated matrix is quantitatively consistent with the observed anomaly reported by O'Connell and Johnson [1991]. However, the correlation is not straightforward since the average field scale velocities are significantly lower than the velocities measured in the laboratory on the reservoir matrix material [Boitnott, 1994].

The discrepancy between field and laboratory velocities is certainly not surprising, and is commonly attributed to the presence of joints and other large scale features not sampled in the laboratory specimens. In order to assess whether the matrix effects measured in the laboratory may be the cause of the field scale anomalies, a model has been developed to incorporate the measured matrix properties with the expected properties of joints in order to predict the field scale properties. As a starting point, we would like to see if, by adding sufficient number of joints to lower the lab velocities to field values, we can still preserve significant V_p/V_s signature of the matrix. An example of such an exercise using the field data of O'Connell and Johnson [1991] is shown in Figure 2. The velocities at depth are assumed to represent the matrix values, being consistent with the laboratory values. The modified Biot-Gassmann theory is used, along with the laboratory values of velocities versus pressure, to constrain realistic dry and saturated matrix velocities. The shear velocity versus depth from O'Connell and Johnson [1991] is then combined with matrix values and the contribution to the rock mass compliance attributed to the presence of joints is determined. Based on theoretical considerations as well as some limited laboratory data, the joint properties derived from the shear velocity data are then used to predict the effect of joints on the compressional velocities. Using this model, along with realistic dry and saturated values for matrix velocities, we can thus predict the sensitivity of the V_p/V_s signature in the fractured rock mass to the V_p/V_s signature of the matrix. These preliminary calculations illustrate that it is conceivable that the observed field scale V_p/V_s anomalies may result from matrix effects, while the overall velocity versus pressure (and for that matter, spatial variations in velocity) are most likely controlled by fracture properties [Boitnott, 1995].

Permeability

In addition to the velocity work, permeability measurements as a function of hydrostatic confining pressure have been performed on five NEGU-17 cores and are summarized in Figure 3. Four of the NEGU-17 samples were from the same piece of core and consisted of a fairly homogeneous, medium grained metagraywacke. Two of these specimens (2y1 and 2y2) were cored perpendicular to the

NEGU-17 core axis, while the others were cored parallel to the core axis. Sample 2u was taken from a highly altered portion of the core, having a porosity near 9 percent (mostly due to macro-pores associated with veins). Sample 2x was taken from a relatively unaltered portion of the core specimen. Sample 12u was taken from a separate specimen that consisted of a finer grained metagraywacke with a porosity of 2.0 percent.

As can be seen in Figure 3, two of the medium grained metagraywackes exhibited permeabilities from 20 nD to 3 nD over a range in effective pressures of 7 to 55 MPa. These two samples had porosities near 1.8 percent. Sample 2x, cored parallel to the NEGU-17 axis, exhibits a lower permeability (by about a factor of three) consistent with its lower porosity (1.0 percent). Interestingly, there is little variation ultrasonic velocities in these three samples, consistent with the additional porosity being in the form of mega-pores associated with variations in degree of alteration and veining between the three samples. It should also be noted that samples 2y1, 2y2, and 2u do not exhibit significant frame weakening with saturation, while samples 2x and 12u do. Thus it appears likely that petrographic and petrologic changes during the alteration and veining may result in increased permeabilities and porosities while decreasing the degree of frame weakening of the shear modulus. There is also the suggestion that the alteration has the tendency to increase ultrasonic velocities, as illustrated by the fact that 2u exhibits the highest velocities despite its high porosity. These trends and their relationship to petrologic features, are being explored with more measurements. The finer grained metagraywacke (12u) exhibited a much lower permeability in comparison with the coarser grained samples. The permeability decreased from 0.8 nD at 7 MPa to 0.5 nD at 30 MPa. It is interesting to note the low permeability despite lower ultrasonic velocities and relatively high porosity (1.5%).

Other Issues

In addition to the work summarized above, experiments studying the effect of partial saturation on ultrasonic velocities and electrical resistivity are currently underway. Velocity data are being combined with permeability and resistivity data to constrain and develop pore structure models for the matrix material.

FUTURE PLANS

Measurements of electrical resistivity are underway to provide further constraints on pore structure and to help interpret the dependence of mechanical properties on partial saturation. Ultrasonic velocity work aimed at characterizing the effect of partial saturation is also being pursued. Similar measurements will be performed on cores the SB-15 when available.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Idaho National Engineering Laboratory Lawrence Livermore National Laboratory	Interpretation and design of field seismic experiments

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Figure 1. Dry (open circles) and saturated (closed circles) compressional velocities, shear velocities, and V_p/V_s ratios as a function of continuing pressure for a fine grained metagreywacke recovered from reservoir depths in NEGU-17. The measurements compare very favorably with a modified Biot-Gassman model in which the shear modulus is weakened by saturation. Model predictions of saturated values based on the dry measurements are shown with the gray shaded lines in each figure.

Figure 2. Comparison of predicted dry and saturated compressional velocities with inferred values from the VSP inversion of O'Connell and Johnson [1991]. The model uses the difference between the matrix shear velocities (as measured in the laboratory) and the field measurements of V_s from O'Connell and Johnson [1991] to infer shear modulus reduction due to the presence of joints and other large scale compliant features. The effect of the fractures on compressional velocities follow from simple theoretical arguments. The field-scale compressional velocities are then predicted based on matrix properties. The predictions are consistent with the reduced compressional velocity at effective pressures near 30 MPa (i.e. at a depth ≈ 1.8 Km) which has been interpreted as reflecting an undersaturated portion of the reservoir.

Figure 3. Permeability versus effective confining pressure for four samples of metagreywacke from NEGU-17.

INVESTIGATION OF EFFECTS OF ADSORPTION ON INJECTION AND PRODUCTION FROM VAPOR-DOMINATED GEOTHERMAL RESERVOIRS

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KEY WORDS

Reservoir performance, injection, adsorption, The Geysers

PROJECT OBJECTIVE

This research program includes several parallel lines of study to produce fundamental scientific information and practical reservoir engineering methods concerning the adsorption phenomenon in vapor-dominated reservoirs and its consequences for the production and injection characteristics of The Geysers steam reservoir. This analysis will allow improved interpretation of field performance data and aid optimization of future production and reinjection operations. In particular, it has been found that adsorption has a profound effect on reinjected water, since any rise in reservoir pressure can cause the injected water to readsorb thereby reducing its effectiveness in increasing steam production.

PROJECT BACKGROUND AND STATUS

A large number of measurements of Geysers reservoir materials have provided an understanding of the overall magnitude of adsorption and the way that adsorption depends on temperature. A typical adsorption isotherm from The Geysers reservoir is shown in Figure 1. A series of experiments is currently underway to investigate the distribution of adsorption character in The Geysers. Preliminary results suggest that adsorption may be more prominent in the southern area.

Experiments in the past year have examined the effects of noncondensable gases on adsorption in Geysers rocks. The results suggested that noncondensable gases have little or no effect on adsorption at The Geysers. However, the experiments are currently being repeated using a different procedure to confirm this result.

APPROACH

This project concerns the effects of adsorption (and subsequent desorption) of water in vapor-dominated geothermal reservoirs. Theoretical work results are being compared with experiments run in the laboratory. The objective is to use the understanding of the fundamental mechanisms to construct mathematical models to be used for analysis of field performance and design of reinjection strategies.

Fundamental studies concern equilibrium and transient flow measurements of adsorption on rock samples from different parts of various geothermal fields. Adsorption experiments are small-scale restored-state physical models of The Geysers, and desorption experiments represent production performance. Reinjection studies involve both processes. We are also investigating the inclusion of adsorption-desorption into numerical models used for reservoir engineering performance matching and forecasting.

Three different types of experiments are being conducted. The first uses equilibrium measurements of adsorption and desorption in geothermal reservoir rocks. The second uses an indirect method in which the pressure transient response of a core of reservoir material is used to infer the adsorption characteristics. The third set of experiments use a computer-aided X-ray tomography method to determine the disposition of the fluids inside the reservoir rocks.

RESEARCH RESULTS

The work over the past year has yielded several very important results:

1. Experimental measurements on Geysers reservoir material have shown the relationships between different locations, depths and rock types from the point of view of their adsorption characteristics.
2. The presence of carbon dioxide does not appear to affect the adsorption of steam, even at higher concentrations than is likely in actual geothermal reservoirs.
3. The effects of adsorption on injection and on tracer transport have been analyzed, using analytical and numerical modeling.
4. Studies have revealed that a large portion of reinjected water may be readsorbed at The Geysers, leading to a reduction in effectiveness of the injection strategy.

FUTURE PLANS

We will repeat the study of the effect of noncondensable gases on adsorption, using a different experimental procedure, and will also extend the study on the adsorption characteristics at The Geysers as a function of depth, location and rock type. We are currently starting a new study involving the examination the fracture distributions and fluid saturations in geothermal reservoir materials using a high resolution X-ray CT scanner.

A new study will investigate the optimization of injection strategy, considering the effect of the readsorption of the reinjected water.

The Stanford Geothermal Program has added two post-doctoral researchers to augment the number of people working in the program, and the Stanford Geothermal Program currently has an active "critical mass" of research assistants.

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Figure 1. Water adsorption/desorption isotherms for Geysers NEGU-17 Graywacke at 120°C.

EFFECTS OF ADSORPTION AND CAPILLARY CONDENSATION ON EXPLOITATION OF GEOTHERMAL RESERVOIRS

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KEY WORDS:

Adsorption, vapor-pressure lowering, capillary condensation

PROJECT OBJECTIVES

As reservoir models become increasingly more sophisticated, we are capable of simulating additional and more complex physics. It is of paramount importance, however, to determine which physical processes are required to accurately model a geothermal reservoir and which can be neglected. The goal of this project is to evaluate the relative importance of adsorption and capillary condensation in geothermal systems.

Specific objectives of this project are to incorporate in the numerical simulator, TETRAD, general expressions for adsorption and capillary condensation. Despite difficulties in separating these mass storage mechanisms experimentally, they are readily separated numerically. Specific objectives are discussed below.

Technical Objectives

- Generalize the vapor-pressure lowering algorithm available in TETRAD to allow for its broader use.
- Add an adsorption algorithm to TETRAD.
- Determine relative importance of adsorption vs. capillary condensation.

Expected Outcomes

- By comparing simulation results with and without adsorption and/or capillary condensation, the dominant mechanism can be determined. This will enable geothermal operators to include all relevant physics in simulations without adding any unnecessary complicating factors. A better understanding of the relative contribution of these two can also lead to a better understanding of reservoir response to injection and an improved use of available injectate.

PROJECT BACKGROUND AND STATUS

It has been apparent from material balance considerations since the 1970s that, although only water vapor is produced from The Geysers wells, a substantial portion of the mass must be stored in a condensed

phase. Various theories to explain the storage mechanism abound, and range from a dispersed liquid phase (White et al., 1971) to an adsorbed phase held in micropores throughout the reservoir (Hsieh and Ramey, 1983). It is thus of paramount importance to determine what effect adsorption/desorption and capillary condensation might have on storage and exploitation of geothermal resources.

Some preliminary studies have been made which investigate the relative importance of adsorption and capillary condensation. However, during the course of this work, several inconsistencies were identified in capillary condensation theories. For example, capillary condensation is an exothermic reaction; however, mass condensed appears to increase with increasing temperature. A theoretical analysis has been undertaken in order to develop a unified explanation for the observed adsorption/condensation behavior.

APPROACH

The approach taken in this study was to implement a general expression for vapor-pressure lowering, as presented by Shook (1993), and an expression for adsorption (Shook, 1994) in TETRAD. Several simulation studies were then run, with the intention of evaluating the relative importance of these two storage mechanisms. A theoretical analysis has also been undertaken to develop a unified theory for phase equilibria between adsorbed, liquid, and vapor phases.

RESEARCH RESULTS

Vapor-pressure lowering was implemented in a general release of TETRAD this year, as formulated by Shook (1993). A flexible constitutive equation for adsorption was also implemented this year. The conservation equations were modified to allow for accumulation of the chemical due to adsorption. The adsorption term, V_j , is usually written in terms of mass of component adsorbed per unit mass rock. The form of the constitutive equation is such that a variety of different isotherms can be modeled:

$$V_j = \frac{W_j k_1 \beta^{k_2}}{1 + k_3 \beta}$$

In the above equation, the k_i are constants that can be selected to obtain the correct isotherm shape, W_j is the mole fraction of component j in the adsorbing phase, and β is the relative vapor pressure (P/P_{sat}). The relationship between adsorption and vapor-pressure lowering has been identified in the Stanford experiments (e.g., Shang et al., 1994). Similar adsorption isotherms were used throughout this study.

Preliminary simulation studies have been carried out to examine the relative importance of adsorption and capillary condensation, including transient test analyses and injection studies. Results of these studies are given in Shook (1994). For the cases using the measured adsorption isotherm, it appears that capillary condensation is the dominant mass storage mechanism relative to adsorption. Cases run with vapor-pressure lowering "on" but without adsorption differed insignificantly from those for which both mechanisms were used. Other simulations used an "enhanced" adsorption isotherm, in which the level of adsorption was increased one order of magnitude. In those cases, adsorption caused a significant delay in tracer breakthrough. It is clear from these results that an accurate measure of adsorption is required in order to determine the relative contribution to mass storage in field studies.

FUTURE PLANS

During the course of the studies summarized here, several inconsistencies were identified with current adsorption/condensation theories. For example, capillary condensation is an exothermic reaction (from Kelvin's equation on vapor-pressure lowering), and increasing temperature should result in decreased condensation at a given relative pressure, β . This is not the case in the experimental results to date. It is thought that a rigorous thermodynamic approach is required to develop an internally consistent model for equilibria between adsorbed mass, a capillary condensed phase, liquid, and vapor. This portion of the project is ongoing.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

We continue to discuss the issues of adsorption, capillary condensation, and vapor-pressure lowering with interested parties, including Stanford and Oak Ridge National Lab experimentalists, and have also presented these results in professional meetings. The distinction between adsorption and capillary condensation may be an important issue for The Geysers injection pipeline, and discussions have also been held with various operators.

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HISTORICAL INJECTION IN THE GEYSERS PG&E UNIT 13 AREA

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KEY WORDS:

The Geysers, injection, reservoir simulation, PG&E Unit 13

PROJECT OBJECTIVE

One of the fundamental operational problems at The Geysers is that the reservoir is undergoing continual depletion of the working fluid (water) in the heat engine (reservoir). To prolong the economic life of the reservoir, it is necessary to make the best use of the limited amount of water available for injection. The objective of this study is to conduct a numerical analysis of historical injection response in an area of The Geysers reservoir to assist Geysers' operators in developing optimal injection strategies.

Technical Objectives

- Evaluate the historical injection response and develop explanations for the observed response
- Evaluate general guidelines for the selection and operation of future injection areas at The Geysers
- Explore alternative injection strategies such as sensitivity to injection rate, distributed injection, and optimum reservoir conditions.

Expected Outcomes

- This research is expected to provide reservoir engineering guidelines for optimizing injection strategies that will lead to the timely and rapid conversion of the injected water into steam by heat mining and the return of this steam to nearby production wells.

PROJECT BACKGROUND AND STATUS

Unit 13 is in the southeast area of The Geysers. The study includes the history from early development at initial reservoir conditions through depletion. The Unit is near Northern California Power Agency well C-11 and Unocal well D&V-11, wells which have been involved in cooperative Department of Energy (DOE) - industry injection tests, and is in the area of The Geysers that will receive injectate from the Lake County effluent pipeline. The study area incorporates approximately 2 square miles, with over 20 production wells and 2 injection wells. Attention was paid to the mapped geologic structure and geometry of the reservoir. Preliminary results of the study were presented at the Stanford Geothermal Engineering Workshop in 1992, and the final project report is in preparation.

APPROACH

One advantage of the Unit 13 area is that a fairly complete isotopic data set exists for the production wells. Deuterium and oxygen-18 were monitored in the produced steam for over eleven years, providing an important data set with which to constrain injection modeling efforts and correlate injection derived steam recovery. The study area has been well documented in the literature, providing a ready source of information to use and to compare to the modeling results. The numerical model was history-matched with the well-by-well production rates and pressures, and a qualitative match was made to the isotopic data.

RESEARCH RESULTS

The initial model incorporated all relevant data about the study area and placed all study wells on a rate constraint to match the historical production and injection masses. A three-component system (original reservoir fluid and two injected waters) was used to track the movement of the in-situ steam and the water injected into each of two injection wells. This allowed detailed tracking and determination of injection-derived steam (IDS) due to each well, allowing the quantitative calculation of historical injection efficiency.

This initial study demonstrated that injection efficiency is strongly influenced by reservoir shape and structure even when capillarity is considered. It was clearly shown that injection into a vapor-dominated reservoir results in fluid migrating downward to the bottom of the reservoir. As noted above, two injection wells were utilized in the study area. The first well, McKinley 5, started injection at the onset of the project. Five years later, injection was split with a second well, Thorne 7. Well Thorne 7 was located down structure from McKinley 5. The simulation results clearly demonstrated that by the time Thorne 7 started injection, injectate from McKinley 5 had migrated to the area of Thorne 7, quenching this area and greatly diminishing the return of IDS from this location. While both wells had approximately the same cumulative mass injection, simulated recovery of IDS from McKinley 5 was approximately three to four times that from Thorne 7. This implies that the selection of injection locations should consider the inferred geometry of the bottom of the reservoir or low permeability areas.

FUTURE PLANS

The project is mature and future plans are to complete the final report in collaboration with Calpine Corporation.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Interested companies and organizations are Pacific Gas & Electric, Calpine Corporation, Northern California Power Agency, Unocal, Central California Power Agency No. 1, and other operators at The Geysers. The companies will use this study to assist them in planning injection in their portion of The Geysers.

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THE GEYSERS LONG-TERM INJECTION TEST

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KEY WORDS:

Injection, industry cooperation, cooperative research, cost-shared research

PROJECT OBJECTIVES

This is a cost-shared project of the Department of Energy (DOE) and the Geothermal Technology Organization (GTO), whose industry partners are Calpine, Northern California Power Agency (NCPA), Pacific Gas and Electric Company (PG&E) and Unocal. The objective of this project is to increase the understanding of injection within known productive intervals in a depleted zone of a vapor-dominated geothermal reservoir and to help explain anomalous reservoir responses observed during an earlier tracer test in the southeast Geysers.

Technical Objectives

- Perform a long-term injection test in the southeast Geysers.
- Evaluate tracers developed for use in vapor-dominated systems.
- Calibrate tracers tested earlier at The Geysers.

Expected Outcomes

- Verify the value of long-term injection.
- Evaluate and calibrate tracers in a vapor-dominated environment.

PROJECT BACKGROUND AND STATUS

In 1989, the GTO and DOE performed a cooperative study of injection at NCPA well C-11 in the southeast Geysers. Steam condensate injection in the productive interval of the well increased steam production and reservoir pressure in nearby parts of NCPA and Calpine leases. The effect was much less pronounced at comparable distances in the adjoining Unocal leasehold around PG&E's Unit 18 powerplant. Identifying the key parameters that caused this difference may have important effects in reducing the risk and expense of expanding injection into more areas of The Geysers, and to sources of water other than power plant effluent.

During the 1989 study, two tracers were simultaneously injected into well C-11. The purpose of the tracer injection was to determine fluid movement after injection and to evaluate the suitability of compounds identified as promising geothermal vapor-phase tracers by DOE-sponsored research at the

University of Utah Research Institute. Dissolved salts and tritiated water have been the traditional tracers at The Geysers. Additional tracer materials that offer greater flexibility and diagnostic capabilities were and are still needed.

Increased monitoring of the production rates and chemistry of wells in the vicinity of the injection well, well DV-6 at Unit 18, began in December 1993. Injection began in January 1994, and a suite of tracers was injected in mid-April.

APPROACH

Baseline data on areal seismicity, along with steam production rate, geochemistry, pressure, and temperature from wells surrounding the injection well, was recorded before the initiation of injection was begun. In addition, pressure-temperature-spinner (PTS) surveys were run in several of the surrounding wells expected to be most influenced by the injection. Once injection was begun in DV-6, increased monitoring of the produced steam's geochemistry and production characteristics occurred, and PTS surveys were rerun. Several months after injection began, a suite of tracers was injected into DV-6, and an extensive sampling program was carried out to determine the movement of the injected fluid and tracers. Injection will continue through 1996, and a final report interpreting the test results will be published.

RESEARCH RESULTS

Injection into Unocal well DV-6 at rates of 400 to 880 gpm have resulted in steam production increases primarily on the Unocal and NCPA leases. Calpine wells showed a combined 10 kph decrease in steam production, but this was later attributed to production interference and water injection in nearby Calpine wells. Later tracer data indicated a minimal influence of DV-11 water injection on the Calpine wells. Considering the Unocal and NCPA gains in steam production, 81 kph and 42 kph respectively, about 41% of the injectate is being recovered.

Responses in the steam geochemistry suggest that a range of processes is occurring, from total flashing of injected condensate to elimination of production interference as a result of the injection.

SF₆, R-13, and tritium were used to compare the behavior of multiple tracers in a geothermal environment. The tracer returns produced by the DV-11 test displayed a broad range of concentrations, confirming geochemical responses by implying that immediate flashing of condensate was occurring and that wells were being supplied by this source. Results from the tracer test continue to be analyzed in an effort to correlate between increased steam productivity, changes in gas chemistry, and the responses of the different tracers.

Preliminary interpretations of the injection and tracer test were reported at the 1994 annual meeting of the Geothermal Resources Council.

FUTURE PLANS

Injection and data collection will continue through 1996 and a final report interpreting the test results will be published in 1997.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This test is being cost-shared by DOE and four members of the GTO: Calpine, NCPA, PG&E, and Unocal. The industrial partners are conducting the test and sharing the test results among themselves and DOE researchers. Hence, the technology is being transferred to the participating companies in near real-time and to the rest of the geothermal community through presentations at about 6-month intervals.

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NUMERICAL SIMULATION OF WATER INJECTION INTO VAPOR-DOMINATED RESERVOIRS

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KEY WORDS

Injection, Geysers steam field, reservoir heterogeneity, numerical modeling

PROJECT OBJECTIVES

Vapor-dominated reservoirs are water-short systems. Fluid reserves at The Geysers are being depleted while heat reserves in place are still enormous. Water injection is the chief means by which energy recovery can be sustained and enhanced. The objective of this research is to develop a better understanding of fluid flow and heat transfer processes during water injection, and to provide robust and accurate engineering tools for the design of injection systems.

Technical Objectives

- Understand and quantify the role of reservoir heterogeneity in injection
- Determine vapor adsorption and vapor pressure lowering effects
- Develop efficient numerical capabilities for simulating injection

Expected Outcomes

- Improve descriptions and designs of fluid injection at The Geysers.
- Develop more powerful numerical simulation capabilities.
- Enhance geothermal energy production rates and reservoir life.

PROJECT BACKGROUND AND STATUS

We have developed a general-purpose geothermal reservoir simulation program TOUGH2 (Pruess, 1991; available from: Energy Science and Technology Software Center, P.O. Box 1020, Oak Ridge, TN 37831). This simulator is capable of modeling most of the reservoir processes during injection, including appearance and disappearance of liquid and vapor phases, boiling and condensation, multiphase flow due to pressure, gravity, and capillary forces, vapor adsorption with vapor pressure lowering, heat conduction, and heat exchange between rocks and fluids. Ongoing research is directed towards enhancing simulation capabilities, by: (1) improved description of physical processes during injection, and (2) improved numerical techniques for efficient solution of large problems.

APPROACH

In collaboration with Italian researchers (Battistelli et al., 1995a, b), and utilizing results obtained in the Department of Energy (DOE) high-level nuclear waste program (Pruess and Antunez, 1995), improved descriptions of physical processes and parameters for fluid flow and heat transfer are being developed (Pruess, 1994c, 1995). Latest advances in computational linear algebra are being introduced in our simulation codes (Moriadis et al., 1994; Moridis, 1995).

RESEARCH RESULTS

1. Multi-scale heterogeneity present in fractured-porous reservoirs such as The Geysers gives rise to a spreading of descending injection plumes which can be approximately described by analogy to Fickian diffusion (Pruess, 1994a, b, c, d; Pruess and Antunez, 1995).
2. Vapor adsorption, capillarity, and associated vapor pressure lowering (VPL) effects can strongly impact reservoir response to injection. VPL effects tend to diminish and delay the enhancement of energy recovery from injection (Pruess, 1995).
3. A preconditioned conjugate gradient module "T2CG1" was completed and transferred to DOE's Energy Science and Technology Software Center, where it is now available to the public as part of the TOUGH2 simulator. This module makes possible the efficient simulation of large 3-D problems with of the order of 10,000 grid blocks or more (Moriadis et al., 1994; Moridis, 1995).

FUTURE PLANS

We plan to continue improvements in numerical simulation capabilities for injection, and applications to field problems.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The TOUGH and TOUGH2 reservoir simulation programs are currently being used by more than 100 organizations in 15 countries. The TOUGH Workshop '95 will be held at LBL from March 20-22, 1995; 55 technical papers have been submitted for presentation at the workshop.

We are continuing to present our research results at conferences and in technical journals.

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NUMERICAL STUDIES OF THE FORMATION OF A VAPOR-DOMINATED RESERVOIR WITH A HIGH-TEMPERATURE COMPONENT

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KEY WORDS:

Vapor-dominated, high-temperature reservoir, The Geysers, vapor-pressure lowering

PROJECT OBJECTIVES

The goal of this project was to develop a numerical model of a high-temperature reservoir (HTR) similar to that observed in Northwest Geysers. A reservoir model that accurately reproduces HTR characteristics allows the user to estimate reservoir properties of concern, e.g., initial liquid saturation and long-term stability of the feature (prior to exploitation). Ultimately, this model is useful in evaluating the long-term behavior and potential for injection into and extraction from the HTR.

Specific objectives of this project were to integrate reservoir observations and analyses into a consistent reservoir description to evaluate possible evolutionary pathways for HTR formation. These are listed below.

Technical Objectives

- Develop a conceptual model description of an HTR using observed data in Northwest Geysers.
- Using the conceptual model described above, numerically simulate a venting episode in a hot, liquid-filled geothermal resource. Compare reservoir response to venting and long-term behavior of the model to that observed in Northwest Geysers.
- Perform sensitivity studies to investigate possible responses to variations in reservoir and vent parameters (e.g., salt content of reservoir fluid, lithologic variations, vent rate and fraction of mass vented).

Expected Outcomes

- Favorable comparisons between observed properties in Northwest Geysers with simulated HTR properties would provide Geysers operators the ability to estimate pre-exploitation liquid saturations and temperature distributions of the HTR. The model could also be used to determine the relative utility of injection into the HTR rather than into the normal vapor-dominated reservoir.

PROJECT BACKGROUND AND STATUS

It is well established that a high-temperature anomaly underlies portions of The Geysers geothermal field in Northern California. Temperatures above that thermal anomaly are about 240°C, with very small temperature gradients consistent with vapor-dominated conditions. Just above the high-temperature feature, the temperature gradient increases to nearly 0.5°C/m, and temperatures in excess of 345°C have been observed within the anomaly. This feature has come to be known as the 'High-Temperature Reservoir' in the literature, although no barrier separating it from the 'normal' overlying vapor-dominated reservoir has been identified. Despite nearly a decade of additional field observations and production data, little more is currently known regarding HTR formation and behavior than was known by the original investigators. For example, possible causes for its formation and initial liquid saturation (and therefore its probable behavior under exploitation) remain unknown.

This project addresses the formation and native-state behavior of a HTR through a numerical analysis of a conceptual model. The model developed represents a possible genesis of The Geysers field, wherein a liquid-filled reservoir is catastrophically vented and allowed to re-equilibrate. Such a model has been used in a variety of studies of vapor-dominated reservoir formation (e.g., Pruess, 1985), as well as several studies specific to HTR formation (Shook, 1993; 1994; 1995).

APPROACH

The approach taken in this project was to accumulate what observations are available for the "High-Temperature Reservoir" (and adjacent "normal" reservoir) in Northwest Geysers, and to develop a conceptual reservoir description of that portion of The Geysers. The reservoir description includes petrophysical properties and estimated fluid compositions. A numerical model was developed from field data to evaluate possible HTR formation. Results of the numerical simulations were compared with field observations (e.g., non-uniform surface of the HTR, large temperature gradients within the HTR, vapor-dominated reservoir in the majority of the reservoir). Finally, sensitivity studies were conducted that evaluate possible effects of variations in the conceptual model parameters.

RESEARCH RESULTS

The conceptual model that was developed was based on the following field observations:

Drenick (1986) observed that pressures are continuous between the normal reservoir and the HTR, suggesting that the HTR is in hydraulic communication with the balance of the reservoir. No barriers to vertical flow have been identified that would segregate the HTR. It was also noted that the depth to the HTR is quite variable.

Sternfeld (1989) noted a facies change at depth in Northwest Geysers, with finer grained turbidites and thicker sections of argillite to the northwest. Sternfeld interpreted this as a change of depositional environments, moving from mid-fan to distal-fan turbidite sequences with the accompanying increase in shale content and reduction in porosity and permeability. Sternfeld (1989) showed a schematic of the facies change; the transition occurred at a variable depth in that schematic.

Fluid inclusion analyses indicate that the reservoir fluid was a brine. Moore (1992) indicated that fluid inclusions indicate large differences in salinities between the normal reservoir and the HTR. Inclusion salinities in excess of 40 wt% were observed in the HTR, whereas inclusions in the normal reservoir

ranged from 0-10 wt%. Moore (1992) suggested that the large salinity contrasts were due to reduced permeability in the HTR, and subsequent concentrating of salt in the HTR upon venting.

Using pure water as the reservoir fluid in a homogeneous reservoir, Pruess (1985) showed that a hot, liquid-filled reservoir would flip to a vapor-dominated reservoir when vented catastrophically. The vent rate suggested in that work was 40 kg/s/m².

From these various studies and field observations, a numerical model was developed. A schematic of the domain is given in Figure 1. Two distinct lithologies were used, with Lithology 1 representing the mid-fan deposits and Lithology 2 the distal-fan sequences. Differences in petrophysical properties for the two are given in Figure 1. All other properties were extracted from the literature and are representative of Geysers rock. The reservoir fluid is a 3.2 wt% sodium chloride mixture. A uniform heat flux is added to the bottom of the reservoir, and heat is lost via conduction to the cap rock. From one corner of the reservoir, a vent is opened, and 60% of the mass originally in place is removed over a period of 60 years at a maximum extraction rate of 31 kg/s/m². The reservoir is then isolated and allowed to equilibrate. Additional details of the model are given by Shook (1995).

Thermodynamic conditions in the fracture domain 10,000 years after the venting exhibit several features similar to those observed in the Northwest Geysers. First, a vapor-dominated pressure regime is noted throughout the domain. The temperature profile shows nearly isothermal temperatures in a majority of the reservoir. This is typical of a vapor-dominated geothermal reservoir, and the values are similar to those observed in The Geysers. In the lower southwest portion of the field, however, relatively large temperature gradients are observed, and temperatures in excess of 350°C are seen at depth. This HTR has a surface depth that varies significantly, also as observed in Northwest Geysers.

The low liquid saturations observed in the fractures are also indicative of a vapor-dominated reservoir. Liquid saturations in the matrix are somewhat larger than shown for the fractures, averaging about 45%. Salt mole fractions are also in agreement with fluid inclusion observations, with salinities very low (<0.01) in the normal reservoir, increasing to about its maximum solubility in the HTR.

In summary, conditions in the simulated reservoir agree quite favorably with observations in Northwest Geysers, including pressure continuity, vapor-dominated pressure and temperature gradients in most of the reservoir, large salinity contrasts between the normal reservoir and the HTR, and a variable HTR surface. Sensitivity studies indicate that the formation of such an HTR is not limited to the specific conditions used in this conceptual model. Three properties appear to be crucial in HTR development: petrophysical non-uniformity at depth, rapid venting of a significant portion of the mass in place, and a saline reservoir fluid. Each property is supported by field observations.

FUTURE PLANS

A manuscript summarizing this project was submitted to Geothermics, and has been accepted for publication. Upon review by the geothermal community, and pending further interest by geothermal operators, the conceptual model can be used to investigate possible HTR reaction to exploitation. This study can be used to evaluate possible injection strategies in Northwest Geysers by determining the possible benefits of injection into the HTR relative to the normal reservoir.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Several conference presentations have been made on this topic, and researchers from Oak Ridge National Laboratory, Lawrence Berkeley Laboratory, UNOCAL, and PG&E have all expressed interest in the work. Additional review comments are anticipated from the Geothermics paper and will be used to direct additional aspects of the study, including reinjection considerations.

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Figure 1. Schematic showing the reservoir model developed from field observations. Lithology 1 represents graywacke; Lithology 2, argillitic turbidites.

HEAT MINING TO EXTRACT HOT DRY ROCK (HDR) GEOTHERMAL ENERGY: TECHNICAL & SCIENTIFIC PROGRESS

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KEY WORDS

Fenton Hill, GEOCRACK, HDR, hot dry rock, logging, reservoir modeling, permeation water loss, reservoir engineering, reservoir lifetime, thermal drawdown

Technical Objectives

- Develop the technical information needed to permit an industrial consortium to construct and operate a facility to produce and market power from an HDR resource.

Expected Outcomes

- The HDR reservoir performance and modeling data are expected to provide the technical basis for an industry-led project to produce and market power from an HDR resource.
- Initiation of the industry-led project is expected in 1995, with operation of the HDR power production plant to begin within two to four years thereafter.

PROJECT BACKGROUND AND STATUS

The technology to extract energy at useful rates from the large, ubiquitous HDR resource has been under development for over 20 years. The concept upon which all modern HDR development work has been based originated in the early 1970's and was disclosed in a patent issued to the Los Alamos National Laboratory in 1974 (now expired). A small HDR reservoir was constructed at Fenton Hill, New Mexico, during 1974-1978 and operated intermittently during 1978-1980 to prove the scientific feasibility of extracting energy from HDR. During 1980-1986, a larger, deeper, and hotter HDR reservoir, the Phase II reservoir, was developed at Fenton Hill. Between 1987 and 1991, a surface plant, designed to power-industry standards and capable of extended operation, was constructed and mated to the Phase II HDR reservoir.

A long-term flow test (LTFT) of the Phase II HDR system was conducted during 1992-1993. Based on intensive discussions with the HDR Program Industrial Advisory Group, the LTFT was designed to simulate as closely as possible the conditions under which a commercial HDR power plant might operate. The test results were extremely promising. Circulation was maintained for a total of about eight months during a test period of slightly over a year. The bulk of the useful technical data was generated during two steady-state test phases lasting 112 and 55 days, respectively. Operating results during both of these steady-state phases were essentially the same. Hot water was produced from the reservoir at a

temperature in excess of 180°C (360°F) at 90-100 gpm, energy was extracted at a rate of approximately 4 thermal megawatts, and an on-line operational factor of greater than 95% was achieved.

No decline in the temperature of the produced fluid was observed over the course of the LTFT. In fact, tracer testing indicated that new hot rock was continuously being accessed by the circulating water. The rate of energy production consistently exceeded the rate of energy consumption for plant operation. Water losses declined throughout the test period, dropping to a level of only 7% of the injected volume by the end of the LTFT. The chemistry of the circulating fluid rapidly stabilized at low levels of dissolved solids and gases at a neutral pH, and there were no emissions to the atmosphere, except waste heat, during steady-state, closed-loop operations. Finally, the plant operated in an automated mode with manning only during daylight hours for most of the test period. Except for a major pump failure, for reasons fundamentally unrelated to HDR technology, there were no significant maintenance problems and no signs of scaling or corrosion of system components.

Complementary studies of the Fenton Hill HDR system coincident with and subsequent to the LTFT showed that it may be possible to significantly increase the energy output of HDR reservoirs by the application of engineered procedures to improve productivity. As discussed in more detail below, operational data also indicated that it should be feasible to create and operate larger HDR reservoirs without concomitant increases in pumping-power requirements.

Thermal energy, not electricity, was produced during the LTFT. In addition, the energy production rate was somewhat lower than that considered economically viable and the duration of the test was far too short to reflect the expected performance over the 20-30 year lifetime required of a commercial power facility. Even so, the LTFT did show that practical amounts of energy could be continuously extracted from an HDR resource by recirculating water through an engineered reservoir. The routine, steady-state operations and the high degree of plant automation accurately reflected the kind of energy production process that would be employed in a commercial HDR power-production facility. There were no indications of resource decline and no problems with the operation of the Fenton Hill plant at the time of the termination of the LTFT. The flow testing was suspended only because of a funding shortfall.

APPROACH

The LTFT effort of 1992-1993 demonstrated that HDR heat mining technology can produce clean energy in significant quantities over an extended time period. Results of the flow testing, although limited, were uniformly positive. These encouraging results provided the basis for the formulation of a solicitation for an industry-led, government co-funded project to establish a facility to produce and market energy derived from an HDR resource.

Upon termination of the LTFT, the Fenton Hill HDR test facility was placed on standby status due to funding limitations. The rental injection pump employed during the second steady-state phase of the LTFT was returned to its owner, and a reservoir pressurization regimen entailing periodic injection with a low-volume pump, but no production, was instituted. Throughout Fiscal Year 1994, activities at the Fenton Hill HDR test facility were directed primarily to maintaining the site and the underground reservoir at a level of readiness such that full-scale operations could be re-instituted within 3-6 months should an interest in additional flow testing develop. Field testing was limited to simple experiments that could be conducted within the framework of the standby plan.

HDR scientific and engineering support work was concentrated on documenting and understanding the results of the LTFT. In particular, the GEOCRACK reservoir simulation model, already under development by Kansas State University, was refined to improve its correlation to the experimental data from the LTFT and expanded by the addition of heat transfer effects to enhance its predictive capability.

RESEARCH RESULTS

Reservoir Modeling

The GEOCRACK finite element model of transient fluid flow/rock deformation within a jointed rock mass has been under development at Kansas State University for more than five years. In 1993, good agreement had been obtained between actual and modeled flow conditions at several different injection and production pressures. Refinement of GEOCRACK to increase its usefulness and believability was one of the major thrust areas of HDR technical and scientific work in 1994.

Correlation of GEOCRACK to Fenton Hill flow test data: During the early part of the year, random flow blockages were incorporated in the GEOCRACK rock block matrix as part of an ongoing effort to assure that the model simulates all aspects of reservoir performance as accurately as possible. These blockages distribute the flow through a broader region of the rock mass and result in what appear to be more realistic flow paths. Figure 1 shows the flow paths for a simulation based on a rock mesh with one-third of the flow pathways randomly blocked. Because the model assigns flow blockages randomly, a different result is obtained each time an analysis is run. The results invariably show major features and trends in important reservoir performance indicators, however, and the run-to-run variations can serve to highlight those aspects of reservoir performance that might be particularly sensitive to changes in reservoir flow paths.

As illustrated in Figure 2a, simulated tracer response curves derived from GEOCRACK now correlate with the general form of the observed response curves from several actual tracer experiments. Figure 2b shows that GEOCRACK now also simulates the transient pressure responses at the injection and production wellheads upon shut-in of the reservoir. The model curves shown in Figures 2a and 2b each represent the average results from three runs of GEOCRACK. Error bars on the figures indicate the maximum and minimum values from each set of model analyses. Obviously, model traces with more statistical significance could be generated by running a larger number of repeat analyses.

Over the past year, GEOCRACK, in tandem with the experimental results of earlier flow testing, provided the following additional information about the HDR reservoir at Fenton Hill and, by implication, HDR reservoirs in general:

Most of the reservoir impedance occurs near the production well (See Figure 2b). This finding implies that increasing the distance between the injection and production wells may give access to significantly more hot rock while inducing only a marginal increase in overall system impedance. It further suggests that reducing only the near-production-wellbore impedance may greatly increase reservoir productivity. However, in the latter case, the effect of reduced near-wellbore impedance may be to simply move this impedance barrier out to the boundaries of the increased-permeability zone.

There appears to be a limit to the maximum injection pressure that can be applied before the pressure relief provided by the production well is exceeded and reservoir growth ensues. A single

production well at each end of the reservoir may thus not provide the optimum pressure shielding of the boundaries. Several kick-off wellbores positioned across the width of the lowest-stress direction of the reservoir zone may be required to provide the most effective pressure relief and permit the use of the highest possible injection pressures without continual reservoir expansion.

Incorporation of thermal effects into GEOCRACK: After the modification of GEOCRACK to faithfully simulate the behavior of the Fenton Hill HDR reservoir under practical operating conditions, temperature calculations were coupled to the hydraulic and mechanical computations. The resulting, fully-coupled analysis includes shrinkage of the rock as it cools and temperature-dependent fluid viscosity. It provides the capability to analyze and predict HDR reservoir thermal performance under a variety of operating scenarios.

This enhanced version of GEOCRACK has been used to evaluate the conditions under which premature breakthrough of cold fluid to the production wellbore (short circuiting) can occur. Figure 3 shows a GEOCRACK analysis in which two different sets of boundary conditions were applied. In the first case (Figure 3a), only the injection pressure was limited. The model indicated that as the rock cooled, the joints opened and the flow increased to the point that short circuiting took place after 150 days. In the second simulation (Figure 3b), both the injection pressure and the flow rate were controlled. Heat could then be mined continuously without short circuiting. These calculations show the importance of matching the rate of heat removal by the circulating fluid to the rate at which heat can be conducted from the interior to the surface of the reservoir rock blocks.

As illustrated in Figure 4, GEOCRACK predicts that the flow rate through an HDR reservoir similar to that at Fenton Hill will decline initially, but will begin to increase after about a year of operation due to a cooling-induced decrease in the flow impedance near the injection wellbore. This increase will continue indefinitely if no measures are taken to limit the flow rate. Short circuiting will then occur well before the full thermal potential of the reservoir has been tapped. Sound reservoir management practice would therefore dictate the imposition of flow controls at the highest flow levels that could be sustained over the planned lifetime of the HDR facility. Reservoir engineering knowledge such as that which can be provided by the GEOCRACK model would be critical to making these important reservoir management decisions.

With the above constraints in mind, a thermal analysis of the Fenton Hill reservoir was performed with GEOCRACK. Figure 5 shows that no significant cooling would occur at the production wellbore even after forty years of fluid circulation at the flow rates prevailing during the LTFT. GEOCRACK does predict that a large cooled region will have developed after 40 years of circulation, but this region will not yet have reached the production wellbore. These modeling results certainly indicate that a heat mine at Fenton Hill could have a very long useful lifetime.

In summary, the GEOCRACK reservoir model was refined during 1994 to closely simulate actual flow test data and its capabilities were significantly expanded by the incorporation of thermal effects. GEOCRACK simulations highlight the importance of sound reservoir management practices to the efficient recovery of HDR resources. GEOCRACK further shows that prudently operated HDR reservoirs can have very long lifetimes. The modeling capabilities developed over the past several years, together with the engineering and operating knowledge resulting from the work at the Fenton Hill HDR test site, are rapidly increasing the level of confidence that economically-viable HDR power plants can be designed and constructed.

Reservoir Engineering

HDR field work was limited during FY 1994 because the Fenton Hill test site was maintained on standby status and no flow testing was conducted. In spite of the restrictions imposed by both budget and operating restraints, several low-cost studies were completed. Some of the more significant findings are summarized below:

Wellbore logging results: A temperature log of the production well conducted early in 1994 showed a normal temperature profile. In particular, it indicated that no significant temperature changes had occurred in the open-hole region of the wellbore (extending from 10,800 to 12,180 ft) in the four-month period since flow testing had been suspended. In contrast, as illustrated in Figure 6, a temperature log of the injection well two months later revealed an anomalous cooling profile extending from a depth of about 10,000 ft to beyond the bottom of the wellbore casing at 11,435 ft. The cause of the temperature anomaly was unclear at first, so repeat logging runs were conducted after the imposition of modified pressure and flow conditions in the wellbore. Evidence from the entire series of logs demonstrated that the cooling observed was a result of upward flow of cold injected fluid through the adjacent fractured reservoir region during the flow testing that had been concluded six months earlier. The logging data confirmed that the primary injection zone is located at 12,000 ft, and also indicated that active flow paths within the reservoir body extend some 1,500 to 2,000 ft above that point to well above the bottom of the cased portion of the wellbore.

Inflow to the reservoir from the overpressured far field: When the pressure on an HDR reservoir declines at a relatively high rate, the region at the boundaries of the fractured zone becomes overpressured. This occurs because the fluid in the open fractures of the reservoir is much more mobile than the fluid forced into the pores and filled joints at its periphery. This far-field region then becomes a potential source for reverse flow back into the reservoir.

During much of the standby period, injection was suspended and the pressure on the Fenton Hill HDR reservoir was allowed to decline. The observed decline in reservoir pressure was thought to be primarily a result of the fluid escape to the surface through a leakage pathway from the reservoir into the annulus of the injection wellbore. This leak typically flowed at a rate of several gallons per minute. At one point in 1994, this leakage pathway was closed off at the surface for a period of about a month. As expected, some of the fluid that would normally have returned to the surface via the injection wellbore annulus instead found its way into an abandoned, shallower HDR reservoir. This was evidenced by belching at a well connected to the abandoned reservoir which was still being regularly monitored. At the same time, the pressure of the current HDR reservoir began to rise, increasing by about 0.02 MPa (3 psi) over the course of a month. The observed increase in pressure of the current HDR reservoir was undoubtedly due to fluid seepage back into the reservoir from the overpressured far-field. This result provides further evidence that some of the water apparently "lost" to the subterranean environment in the operation of an HDR system is, in reality, simply stored within rock in the vicinity of the reservoir and is ultimately retrievable upon reduction of the reservoir pressure.

Variation of reservoir inflation volumes with pressure: A simple study conducted during 1994 clearly demonstrated the nonlinear response of the reservoir to changes in the imposed pressure. In repressurizing the Fenton Hill HDR reservoir after a prolonged shut-in period, equilibrium conditions were carefully established at several pressure levels, and the volume of water required to increase the pressure from one level to another was measured.

The following table compares injection data from three periods of incremental reservoir inflation during this experiment:

<u>Inflation Pressure Interval, psi:</u>	<u>725-2088 psi</u>	<u>1088-1450 psi</u>	<u>1450-1813 psi</u>
Pump-up Time, hr.	50.5	78.6	95.5
Incremental Vol., gal.	56,100	83,600	105,200

The above figures are only semi-quantitative. They do not account for permeation water losses or gains at the reservoir periphery, or for the additional water volume required to pressure-saturate the reservoir after initial attainment of the target pressure. However, since the data in the table show that for each increment of inflation a significantly greater length of time and volume of water was required, the strong indication is that the Fenton Hill HDR reservoir inflates in a nonlinear manner with pressure.

Production wellbore pressure response time: The response time at the production wellbore to pressurization at the injection wellbore was measured as an adjunct to a pumping exercise to replace water that had escaped from the injection wellbore during a logging run. A pressure rise was observed at the injection wellbore about 14 minutes after pumping into the production wellbore was begun. The open-hole interval in the injection wellbore is very generally about 300 feet distant from the open-hole interval in the production wellbore. After this brief pumping operation, the pressure decline curve of the reservoir, as measured at the production wellhead, resumed the downward trend that generally had been observed ever since the system was shut in at the close of flow testing.

Variances

The FY 1994 Operating Plan for the Los Alamos HDR Program called for maintenance of the Fenton Hill HDR facility on standby status with no provision for flow testing of any kind. In light of the extremely limited budget provided, the supporting research and development work was concentrated on modeling and on simple, low-cost field experiments which could be conducted within the authorized and funded operating framework. There were no significant variances from this strategy.

FUTURE PLANS

With the issuance of a solicitation for an industry-led HDR project imminent, and an improved funding outlook for 1995, steps to re-institute full-scale circulation at Fenton Hill were being taken towards the end of FY 1994. An injection pump with the capacity required for full-scale circulation at Fenton Hill will be acquired and installed during the early part of FY 1995. Reservoir verification flow testing will then be conducted to assure that the Fenton Hill reservoir is still in a condition suitable for long term energy extraction. Specific test strategies during 1995 will be directed toward answering questions related to the commercial operation of HDR reservoirs. After definitively re-establishing steady-state operating parameters, methods for improving the productivity of the Fenton Hill HDR system will be investigated. These will be limited to techniques that can be readily applied to routine operation of an HDR power plant, including such practical measures as recovery of the residual mechanical energy in the circulating fluid and operation of the plant in a pumped-storage mode.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Industry interest in HDR technology has been growing for several years. By 1994, the outlines of a proposed industry-led HDR project had been developed and a solicitation seeking private sector leadership

of a co-funded effort to produce and market power from an HDR resource was being formulated. Details of the technology transfer aspects of HDR development are addressed in a separate report.

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Figure 1. Flow paths in an HDR reservoir resulting from a reservoir simulation with one third of the flow pathways randomly blocked. The darker shaded pathways carry relatively larger portions of the flow.

Figure 2a

Figure 2b

Figure 2. Experimental results from Fenton Hill compared to GEOCRACK simulations. Figure 2a shows real and simulated tracer data. Figure 2b shows real and simulated pressure responses upon shut-in of the injection and production wellheads. The error bars indicate the range of individual model analysis results.

Figure 3a

Figure 3b

Figure 3. GEOCRACK analyses of rock cooling. In Figure 3a, the flow rate is not limited and cooling occurs at the surface faster than heat can be conducted from the interior of the blocks. In Figure 3b, the flow rate is limited so that the cooling rate is matched to the rate of heat conduction from the body of the rock. The analyses show cooling from 230°C (darkest shading) to 70°C (lightest shading).

Figure 4. GEOCRACK predicts that the flow rate through an HDR reservoir will begin to increase even at constant injection conditions after about a year of operation. Flow control measures will then be required in order to prevent decline in the temperature of the produced fluid.

Figure 5. Cooling contours within the Fenton Hill HDR reservoir after 40 years of circulation at flow rates employed during long-term testing of 1992-1993 as simulated by GEOCRACK. Although a large volume of cooled rock extends outward from the injection wellbore, no significant cooling has yet occurred in the vicinity of the production wellbore. The analysis shows cooling from 235°C (large, outer shaded region) down to 70°C (light region closest to injection wellbore).

Figure 6. A temperature log conducted six months after the termination of flow operations at Fenton Hill showed an anomalous cooling profile in the lower portion of the injection wellbore.

HEAT MINING TO EXTRACT HOT DRY ROCK (HDR) GEOTHERMAL ENERGY: TECHNOLOGY TRANSFER ACTIVITIES

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KEY WORDS

Cost-shared research, Electric Power Research Institute (EPRI), Fenton Hill, HDR, hot dry rock, industry, notice of program interest, solicitation, technology transfer, United World College

Technology Transfer Objective

- Transfer HDR technology to the private sector completely and effectively enough to stimulate the development by private industry of a practical facility to produce energy from an HDR resource for sale in the competitive marketplace.

Expected Outcomes

- An industry-led, government cost-shared HDR project will be initiated in FY 1995. This project will entail construction and operation of a plant to produce and market energy derived from an HDR resource. The Department of Energy (DOE) will contribute up to a 50 percent cost-share during the construction phase and an additional \$1.5 million per year in reservoir verification funding during the first three years of operation of the project. Construction and operation of this first HDR energy production plant is expected to provide the hard data regarding the capital and operating costs of HDR energy plants that will justify the establishment of a fully-privatized HDR power industry by the early years of the 21st century.

PROJECT BACKGROUND AND STATUS

Industry has been directly involved in the HDR Program from its beginning. All the drilling and completion work at the Fenton Hill HDR test facility during the 1970's and 1980's was performed by private companies under contract. Novel drilling and coring bits, downhole motors, open-hole packers, and other equipment developed specifically for the HDR Program have now found widespread uses in the geothermal, petroleum, and drilling and wellfield services industries. Logging instruments initially designed for use at Fenton Hill have also been widely adapted by private industry. Finally, the seismic techniques that were refined and brought to a high degree of sophistication as a result of HDR work at Fenton Hill are now being applied around the world to evaluate oil and gas reservoirs and develop methods for more efficiently recovering these fossil resources.

In recent years, the focus of HDR technology transfer has moved away from spin-offs of products and techniques developed as adjuncts to research and development activities, and toward the privatization and commercial implementation of the fundamental HDR energy production technology. Several industry advisory panels were convened to help develop a protocol for a long-term flow testing (LTFT) program

conducted at Fenton Hill during 1992-1993. Based on the advice of these panels, the test was designed to help provide answers to the questions considered by private industry to be most critical to the successful commercialization of HDR technology.

More recently, formal agreements to promote the private development of HDR were reached with several organizations and the stage was set for the initiation of an industry-led HDR effort. Toward the end of 1993, a Notice of Program Interest (NOPI) was issued by the DOE. The NOPI requested input from private industrial organizations and non-federal public institutions in regard to their potential participation in a joint industry/government project to construct a plant to produce and market energy from an HDR resource. Publication of the NOPI marked the formal beginning of the shift from an HDR research and development effort fully funded by the federal government toward the establishment of a private-sector HDR industry with government support to get it off the ground.

APPROACH

The LTFT demonstrated the potential for applying HDR technology to produce clean energy in significant quantities over an extended time period. Results of this flow testing, although limited, were uniformly positive. These encouraging results provided the basis for the publication of the NOPI mentioned above. As described in detail below, a large number of responses to the Notice were received from a variety of organizations. On the basis of these replies and the strong technical potential for success, a DOE solicitation to establish an industry-led, government cost-shared HDR project was formulated in 1994 with implementation scheduled to begin in 1995. The solicitation invites industrial consortiums to bid for up to \$30 million in government co-funding of an HDR facility designed to sell power derived from an HDR resource into the commercial marketplace.

TECHNOLOGY TRANSFER INITIATIVES

Replies to the DOE Notice of Program Interest

By the end of the first quarter of FY 1994, a total of 41 replies had been received to the NOPI. As shown in Table 1, respondents included a wide variety of organizations ranging from geothermal power producers, non-conventional energy companies, resource owners, equipment manufacturers, electric utilities, and engineering firms — to educational institutions and state government energy departments. The breadth of the responses indicated a widespread interest in the development of HDR geothermal energy.

Table 2 is a compilation of the responses received based on the level of interest expressed. Of the 41 respondents, 29 organizations indicated a definite interest in participating in the project. Five of these expressed a direct willingness to share in funding the work, while five more appeared interested only on a basis which did not involve a commitment of their own funds. Most of the others addressed funding in a more oblique fashion. As is always the case, real commitments of funding will be much more difficult to obtain than expressions of interest, but the number and diversity of organizations replying to the NOPI certainly lends encouragement to the prospects for establishing an industry-led, government co-funded, HDR project.

<u>Table 1</u>		<u>Table 2</u>	
Interest Notice Respondents' Type of Business		Interest Notice Respondents' Level of Interest	
Geothermal Operators			
Cost-shared Participation	2	Funding Offered	5
Under Right Conditions	7	Funding Discussed	8
Non-Conventional Energy Companies		Interested in Participating	10
Project Organizers /		Cost Shared Participation	5
Project Engineers	11	Under Right Conditions	
Power Plant Manufacturers/Developers	6	Interest, but Funding - Participation Unclear	5
Other Equipment Manufacturers	2	Potential participants	29
Electric Utilities/Utility Groups	5	Support in Principle	1
Government/Educational	4	Interested but Think They are Ahead	1
Unclassified	1	Information Request Only	7
Total Replies	41	Replied Expressing No Interest	3
		Total Replies	41

DOE Solicitation for an Industry-led HDR Project

Based on the number and nature of the replies to the NOPI, the DOE reached a decision in 1994 to proceed with the formulation of a solicitation for an industry-led, Government cost-shared HDR project. The solicitation was issued by the DOE Albuquerque Operations Office (ALOO) in the first quarter of FY 1995. It will be funded through the Geothermal Division of the DOE (DOE/GD). During 1994, the Los Alamos HDR Program worked with the DOE/GD and ALOO in the preparation of all technical parts of the solicitation. Some key aspects of the solicitation are summarized below:

Purpose: The primary purpose of the solicitation is to provide an incentive for private industry to construct and operate a facility to produce and market energy from an HDR resource. Government cost-sharing of the installation phase of the project will serve to reduce the private capital commitment level to the point where the potential return on the project is commensurate with the increased risk incurred due to the "first-of-its-kind" nature of the anticipated facility. The DOE will also provide reservoir verification support funding for the first three years of operation of the facility in order to assist in the development, implementation, and verification of reservoir management strategies intended to maximize the efficiency of utilization of the HDR resource.

Philosophy: The solicitation is directed toward the installation and operation of an energy production facility. The DOE will maintain rights to access the HDR resource and assess its performance during the three-year period when government operating support is provided. Such activities will be conducted only on a non-interference basis with the ongoing operations of the plant, however. In order to encourage efficient operation, all income generated from the sale of the energy will accrue to the private operator. In addition, the private operator may take possession of all the project assets at the end of the three-year period of government reservoir verification support and continue to operate the facility as a fully-privatized entity.

Qualifications: The solicitation contains a number of qualifications: 1) Government participation is limited to 50% of the total project installation costs and to reservoir verification support in the amount of \$1.5 million per year for the first three years of operation. Industry "in-kind" contributions to the project may be applied toward the 50% private sector cost share. 2) The solicitation requires that all bids be submitted by a consortium of organizations rather than a single company. A consortium may be as simple as a producer of the energy and a customer for the energy. 3) The project will be conducted in several stages with go/no-go decisions at the points of resource verification, reservoir operational verification, and successful initial operation of the entire system including the surface plant. In addition, the reservoir verification funding during the operational phase of the joint project is contingent upon meeting minimum "on-line" time and production rate requirements. 4) Because the goal of the project is to produce and market power, a customer for that power must be identified at the beginning of the project.

Funding: The DOE will provide funding of up to 50% of the total project installation cost up to a limit of \$30 million and a further \$1.5 million per year in reservoir verification funding during the first three years of operation of the HDR energy facility. It is anticipated that applicants will propose projects that are large enough to allow operating costs to be covered by anticipated income, but not so large as to put excessive amounts of their capital at risk. It is therefore possible, and even likely, that the total project size will be well under \$60 million, and the DOE installation funding consequently proportionately less than \$30 million. In any case, DOE funding will be subject to the yearly federal funding allocation process.

Duration: The installation phase of the project envisioned in the solicitation is expected to take two to four years, dependent upon both technical and funding considerations. The operational phase will entail government participation for three additional years. When government participation terminates, the private operator may take full possession of the project assets and will be free to continue to operate the project indefinitely.

Other HDR Technology Transfer Activities

Second EPRI Workshop on HDR: The second Electric Power Research Institute (EPRI) Workshop on the Potential of HDR Resources for the U.S. Electric Utility Industry was the most significant public meeting of 1994 from the standpoint of HDR technology transfer. The workshop was held on May 23-24 at the Customer Technology Applications Center of Southern California Edison in Inglewood, California. About 40 representatives from private industry, utilities, and government agencies participated. More than a dozen private companies were represented in what proved to be a very interactive and productive forum on the potential for the commercialization of HDR technology and what it would take to make it happen.

The workshop featured speakers on the status of HDR technology and on HDR developments in several states. A U.S. Geological Survey-led panel reviewed potential HDR sites, and an industry group discussed possible routes to HDR development. One private company, US Geothermal, took the opportunity to present an overview of their new drilling technology to the group. Virtually every attendee was an active participant in the discussions. A report on the meeting was issued by EPRI late in 1994. It may be obtained by contacting Dr. Paul Kruger of Stanford University, the primary organizer of the workshop, or Dr. Evan Hughes, EPRI Program Manager for Geothermal Projects.

Additional HDR technology transfer interactions: As part of a continuing effort to present HDR information to the broader geothermal community, Los Alamos HDR personnel actively participated in the Hot Dry Rock session at the Geothermal Resources Council Annual Meeting, the Stanford Geothermal Workshop, the DOE-sponsored Geothermal Program Review XII, and several other technical forums during 1994. In addition, Los Alamos HDR Program people met individually with representatives of dozens of industrial firms. Participation in a geothermal sub-group of a Renewable Resources Working Group sponsored by Portland General Electric Co.(PGE) resulted in extensive consideration of HDR in the sub-group report on the potential for geothermal development by PGE.

HDR evaluation at the United World College: A series of hot springs on the property of the United World College of the American West (UWC) in Montezuma, New Mexico, indicates the potential for the existence of a significant geothermal resource there. The buildings on the campus are currently heated primarily by hot water from a coal-fired heating plant. One large structure, known as Montezuma's Castle, is presently unused in large part because the costs of heating it are prohibitive. The school has wanted for some time to replace the heating plant with an environmentally cleaner source of energy and also to develop Montezuma's Castle into a conference center. During the past year, the UWC, the Los Alamos HDR Program, Sandia Laboratories, and the Southwest Technology Development Institute at New Mexico State University have been working toward developing a project to investigate the hydrothermal and HDR potential at UWC. The primary goal of any geothermal development at the school would be to replace the current coal-fired heating plant with a geothermal heat source, but the establishment of a geothermal conference center would also be a possibility if a unique geothermal facility, such as a direct-use HDR system, could be developed. The possible roles of the hydrothermal resource, geothermal heat pumps, and HDR in accomplishing either or both of these goals will all be examined as part of this project. As a forerunner to a more extensive resource evaluation project, the Los Alamos University Outreach Office provided a \$12,000 grant to the UWC in mid-1994. The funds were used to study the flow characteristics and geochemistry of the hot springs and to develop a curriculum that will provide students with a hands-on education in several aspects of geology and geochemistry, while at the same time building a long-term record of the nature of the geothermal activity of the springs. Funding from a combination of sources has recently been procured. During 1995, test drilling will be conducted to evaluate the flow and temperature characteristics of the hydrothermal resource on the school property, and to determine the local geothermal gradient and the nature of a possible HDR resource there.

HDR Technology Transfer in Other Countries: HDR technology transfer in Japan was significantly advanced by the 2nd HDR Forum held at Yamagata, Japan on Oct. 31- Nov. 2, 1993. By intent, the meeting was sponsored by a Japanese private sector organization, the Central Research Institute for the Electric Power Industry (CRIEPI). Although the international participants represented primarily publicly-funded HDR programs, there was a strong private sector presence among the 56 Japanese participants, including representatives from all nine of its electric power companies. It became clear

at the meeting that the Japanese utility industry is very serious about implementing HDR technology. With the high electricity costs in Japan (about 11¢/kwh), the economics of HDR may be more favorable there than in many parts of the United States. Field trips to the Hijiori and Ogachi HDR sites, as well as to the 27.5 MW hydrothermal power plant being constructed by Tohoku Electric Power Company at Uenotai in northern Honshu, further emphasized the Japanese commitment to making HDR a practical source of electric power.

Variances

The plan to transfer HDR technology to the private sector by means of the establishment of an industry-led project to produce and market energy from an HDR resources is proceeding according to the plan developed in 1993. There have been no major variances from the goals or procedures envisioned at that time.

FUTURE PLANS

The solicitation for an industry-led HDR project was published early in 1995, with applications due to the DOE/ALOO by late March. The successful applicant will be selected and a formal contract subsequently put in place so that the project can begin late in 1995. DOE funding in the amount of \$1.5 million is available in FY 1995 to begin implementing the project. Depending upon technical and financial considerations, the installation phase of the industry-led project should be completed in two to four years. This will be followed by a three-year operating phase during which the DOE will contribute toward the operation of the HDR system and participate in reservoir analysis and resource verification testing. At the end of the three-year period, the entire facility will be turned over to the private operator. It should then continue to operate as a fully-privatized entity. The reservoir development and operating data generated during the course of the installation and operation of this HDR facility should provide the information needed to prove the viability of HDR as a practical and economically competitive energy source and should set the stage for the development of additional HDR power plants financed entirely with private funding at appropriate locations around the world.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The 41 replies received to the Notice of Program Interest published by the DOE late in FY 1993 (Tables 1 & 2) provided some insight into the breadth and depth of private industry interest in HDR technology. It is expected that a number of proposals will be received in response to the DOE solicitation for an industry-led HDR project.

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INDUSTRY COOPERATIVE RESEARCH GEOTHERMAL TECHNOLOGY ORGANIZATION

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KEY WORDS

Industry cooperation, cooperative research, cost-shared research

PROJECT OBJECTIVES

The Geothermal Technology Organization (GTO), an organization of geothermal companies, and Department of Energy, Idaho Operations Office (DOE-ID) entered into an agreement in early 1988 to share in the cost of geothermal research. The agreement allows consideration of short- to long-term research in the areas of reservoir performance and energy conversion is available for cost-shared research and development. Industry proposes research to DOE and is obligated to share in at least 51% of the costs to obtain government cost share. INEL causes the research to be conducted and provides organizational support to GTO.

Technical Objectives

- Conduct research that is cost-shared by DOE and the GTO.

Expected Outcomes

- Develop technology that industry would not be able to develop alone.

PROJECT BACKGROUND AND STATUS

INEL assisted the geothermal industry in forming the GTO and in reaching an agreement with the Department of Energy to perform cost-shared geothermal research. The GTO was formed to advance the state-of-the-art of geothermal technology by presenting proposals for industry research projects, exploring potential technological programs, and advising the geothermal research community of industry's research needs. The DOE-GTO agreement allows the industry to pool their resources with those of DOE to sponsor research of benefit to the industry that individual companies could not afford to conduct independently. The GTO operates under the exclusion of joint research and development from anti-trust laws provided by the National Cooperative Research Act of 1984 (Public Law 98-462).

GTO and DOE have sponsored seven research projects during the course of the agreement. The GTO has provided access to the operating companies so that additional research of a cooperative nature, but in which no money changes hands, has become an important part of the INEL reservoir technology research program. One of the projects has also received additional funding to broaden the original scope of the project.

The DOE-GTO projects have included: 1) Development and interpretation of microseismic data at The Geysers; 2) Interpretation of injection tracer tests at The Geysers; 3) Characterization of subsurface fracture patterns in the Coso geothermal field; 4) Processing and interpretation of seismic reflection and refraction data from the Coso field; 5) Conducting and interpreting a long-term injection test at The Geysers; 6) Collection and interpretation of geochemical data at The Geysers; and 7) Study and interpretation of regional tectonics and igneous activity as it relates to the Coso geothermal field.

APPROACH

Industry, researchers, and the DOE suggest research topics to GTO. If GTO approves of the project, they propose the project to DOE. After DOE and GTO reach agreement on a project and the funding becomes available, INEL either conducts the research or establishes suitable subcontracts to complete the work. Results of the investigations are reported periodically to the participants, and after completion of the project, the results of the studies are generally made available to the industry with proper restriction of proprietary information.

RESEARCH RESULTS

Seven projects have been funded throughout the lifetime of the GTO-DOE agreement. The projects have involved more than \$2,000,000. The results of these studies have been used by operators at The Geysers to enhance injection operations and monitor microseismic activity. At Coso, results of studies are being used to improve seismic interpretation of the field. The status of several of the current studies are summarized in this volume. See the reports by Rial, Truesdell, and Walker in this volume.

FUTURE PLANS

GTO and DOE intend to continue to conduct cost-shared research as funding and suitable projects become available.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Current sponsors of GTO projects include: Calpine Corporation, California Energy Company, Coldwater Creek Operating Company, Northern California Power Agency, Pacific Gas and Electric Company, Unocal, and U.S. Navy.

Thirteen companies are members of GTO.

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INTERNATIONAL COOPERATION

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KEYWORDS:

Field case studies, U.S. industry competitiveness, foreign markets

PROJECT OBJECTIVES

The objectives of the International Cooperation activities are to facilitate the expansion of the U. S. geothermal industry into markets abroad, and to provide data and interpretations of geothermal projects worldwide so that the U.S. industry can learn from the experience of operations in foreign countries.

Expected Outcomes

- Increase opportunities for U. S. companies to develop geothermal projects abroad.
- Compile and develop conceptual models of foreign geothermal systems that can serve as analogues to U.S. fields.

PROJECT BACKGROUND AND STATUS

DOE has had cooperative agreements with Mexico and Italy since the late seventies, although funding levels have precluded substantial activity recently. The earlier studies however were able to document long-term changes in reservoirs during exploitation and the accuracy of modeling predictions. Recently the emphasis of the activities has shifted from the scientific and technical aspects to support for the U.S. geothermal industry in the development of geothermal projects, particularly those of smaller capacity for remote areas and rural electrification.

APPROACH

Formal agreements between the Department of Energy (DOE), Comision Federal de Electricidad (CFE) of Mexico, and Ente Nazionale per l'Energia Elettrica (ENEL) of Italy have provided ongoing technical cooperation between Italian and Mexican geothermal developers and researchers and U.S. private and government organizations. In addition, DOE with support from Lawrence Berkeley Laboratory (LBL) and Idaho National Engineering Laboratory (INEL) is sponsoring trade missions and technical contacts with foreign geothermal developers, particularly in Central and South America and the Far East.

RESEARCH RESULTS

During FY 94 the activities under this project were quite limited due to funding restrictions. However, an industry/DOE trade mission to Costa Rica arranged by Mr. William White, Deputy Secretary of Energy, DOE, took place in June 1994. The results of the mission are described in a report prepared by the Geothermal Energy Association (1994). Only a small amount of work was carried out under the DOE/CFE agreement during FY-1994. A technical meeting to review the status of the various projects was held in Mexicali, Baja California, on January 25, 1994. In the future, as much as possible, the new cooperative research will be conducted with the participation of U.S. industry.

The interaction with ENEL was limited to informal contacts; these will possibly increase at the time of the World Geothermal Congress to be held in Florence, Italy, in May 1995.

Various LBL and INEL scientists continued their technical cooperation with scientists and engineers abroad, especially from CFE, Instituto de Investigaciones Electricas (Mexico), University of Auckland (New Zealand), and Orkustofnun (Iceland).

FUTURE PLANS

DOE in cooperation with the World Bank plans to assist the government of Indonesia with a prefeasibility study of a number of small geothermal sites. This study will be followed with feasibility studies at selected areas. Experts from the U.S. geothermal industry will form the core of the teams performing these feasibility studies.

Visits of foreign scientists to LBL and other DOE-funded organizations to work with U.S. scientists will continue to be encouraged, especially if they are supported by their own institutions.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Geothermal Energy Association	Participation in trade missions

Several U.S. companies have expressed interest in working on cooperative projects with CFE and participating in feasibility studies.

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CONVERSION TECHNOLOGY

BINARY CYCLE PERFORMANCE IMPROVEMENTS FROM SUPERSATURATED TURBINE EXPANSIONS

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KEY WORDS

Binary power cycles, cycle performance improvements, turbines, supersaturated expansions, metastable turbine expansions

PROJECT OBJECTIVES

The objective of the Heat Cycle Research project is to provide an energy conversion system technology base that will result in the greater use of geothermal resources for generating electrical power. The utilization of supersaturated turbine expansions in binary power cycles represents a potential mode of operation that will increase the amount of power that can be produced from a given quantity of brine. The objective of this project activity is to determine whether these metastable expansions can proceed without adversely affecting the turbine, allowing the projected improvements in the brine utilization to be realized.

Technical Objectives

- Investigate the condensation behavior of metastable, supersaturated vapor expansions to identify the turbine operating parameters that will support a supersaturated vapor during the turbine expansion process, as well as those that will result in condensate formation. Determine the size of the droplets that form at the onset of condensate formation, and ascertain whether these droplets tend to re-evaporate as predicted.
- Identify the turbine operating parameters that degrade turbine performance (efficiency).
- Correlate the degradation in turbine efficiency with the condensation behavior investigations to determine the degree of supersaturation and/or moisture that can be tolerated during the expansion process before the turbine performance begins to degrade.
- Determine the erosion effects of these metastable, supersaturated expansions on the turbine internals (rotor and nozzle surfaces).

Expected Outcomes

- Investigations will demonstrate that the metastable, supersaturated vapor expansions proceed without adversely affecting turbine performance.
- Modes of operation will be defined that produce a degradation in turbine performance, as well as those that result in condensate formation.

Expected Outcomes (continued)

- Droplets at the onset of condensate formation will be sized.
- Investigations will show that the erosion effects of the supersaturated vapor are not significant.
- Investigations will show that the short-term effects of condensate formation on the turbine during an upset condition (loss of brine flow) are not significant when the turbine inlet pressure is above the critical pressure.
- With the confirmation that the supersaturated vapor expansions can proceed without adversely impacting the turbine, the technology will be available that will allow gains of 5 - 15 percent in the brine utilization. The magnitude of the improvement in the brine utilization will depend on the degree of conservatism incorporated into the current, or existing, cycle design. Based upon the turbine inlet conditions typical of a plant where these expansions would be appropriate, an improvement of 10 percent or more is feasible.

PROJECT BACKGROUND AND STATUS

The Heat Cycle Research Project began investigating improvements to the performance of binary power cycles in the early 1980s. These investigations initially examined the improvements in performance possible by using supercritical cycles operating with mixed-hydrocarbon working fluids. The brine utilization for this cycle was projected to be ~20 percent greater than that of the most recent commercial binary plants. The performance of this cycle was shown to approach thermodynamic maximums, provided that assumptions relative to integral phase changes and counter-current flow paths in heat exchangers were validated. The project investigations confirmed that these assumptions were valid, as well as the adequacy of the existing technology for the design of the heat exchanger components necessary to realize these assumptions. These project investigations were conducted at the Heat Cycle Research Facility. This facility was a small-scale binary plant located in California's Imperial Valley.

Analytical studies by the project suggested that the brine utilization for this supercritical cycle could be increased an additional 8 percent if the turbine inlet state points were modified to allow the turbine expansion process to "pass through" the two-phase region. These studies projected that the vapor would be in a "supersaturated" state, and that if condensate formed, the droplets would be small and tend to re-evaporate.

In 1992, a two-dimensional expansion nozzle was installed at the Heat Cycle Research Facility (HCRF) to investigate the condensation behavior of these metastable expansions. This nozzle contained a window that allowed the entire expansion process to be visually monitored. The nozzle was also equipped to allow a light beam (from a laser) to be passed axially through the nozzle along the expansion path. Any condensate or particulate present in the vapor, would scatter the light. Optics were used to gather this scattered light and transmit it to light-sensitive detectors, providing investigators with a quantitative measurement in addition to the visual observations.

These nozzle investigations generated sufficient interest that, following their completion in 1993, an axial-flow, impulse turbine was installed at the HCRF. During 1994, this turbine, as well as a radial-inflow,

reaction turbine, were tested at conditions that produced "dry" expansions, supersaturated expansions, and "wet" expansions. At the conclusion of the testing with the reaction turbine, the Heat Cycle Research Facility was shut down during the summer of 1994. The results of these investigations were sufficiently encouraging that the project currently is arranging for the extended operation of a turbine at a commercial plant at inlet conditions that will produce a supersaturated vapor during the expansion process. This extended test is expected to provide the final confirmation that these expansions do proceed without adversely affecting turbine performance, by monitoring performance and examining the erosion of the turbine internals (rotor and nozzle surfaces) over an extended period of operation. This extended test is expected to start in 1995 and conclude in 1996.

APPROACH

The approach used by the project has been to sequentially address each of the stated technical objectives. The two-dimensional nozzle and laser droplet-detection system were used to investigate the condensation behavior of the metastable, supersaturated expansions. The De Laval nozzle allowed an isentropic (ideal) turbine expansion process to be simulated. The droplet-detection system was used to determine the presence of condensate during the expansion process. These simulated turbine expansions allowed the investigators to determine which inlet conditions produced condensate formation, as well as provided data relative to the size of the droplets that form at the onset of condensation. From this data, investigators can identify the degree of supersaturation that can be maintained before condensate forms.

An axial-flow, impulse turbine and a radial-flow, reaction turbine were used to determine the effect of the metastable, supersaturated expansions on performance. The turbine inlet conditions were varied to produce "dry" expansions, supersaturated expansions, and "wet" expansions. In evaluating the turbine performance, the investigators maintained constant inlet and exhaust pressures, while varying the turbine inlet temperature. Starting at a temperature that produced a completely dry expansion, this temperature was decreased until a degradation in turbine performance could be measured. This process was repeated at different inlet and exhaust pressures, as well as with different working fluids.

To determine the erosion effects of the supersaturated expansions on the turbine internals (rotor and nozzle surfaces), a turbine will be operated for an extended period at inlet conditions that produce the desired degree of supersaturation or moisture content during the expansion process. The turbine internals will be thoroughly examined before and after the operating period to determine the effect on internal surfaces. In addition, the turbine performance will be monitored to identify any degradation with time, indicative of erosion damage to internal surfaces.

The project has solicited industrial participation throughout each phase of the investigation. This participation is in the form of review and comment on the status of the investigation, subcontracts to provide materials and services, and/or donation or "lending" materials and services (in-kind contributions). Participation is solicited from turbine manufacturers, plant operators, and engineering-design firms active in the geothermal industry. With the successful completion of each phase, the industry participation will increase, with the objective that the final phase (the extended test) will be conducted at a commercial binary plant.

RESEARCH RESULTS

The field investigations with the two-dimensional De Laval expansion nozzle in 1993 confirmed that the expanding vapor could be maintained in a supersaturated state during the simulated isentropic turbine expansion between the inlet and exhaust pressures. The degree of supersaturation was not as great as initially projected. Condensate formation occurred approximately mid-way (on a T-s plot) between an expansion that would pass just outside of the two-phase region and an expansion that would not exit the two-phase region. Initial studies projected condensate would not form until the isentropic expansion did not exit the two-phase region. Because of the conservatism in current plant designs, significant improvements in the brine utilization are still possible up to inlet conditions resulting in condensate formation (10 percent or more improvements still appear to be feasible).

In 1994, the testing with the axial-inflow, impulse turbine was completed. This turbine with isobutane, was tested at an inlet pressure of 600 psia. Results indicate that the turbine performance was not adversely affected until an isentropic expansion from the inlet conditions would exhaust the turbine well inside the equilibrium, two-phase region. The results indicate that turbine efficiency is not affected until the vapor actually exiting the turbine is "wet". This occurred at a significantly lower inlet entropy than that which produced condensate formation in the De Laval nozzle, suggesting that the condensate that forms in the nozzle is either too small to affect performance, or re-evaporates before entering the turbine rotor. In the impulse turbine, the expansion process occurs primarily in the turbine nozzles. The results of the testing with this turbine imply that the turbine could be operated at a lower inlet entropy (temperature) than would be indicated by the nozzle testing, allowing even larger improvements in the brine utilization.

Following the testing with the impulse turbine, a radial-inflow, reaction turbine was installed and tested until the Heat Cycle Research Facility was closed in September 1994. The evaluation of the data collected is not yet complete; however, two observations can be made about the performance of this turbine relative to the impulse turbine:

- The performance of the reaction turbine was affected at a higher inlet entropy condition than the impulse turbine.
- The internal surfaces of the reaction turbine are more susceptible to erosion damage than the impulse turbine.

Although the reaction turbine would not support the same degree of supersaturation or moisture content before its performance was impacted, it still operated without being affected at a lower inlet entropy than that which produced condensate formation in the nozzle. In the reaction turbine, a portion of the turbine expansion occurs within the turbine rotor. As a result, the vapor entering the rotor becomes "wet" sooner than in the impulse turbine, where the expansion occurs primarily in the nozzles. Condensate that forms does not have the same opportunity to re-evaporate before it enters the rotor.

While trying to establish the baseline performance of the reaction turbine with completely dry expansions, investigators noted a degradation in turbine performance with time. An examination of the turbine revealed erosion of stationary internal surfaces, including the nozzles. This erosion was apparently caused by small particulate being circulated in the working fluid stream. This phenomena had been noted during initial startups of similar turbines at commercial plants. This problem was resolved in these facilities by installing filters and/or centrifugal separators upstream of the turbine. The rate of

degradation with time did not change significantly during the reaction turbine testing at the HCRF, and did not appear to be affected by operating with either the supersaturated or "wet" expansions. It should be noted that this testing was conducted with the same working fluid and essentially the same facility configuration, as the testing with the impulse turbine, i.e., the same particulate was present during the impulse turbine testing.

To date, the investigation of the impact of the supersaturated expansions on turbine performance has shown that the turbine can operate at conditions beyond the point where condensate would form, without adversely affecting performance. The investigations also showed that over a short period of time, the turbine could operate with an exhaust moisture level in excess of 20 percent. When returned to a dry expansion after operating with this high level of moisture, the turbine performance was unaffected. This suggests that, at least for the supercritical inlet pressures, the conservatism currently used to prevent turbine damage during transients may not be necessary.

FUTURE PLANS

The project will prepare a solicitation for conducting the final phase of these investigations at a commercial plant. During this phase, the turbine will be operated for a period of up to one year, at inlet conditions selected to provide the desired degree of supersaturation. The objective of this phase of the investigation is to identify the erosion effects, if any, of these expansions on the turbine internals. Before starting the extended period of operation, a reference condition will be established with a detailed examination of the turbine internal components exposed to the expanding vapor. After the period of extended operation, a detailed examination will again be made of these components to determine what impact the supersaturated expansions had on the component surfaces. The turbine performance will also be monitored throughout this period to identify any trends that might be indicative of damage to these components.

This phase of the investigations is expected to be a collaborative agreement with industry, where the geothermal operator assumes a majority of the costs associated with the plant operation, and the project and/or turbine manufacturer assume the risk for the damage to the turbine components. This will be the final phase of the supersaturated expansion investigations. It is expected that this work will be completed in 1996. At that point, the project will have established the range of turbine inlet conditions which will produce expansions having a degree of supersaturation which will not have any long term adverse effect on turbine performance.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Barber-Nichols, Inc.	Turbine manufacturer and engineering firm: assisted with the field testing of the impulse and reaction turbines at the Heat Cycle Research Facility and the subsequent data evaluation; provided (at no cost) equipment for field testing of the impulse turbine.

Organization(s)	Type and Extent of Interest
Rotoflow Corporation, Inc.	Turbine manufacturer: provided (at no cost) the turbine rotor and nozzle set for the reaction turbine tested at the Heat Cycle Research Facility; provided review and comment on project activities; assisted the project in soliciting interest from the geothermal plant operators in conducting the extended test for the final phase of the investigations.
Ben Holt Company	Engineering firm: provided review and comment on project activities; assisted the project in soliciting interest from the geothermal plant operators in conducting the extended test for the final phase of the investigations.
Pacific Energy	Binary plant operator: considering allowing extended operation using supersaturated expansions with one of the facility turbines.
Mission Energy	Binary plant operator: provided review and comment on project activities; considering allowing extended operation using supersaturated expansions with one of the facility turbines.

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NEXT GENERATION GEOTHERMAL POWER PLANT

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KEY WORDS

Cooperative agreement, power plants, energy conversion, binary power plants, flash power plants

PROJECT OBJECTIVE

The project objective is to develop concepts for the Next Generation Geothermal Power Plant(s) (NGGPP). The NGGPP would utilize geothermal resources efficiently and will be equipped with contingencies to mitigate the risk of reservoir under-performance. The NGGPP would also attempt to minimize emission of pollutants and consumption of surface water and/or geothermal fluids for cooling service.

APPROACH

Different power plant concepts were compared at real-world geothermal locations. Seventeen (17) specific geothermal power plant concepts were evaluated against ten different real-world geothermal resources. Therefore, each power plant concept was evaluated and then ranked according to thermal efficiency and economic feasibility for each resource.

Each power plant concept evaluated in this study was sized at 50 MWe. Such sizing permits comparing one plant concept to another, on an apple-to-apple basis.

The different power plant concepts that were analyzed in this study fall into the following categories:

- Baseline binary and flash plants;
- Advanced binary plants;
- Advanced flash plants;
- Kalina cycles;
- Flash/binary hybrid plants; and
- Geothermal/fossil hybrid plants.

PROJECT BACKGROUND AND STATUS

The Electric Power Research Institute (EPRI) issued a Request for Proposal (RFP), RFP3657-01 entitled "Next Generation Geothermal Power Plant (NGGPP) - Phase 1 Studies" on June 2, 1993. After a competitive evaluation process, EPRI selected the Ben Holt Company to perform the study. Negotiations with the Department of Energy (DOE) for additional funding resulted in three additional power plant concepts to be added to the scope of work.

RESEARCH RESULTS

The Ben Holt Company will release the final report for the NGGPP in February 1995. A draft version of the final report indicates that dual flash plants are preferred at resources with temperatures above 400 °F. Closed loop (Binary or Kalina type) plants are preferred at resources with temperatures below 400 °F. A rotary separator turbine upstream of a dual flash plant can be beneficial at high-temperature resources where there is a significant variance in wellhead pressures from well to well. For the closed-loop cycles, a hydrocarbon working fluid is preferred for 330 to 400 °F and ammonia-water working fluid at temperatures lower than 330 °F. If natural gas prices remain low, a combustion turbine/binary hybrid is an economic option for the lowest temperature sites.

It was found that the NGGPP concept would be unlikely to reduce the cost of power generation by much more than 10 percent. Colder resources will benefit more from the development of a NGGPP than will hotter resources.

FUTURE PLANS

The Ben Holt Company will be releasing the final report during February 1995.

REFERENCES

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DEMONSTRATION OF AN ADVANCED BINARY GEOTHERMAL PLANT USING THE KALINA CYCLE SYSTEM 11

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KEY WORDS

Advanced binary geothermal plant, binary geothermal plant, cooperative agreement, demonstration, Kalina cycle, energy conversion

PROJECT OBJECTIVE

The project objective is to demonstrate the economic benefits of an advanced binary system that utilizes the Kalina cycle system 11.

APPROACH

The approach will be to design, build, and operate the Kalina cycle plant.

PROJECT BACKGROUND AND STATUS

A solicitation was issued by the Department of Energy (DOE) entitled "Demonstration of Economic Benefits of Improved Electrical Power Generating Systems for Geothermal Applications." Exergy, Inc. submitted an application to demonstrate an, advanced, binary geothermal power plant utilizing the Kalina cycle. The Kalina cycle uses an ammonia-water mixture as the working fluid and takes advantage of regenerative heating. The ammonia-water mixture has a low boiling point. Therefore, the excess heat coming from the turbine's exhaust can be used to vaporize a substantial portion of the working fluid. This plant is estimated to be up to 40 percent more efficient than existing binary geothermal power plants.

After a competitive process, Exergy, Inc. was selected for an award.

RESEARCH RESULTS

The Environmental Assessment for the proposed site at Steamboat, Nevada, is nearing completion.

The Cooperative Agreement between the DOE and Exergy, Inc. was signed in the final quarter of FY 94. Since that time Exergy's team has been working on the basic engineering design of the power plant. Exergy and Far West Capital (the plant owner/operator) have also been active in establishing a power sales agreement, under which the plant would sale its power as a commercial operation.

FUTURE PLANS

The future plans for this project are as follows:

- Complete Basic Engineering and Design;
- Detailed Engineering and Design;
- Plant Construction;
- Testing and Start-up; and
- Commercial Operation.

The economic benefits of the Kalina cycle plant will be determined by comparing the Kalina cycle plant to a Rankine cycle plant that sits adjacent to the new plant. Both power plants will be/are operated by Far West Capital

REFERENCES

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DEMONSTRATION OF A BI-PHASE TOPPING TURBINE

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KEY WORDS

Bi-phase turbine, cooperative agreement, demonstration, flash plants, energy conversion

PROJECT OBJECTIVE

The project objective is to demonstrate the economic benefits of replacing a separator in a steam-flash geothermal power plant with a bi-phase topping turbine.

APPROACH

The approach to this project included testing a sub-scale biphasic turbine on a slip stream from a geothermal production well. The small turbine would be tested on high, medium, and low enthalpy production wells to establish operating parameters and operating efficiencies. Then, a full-size bi-phase turbine is to be built and operated on the full flow from a production well. The data taken from the full size biphasic turbine will prove the economic viability.

PROJECT BACKGROUND AND STATUS

A Solicitation was issued by the Department of Energy (DOE), titled "Demonstration of Economic Benefits of Improved Electrical Power Generating Systems for Geothermal Applications." Douglas Energy submitted a proposal to demonstrate a bi-phase turbine. The bi-phase turbine extracts useful energy through capturing the kinetic energy of the geothermal fluid during the flashing process of the brine. Conventionally, the geothermal brine enters a tank where the pressure is reduced and a portion of the brine is flashed into steam. In the proposed process, the pressure is reduced in a nozzle which directs the two phase geothermal fluid tangentially onto the inside of the bi-phase turbine. The force of the brine causes the turbine to rotate, transferring the kinetic energy from the brine to the turbine. The centrifugal force separates the brine from the steam. A steam wheel is also used to capture the energy from the pressure drop. As the brine is scooped from the turbine, the brine is pressurized and can then be injected directly into the geothermal resource. The bi-phase turbine is directly coupled to a generator which then converts the kinetic energy into electricity. With the addition of the bi-phase turbine, it is estimated that a steam/flash plant can produce approximately 20 percent more electricity.

RESEARCH RESULTS

The Biphasic project can be broken down in to three main areas:

- 1) Year 1 - Operation of the subscale biphasic turbine;
- 2) Year 2 - Design and fabrication of the full size biphasic turbine; and
- 3) Year 3 - Operation of the full size biphasic turbine.

Douglas Energy has completed the first year of the project. The sub-scale turbine operated on a slip stream of a production well in Coso Hot Springs, California. The test apparatus included a water brake dynamometer to measure the power output from the turbine. Three test runs of approximately 250 hours each were made.

The first test run, high enthalpy, measured the efficiency of the steam turbine stage. The steam turbine stage efficiency was measured by operating the turbine on steam only. By operating with all steam and no liquid, the efficiency of the steam turbine stage clearly could be evaluated as the ratio of the total measured output power to the exit kinetic energy of the steam. During this test run, the turbine speed and the steam pressures were varied independently. The efficiency of the biphasic turbine varied from 50 percent to 65 percent.

The second test run, medium enthalpy, measured the efficiency of the biphasic turbine with varying steam/brine fractions. The steam fraction (by weight) was varied from 0.4 to 0.8. When the biphasic system was operated with a steam fraction of approximately 0.8 the efficiency was between 40 percent and 50 percent. When the biphasic system operated between 0.4 and 0.5 steam fraction the efficiency varied between 30 percent and 45 percent. The general trend showed that as the steam fraction increased the efficiency increased.

The third test run, low enthalpy, accumulated 215 hours before the test was terminated. The test was terminated prematurely due to erratic and undependable well characteristics, debris regularly was being delivered by the well and the well owner, California Energy Company (CEC), wished to terminate the well operation. Carbonate and silica scale was also encountered during this test run. An inhibitor was injected within the well, but afterwards silica scale remained a problem. Douglas Energy improved their rock/sand catcher design and installed a hydro-blast system that was found to be effective at removing scale from the turbine during operation.

The steam fraction for the third test run varied from 0.18 to 0.30. While the biphasic system operated at a steam fraction of 0.18, the efficiency was approximately 10 percent. With the steam fraction at 0.30, the efficiency varied between 20 percent and 25 percent.

As part of the lessons learned from the subscale turbine operations, a rock/sand catcher and a hydro-blast de-scaler will be incorporated into the full-size design.

Currently, Douglas Energy is working on the full-size design in preparation for fabricating and installing the system on a production well.

FUTURE PLANS

During the next two years of this three-year project, the full-size biphasic turbine will be fabricated, installed, and operated on the flow coming from a production well. As currently designed, the biphasic turbine will generate an additional 1 MW of electricity. The data collected from the operation of the biphasic turbine will ultimately show the economic benefits of this technology within a geothermal environment.

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BINARY CYCLE HEAT REJECTION

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KEY WORDS

Binary cycles, heat rejection, geothermal power plants

PROJECT OBJECTIVES

The objective of this activity is to employ the thermodynamic cycle analysis to evaluate various cooling and mixed-working-fluid options for binary geothermal power plants, based on the impact that each option makes to the levelized energy cost of electrical energy.

Technical Objectives

- Predict the impact made on the levelized energy costs by the heat-rejection and mixed working-fluid options that were identified during the previous year. The analysis will be carried out using a computer model developed under a separate task.
- Develop the ranking methodology necessary to select appropriate operating strategies as a function of water availability.

Expected Outcomes

- Document the impact of staged dry/wet cooling systems and mixed working fluids for geothermal power plants operating at low temperatures.
- Develop guidelines for selection of operating strategies to optimize water consumption.

PROJECT BACKGROUND AND STATUS

Geothermal power plants are often located in arid areas with scarce water resources, requiring use of dry cooling. However, many sites do provide limited supplies of cooling water of varying quality. Because dry cooling results in a severe performance penalty during the hotter portion of the year, judicious use of the water available could improve significantly the yearly power output of the plant and its overall capacity factor. It would also provide greater flexibility to operate the plant in a peaking mode during the times of greatest demand. Depending on its quality, the water could be used in a separate cooling tower, or sprayed onto the heat transfer surfaces to enhance the overall heat transfer, or used to cool the air temperature before it is supplied to the dry condenser or heat exchanger.

Binary plants generally have used single working fluids for ease of operation, with the exception of the Kalina cycle that uses a water-ammonia mixture. Other mixtures of working fluids could lend themselves to better utilization of the geothermal brine and to higher plant efficiency, for new plants as well as for

existing plants with dwindling resource temperatures. In turn, this would lead to a proportionally decreased load on the cooling system.

The basic computer model development and the selection of the options to be considered were carried out in FY 94. Expansion of the model is taking place under a separate task in early FY 95. As equipment modules are developed, validation of the results will be carried out, when possible, by comparison to results obtained from more extensive computer codes of power-plant cooling systems. As components of the revised model are completed, analysis of the various configurations for heat rejection will be carried out. Reporting of the results will be completed in late FY 95.

APPROACH

The thermodynamic cycle analysis model developed under a separate NREL task will be used to perform comparative analyses of the options listed below. One representative location will be selected (i.e., fixed ambient conditions, resource temperature and limits); and good quality water will be assumed. Three or four different ambient conditions representative of the yearly cycle at the selected location will be analyzed to verify that the relative ranking of the various options is maintained over the year. As the code is upgraded and expanded, we will investigate the relative benefits of the following options, based on calculated changes of busbar electrical cost :

a) Staged dry/wet cooling

- comparison of operating dry and wet cooling components in series and parallel
- comparison of direct (air condenser) and indirect (shell and tube condenser to air or water heat exchanger) configurations
- allocation of condensing duty between dry and wet cooling components, as a function of water availability (four points to be analyzed are: all dry, all wet, and two nearly dry intermediate points).

b) Mixed working fluids

- selection of mixed working fluid composition as a function of operating temperature (e.g. periodic adjustment of composition)
- assessment of penalties associated with fractional condensation of working fluid mixtures
- measures required to maintain the working fluid well mixed.

Close attention will be paid to interfacing the model development and the analysis tasks.

RESEARCH RESULTS

The basic computer model has been developed and the results compare favorably to analyses carried out by an engineering firm on small, low-temperature plants. System layout and operating conditions for the various options have been identified and are being incorporated into the model. Comparison of performance predictions from the existing portions of the model compare favorably with results from more extensive codes. No variances have been identified so far.

FUTURE PLANS

Based on the results obtained during the mixed working fluid analysis, we will assess if other heat rejection configurations need to be considered in FY 96, to take better advantage of the fractional condensation of the working fluid. We will also design and prepare the laboratory for experiments to verify the behavior of selected mixed working fluids and their heat-rejection requirements.

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DEVELOPMENT AND TESTING OF ADVANCED DIRECT-CONTACT CONDENSERS

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KEY WORDS:

Direct-contact condensers

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 the development and implementation of advanced direct-contact condenser concepts, developed at NREL, which offer a potential for reduced condenser back pressure and improved non-condensable gas handling in geothermal power systems.

Technical Objectives

- Develop analytical and design methods for improving the performance of existing direct-contact condensers at the Geysers.
- Retrofit one of the units at The Geysers for performance verification.

PROJECT BACKGROUND AND STATUS

Pacific Gas and Electric Company (PG&E) owns and operates a set of approximately 14 power plants at the Geysers, utilizing the geothermal steam resource. PG&E produces about 750 MWe from The Geysers steam resource, making the power available to California consumers. On some of the power systems (called units), PG&E has experienced performance problems from existing condensers as evidenced by increased operating back pressures and a high concentration of steam in the stream of noncondensable gases which must be vented. Over the years, PG&E has pursued different approaches to improve condenser performance with limited success.

PG&E recognizes the potential merit of the NREL-developed condenser concepts for gaining substantial improvement in the condenser performance and is interested in developing those concepts into workable hardware.

NREL, DOE, and PG&E have a mutual interest in carrying out a collaborative research and development effort to develop field test equipment and test data which will quantify the potential heat-transfer performance and noncondensable gas handling characteristics of these advanced condenser concepts.

These condenser developments will be applicable to all steam power plants with a potential for improvement of plant heat rate by as much as five percent.

NREL and PG&E are working under a Cooperative Research and Development Agreement (CRADA) to demonstrate the use of advanced design techniques and designs to improve thermal performance and scavenging of noncondensable gases in direct-contact steam condensers thereby improving the utilization of geothermal steam and reducing emission of noncondensable gases.

The following work statement describes the basic working arrangements for the CRADA.

The work will be carried out in three Phases, with the indicated subtasks:

- I. Conceptual Design Development
 - A. Condenser code upgrade for geothermal applications
 - B. Selection of packing
 - C. Performance projections
 - D. Conceptual design
 - E. Decision analyses for proceeding to the following phases
- II. Engineering Design and Installation (pending Go/No go decision)
 - A. Steam, gas and water chemistry acceptability analyses
 - B. Engineering design
 - C. Procurement and Installation
- III. Operational Tests
 - A. Instrumentation
 - B. Operational tests
 - C. Model validation
 - D. Reporting

The schedule for the project is matched to accommodate the installation at the time of the next scheduled major overhaul and maintenance of the selected unit. The next opening of the condenser is now scheduled to occur in June 1996.

Phase I was carried out in FY 94 by NREL.

Phase II will be implemented in FY 95, with the definition of design and costs by March 1995.

APPROACH

Phase II. Engineering Design and Installation

Initial efforts in this phase will allow PG&E to assess the impact of varied chemistry of the effluents from the condenser, their influence on existing abatement systems, and acceptability of the emissions based on existing regulations. Additional assessments early in this phase will allow PG&E to confirm the economic

viability of the proposed modifications. These two assessments will allow PG&E to make an informed decision by early 1995.

Contingent upon the decision, PG&E will then undertake a detailed engineering design of the proposed modifications, and initiate procurement and schedule installation. NREL will participate in a continuing series of meetings with PG&E to provide technical guidance and allow uninterrupted progression of the project from the conceptual stage to the engineering stage.

The second phase will be carried out during FY 95.

During Phase II, NREL will evaluate the requirements for instrumentation to allow model validation when data can be gathered.

RESEARCH RESULTS

A working version of a computer code for modeling the direct-contact condenser together with the accompanying chemical reactions has been developed by NREL. This code has been exercised to evaluate the operation of Unit #11 of the PG&E power plants at The Geysers. These results are being used to develop designs for the retrofit. The project is progressing according to the original plan with no significant variances thus far.

FUTURE PLANS

Upon successful demonstration of the improvements at one particular unit at The Geysers, modifications to other units may be pursued depending upon the established economic viability of the system.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This project was initiated upon expressed interest of PG&E. Upon completion of the project with validated results, substantial interest from other power producing organizations may be expected.

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MODEL DEVELOPMENT FOR CYCLE AND ECONOMIC ANALYSIS IN ADVANCED HEAT REJECTION STUDIES

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KEY WORDS

Computer model, binary cycle, geothermal power plant, heat rejection system, economic evaluation, thermodynamic evaluation

PROJECT OBJECTIVES

During the past year, a computer program was developed which allowed changes in the levelized energy cost (LEC) to be determined for changes in small, binary geothermal power plants. The effects of component size change and their impact on LEC were determined for some low temperature applications. The objective of this work is to extend the computer program to include different types of heat rejection systems. The initial model simulated air-cooled condensers.

Additional systems to be considered are: (a) Shell-and-tube condensers with water cooled in an evaporative cooling tower; (b) Shell-and-tube condensers with water cooled in an air cooler; (c) Series combinations of one of the air cooled systems over an evaporative water cooled system; and (d) Parallel combinations of the systems mentioned above.

Technical Objectives

- Produce a computer program that will be able to rank systems with different heat rejection processes by evaluating their impact on LEC.
- The model will be updated to consider various working fluids for the binary cycle and the results of the Next Generation Geothermal Power Plant Study will be included as an economic standard for higher-temperature, larger plants.
- The computer program will be made more "user friendly" to allow use by a larger group of interested people.

Expected Outcomes

- One outcome of this work will be the production of the tool to be used by the Geothermal Power Program to evaluate advanced heat rejection systems.
- Different operating strategies will be evaluated to minimize water consumption along with LEC.

PROJECT BACKGROUND AND STATUS

Determining the best heat rejection system for power plants using liquid-dominated, hydrothermal resources is a crucial issue in producing low-cost energy. The resources being considered are generally in the low- to moderate-temperature range and, therefore, reject a large amount of heat. In addition, most of the resources are located in areas where water is scarce and total wet cooling may not be possible. It is imperative to investigate heat rejection systems to produce economical electrical energy.

In the past year, we developed models to evaluate cycle performance and impact on the levelized cost of energy produced from binary plants. This procedure included a computer program to perform the cycle analysis and component sizing for binary systems with dry cooling (air-cooled condensers) and a spread sheet in which the economic data was calculated. The method of computing the levelized energy cost was an incremental method to determine the percentage change from a base case. The method is an updated version of a method proposed by Demuth and Whitbeck in Report EGG-GTH-5821. Results have been used to consider base cases as defined by Barber Nichols, Inc. for small, low-temperature plants (four production wells and <300°F). Additional baseline data will be incorporated into the model from the Next Generation Geothermal Power Plant Study currently being carried out under the direction of Electric Power Research Institute (EPRI) and the Department of Energy (DOE).

Studies of heat rejection systems and their impact on cycles are to be carried out during FY 95. The tool mentioned above will be quite useful in carrying out this task. Some additional work will be necessary to make the tool general enough to be useful. This is the purpose of this task.

APPROACH

The approach taken will be to apply the "value analysis" as described in the Background section to binary cycles with various types of heat rejection systems. The value analysis is a simplified screening method that provides a means of comparing one concept with another by evaluating the impact of the concept on the change in the levelized energy cost. The procedure lends itself to "ball-parking" at the value of possible research paths as well as providing an accurate estimate of the value of the more fully developed concepts.

During FY 95, this methodology will be expanded to allow for the study of various heat rejection concepts and their impact on binary cycle performance and economics. This task will be closely coordinated with the actual heat rejection at NREL. Modifications and timing of results will be worked out together to expedite the analytical study. The steps required for this task will include:

1. Incorporating the results of the Next Generation Geothermal Power Plant as an additional baseline for consideration. The present baseline applies to small, low temperature plants. The results of the Next Generation Geothermal Power Plant Study will extend this to higher-temperature resources and to large plants.
2. Developing additional heat rejection models. This will include developing thermodynamic and sizing models for heat rejection systems in addition to the air cooled condenser which is now in the model. Models to be developed include: shell and tube condensers with wet cooling towers; parallel and series dry and wet cooling systems; and systems with intermediate loops with a sensible fluid separating the cycle from the heat rejection system.

3. Extending the computer program to calculate performance of previously sized components. Presently, the computer program is a "design" program which sizes components to fulfill the design requirements. This extension is necessary because the heat rejection problem must account for variable environmental conditions with the same hardware. This will be the most involved task.
4. Extending the thermodynamic data working fluid database. At this time, no interpolation schemes are available for determining properties of mixtures between pressures in the database. A scheme to approximate other pressures will be determined and used. More data will be added to the database. At this time, pure hydrocarbons including propane, normal and iso-butane and normal and iso-pentane are included in the database as well as a few mixtures of these components. The mixture data will be increased.
5. The computer program and spread sheet are in the developmental stage at this time. Some time will be used to make the system more "user-friendly." This may include the automation of transfer of data from the computer program to the database as well as making it easier to run the computer program. A more comprehensive write-up on the method will be included in this subtask.

RESEARCH RESULTS

Last year, the initial model was used to compare with some more detailed conceptual designs of small, low-temperature, power plants using air-cooled condensers done by Barber Nichols, Inc. The results compared favorably to the degree of accuracy of this simplified model. These results are described in a draft report mentioned in the References section.

FUTURE PLANS

This model is to be used in the Advanced Heat Rejection Project of the Geothermal Energy Conversion Program. This project and its research activities are discussed in another section.

When the computer model is completed and made "user friendly," it will be made available to any interested parties.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The computer program will be made available to industry when it is completed.

REFERENCES

The original "value analysis" work for geothermal power plants is discussed in the report: Demuth, O.J. and J.F. Whitbeck, "Advanced Concept Value Analysis for Geothermal Power Plants," EGG-GTH-5821, March 1982.

A draft report on the work to date can be obtained from one of the Contacts listed below.

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THERMOPHYSICAL PROPERTIES OF AMMONIA-WATER MIXTURES

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KEY WORDS

Interagency agreement, Kalina cycle, energy conversion, National Institute of Standards and Technology (NIST)

PROJECT OBJECTIVE

The objective of this project is to develop a predictive model for the calculation of thermophysical properties of ammonia-water mixtures applicable over real-world conditions.

APPROACH

The National Institute of Standards and Technology (NIST) is to collect and critically evaluate thermodynamic data needed to optimize the high pressure VLE model (Leung-Griffiths model) for the ammonia-water system and optimize the empirical shape factors to obtain a preliminary thermodynamic surface. From this, NIST will develop an accurate thermodynamic surface for the ammonia-water system. Selected measurements on ammonia-water mixtures will then be carried to resolve inconsistencies in the available data.

NIST will do comprehensive, state-of-the-art Pressure-Volume-Temperature (PVT), heat capacity, and thermal conductivity measurements for several ammonia-water compositions at temperatures from 250 to 450 K at pressures to 10 MPa. NIST will optimize the extended corresponding states model with exact experimental data for PVT and caloric properties in order to improve the binary interaction parameters needed in the thermodynamic surface model.

PROJECT BACKGROUND AND STATUS

Accurate thermophysical properties of ammonia-water mixtures are needed to evaluate the performance of proposed ammonia-based systems for geothermal power cycles using binary fluids. Operating conditions extend from approximately 280 to 450 K with pressures to 3.5 MPa. Mixture compositions range from 80 to 100 percent ammonia by mass.

RESEARCH RESULTS

Preliminary results have been shown to the Department of Energy on the empirical model. However, the final report and updated version of the extended corresponding states model is not scheduled to be delivered until approximately April 1995.

FUTURE PLANS

NIST is continuing to work toward completion of this project and provide the deliverables as specified.

REFERENCES

Department of Energy Interagency Agreement; No. DE-AI36-CH10558; Dated March 31, 1993.

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CORROSION MITIGATION AT THE GEYSERS

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KEY WORDS

Corrosion protection, polymers, composites, pre-ceramics, piping, well casing, cooling towers, acid condensate

PROJECT OBJECTIVES

Increased HCl concentrations in the steam condensate produced from geothermal wells in some portions of The Geysers have resulted in severe corrosion problems in the upper regions of the well casing where condensation may occur, in steam collection piping, and on turbine blades and rotors. Geothermal fields in other countries have reported HCl production after many years of operation, and it is expected that HCl will cause problems in other U.S. fields. In addition, before dry cooling towers can economically be used as a means of conserving water needed for reinjection, low-cost corrosion protective systems for use on structural components must be identified. Solving these materials problems is the objective of this project.

Technical Objectives

- 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 which will withstand the highly corrosive acidic environments being encountered in some areas of the geothermal field.

Expected Outcomes

- 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 resulting in reservoir life extensions due to increased fluid reinjection.

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 90, BNL initiated cost-shared work with geothermal companies active at The Geysers which focuses on low-cost solutions to these difficult materials problems. The research and development (R&D) approach is to select and then optimize previously developed and, in some cases, industrially

utilized organic and inorganic polymer formulations for specific end-use applications at The Geysers. The identification of needs, performance of prototype and full-scale field evaluations, and subsequent economic studies are performed as cost-shared activities with firms active at The Geysers.

As of October 1994, a series of field tests of coating systems for well casing had been completed with the Central California Power Agency (CCPA), and evaluations of pipe line and dry cooling tower coatings were ongoing with the Northern California Power Agency (NCPA) and Pacific Gas and Electric (PG&E), respectively. In addition, laboratory work directed towards other components was underway.

APPROACH

The approach being used to meet the project objectives is to optimize polymer, polymer cement composite, and pre-ceramic formulations, previously developed under Geothermal Division sponsorship, for specific end-use applications at The Geysers. The identification of needs, performance of prototype and full-scale field evaluations, and subsequent economic studies are performed as cost-shared activities 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.

RESEARCH RESULTS

The emphasis of the work currently underway is on the field evaluation of prototype and full-scale components. Tests are ongoing with NCPA and PG&E and others with CCPA were completed in FY 94. Results to date are summarized below.

A. NCPA Field Tests

Two polymer cement (PC) lined 12-inch diameter pipe tees were installed in a steam transmission line in March 1992. The first visual inspection was completed in April 1993. At the time of inspection, one section had been exposed for 13 months, the second for 12 months, both at a steam flow rate of 30,000 lb/hr, 120 psi pressure, and a temperature of 173°C. Observations noted are listed below.

- After 13 months in service, the non-reinforced PC showed no wear or chemical deterioration of the liner except at the upstream end where some erosion at the edge of the 5/16-inch thick liner occurred. This probably resulted from the step change in the diameter of the pipeline at this point which caused the direct impingement of solid particles and condensate droplets in the high-velocity steam onto the unsupported edge of the liner.
- A network of fine surface cracks in the PC that formed during fabrication as a result of excessive shrinkage did not appear to enlarge as a result of field exposure or to promote disbondment.

- Similar observations were noted for the second tee which contained 0.23 percent graphite fibers by weight of the PC as a means for reducing shrinkage cracking. One small (approximately 2 to 3 in²) area where disbondment of the PC from the metal occurred was detected. A defect in the liner was originally present at this point probably due to air entrapment during casting, and a patch had been applied. The clean, bright surface of the steel after the 12-month test would indicate that the disbondment occurred late in the test cycle.

Based upon the excellent condition of the tees, both were reinstalled for continued exposure. Trouble-free operation of both tees has continued but additional inspections have not been made. As of October 1994, the total exposure time has been 30 months.

B. PG&E Field Tests

Prototype sections of polymer-coated, finned-tube, heat exchanger tubing for dry cooling tower applications were placed into test by PG&E at The Geysers in June 1994. In the test environment, the corrosion rate of carbon steel is approximately 15 mpy. Aluminum corrodes at a lesser but unacceptable rate. Two metal systems, aluminum fins on stainless steel tubing and electrogalvanized steel on carbon steel tubing, are being evaluated. Polyphenylene sulfide and vinyl ester resin-trimethylolpropane trimethacrylate applied to surface modified and "as-received" metal surfaces were used for corrosion protection. Visual inspections were made by PG&E after approximately two and five months. No signs of blistering, chaulking, or delamination were apparent on any of the coated samples. The next inspection is scheduled for March 1995.

C. CCPA Field Tests

In this completed effort, two polyphenylene-sulfide-coated well casing spool sections, 8-inch i.d. x 12-inch long, used for the injection of NaOH solutions into chlorine-containing steam, were in service for approximately 16 months, but not always under the caustic injection condition. Typically, 0.5-inch-wall steel casing will corrode through within 14 days when exposed to the low pH (approximately 2), high-temperature (approximately 170°C) condensate produced when NaOH injection is used. Both spool sections were installed in September 1992 and removed in December 1993. One was exposed to a 54,000 lb/hr steam flow at 145 psi, 176°C and 10 ppm chloride. Conversion of the well to allow NaOH injection at the bottom of the casing string was made after one month, but the test spool was left in place at the wellhead. Operation was trouble-free for the remaining 15 months.

The second section was in a well operating at essentially the same conditions except that the steam flow was 70,000 lb/hr. During the 16 month period, caustic injection into the section was conducted for 3 months. Visual examination of both spool sections after removal indicated no peeling or blistering, but some wear of the coating specifically in the region of acid condensate flow. The remainder of the coated regions appeared unaffected. No corrosion of the steel substrate was apparent.

FUTURE PLANS

Field testing at NCPA and PG&E will be continued. Laboratory work to select promising systems for possible use on turbine blades and rotor housings will be completed. Contingent upon these results, larger-scale tests for these applications will be initiated at PG&E. Other corrosion-related projects will be started as their needs are identified by the DOE/Industry Geysers Working Group.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Central California Power Agency (CCPA)	Research collaborators for corrosion protection for well casing. Potential user of technology.
Northern California Power Agency (NCPA)	Research collaborators for corrosion protection for transmission piping. Potential user of technology.
Pacific Gas and Electric (PG&E)	Research collaborators for corrosion protection of dry cooling tower components, turbine blades, rotor housings. Potential user of technology.

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THERMALLY CONDUCTIVE COMPOSITES FOR HEAT EXCHANGER TUBING

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KEYWORDS

Bottoming cycles, corrosion protection, fouling coefficient, heat transfer, mild steel, polymer cement composites, silicon carbide, thermal conductivity

PROJECT OBJECTIVE

The economic utilization of binary working fluids in geothermal energy conversion cycles operating in the 150° to 200°C temperature range would dramatically increase the size of the exploitable hydrothermal resource. Therefore, a key objective of the Geothermal Division Conversion Technology Task is to reduce the cost of power from a binary plant by 8 to 20 percent through improvements in efficiency and in operation and maintenance (O&M) cost components. A significant item of cost in a binary plant is the shell-and-tube heat exchangers, primarily due to the necessity of using high-alloy steel tubing to prevent corrosion. Even then, excessive fouling prevents the economic use of binary processes with hypersaline brines. Both problems possibly could be solved with the development of a thin, scale-resistant, thermally conductive, polymer matrix composite which could be used as a liner on low-cost mild steel tubing. Cost-effective utilization of bottoming cycles in flash processes as a means of increasing energy conversion efficiency also will become possible.

Technical Objectives

- The technical objective of the research which is being performed as a cooperative effort with the National Renewable Energy Laboratory (NREL) and a cost-shared activity with the geothermal industry, is to develop, fabricate, and field test in a prototype, single-tube, shell-and-tube, heat exchanger, polymer-cement-lined tubing (PCL) meeting the following criteria:
- Heat transfer coefficient and fluid-flow characteristics are similar to those of AL-6XN tubing.
- Fouling coefficient is less than 50 percent of AL-6XN when used in brines typical of the Salton Sea Known Geothermal Resource Area (KGRA).
- The Cost is less than twice that of mild steel.

Expected Outcomes

- Electric generation capacities in geothermal flash processes could be improved by 10 percent with the availability of cost-effective materials for use in bottoming cycle heat exchangers.

Expected Outcomes (continued)

- Low-temperature geothermal resources which 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.

PROJECT BACKGROUND AND STATUS

A serious problem in the development of geothermal energy is the lack of cost-effective, durable materials of construction for handling hot brine, steam, cooling water, and binary fluids. Scaling and corrosion are encountered in all geothermal plants, and to various degrees, they adversely affect plant availability, lifetime, and power output. These problems are becoming more acute as higher-temperature and chemically aggressive fluids are encountered, and ultimately the lack of cost-effective materials of construction could seriously constrain the development of the nation's geothermal resources.

The technical feasibility for the use of high-temperature, composite materials for corrosion protection was demonstrated by BNL in the early 1980s, and since then they have been used successfully by the geothermal industry. It was shown that significant increases in the thermal conductivity of the polymer-matrix composites could be achieved by the incorporation of high conductivity materials as fillers. Conductivities approaching those of type-410 stainless steel were obtained. In addition, it was shown that the addition of high-temperature anti-oxidants into the composite significantly reduced the rate of scale deposition and adhesion to the surface. Work to develop a low-cost, low-fouling replacement material for the high-alloy steels used in geothermal heat exchange applications was then initiated.

As of October 1994, a 75-day test of PCL tubing exposed to flowing hyper-saline brine under heat exchange conditions typical of those utilized in a bottoming cycle was completed. Concurrently, AL-6XN control tubes were evaluated under similar temperature, pressure, and flow conditions. The lower-cost PCL exhibited an overall heat transfer coefficient and a fouling coefficient similar to that of the AL-6XN. Preliminary inspections revealed that the PCL provided excellent corrosion protection to the carbon steel substrate. A second test using PCL modified by the inclusion of anti-oxidants is planned for FY 95.

APPROACH

The work is being performed as a collaborative effort between BNL, NREL and private industry (Magma Operating Company). BNL performs the fundamental and applied research necessary to define the polymer cement formulations, determines protective coating thickness requirements, and develops methods for the placement of thin, uniform coatings on heat exchanger tubes. Post-field test evaluations also are performed at BNL.

Engineering analyses and heat transfer tests are conducted by NREL. This work includes measurements of heat transfer coefficients, cost estimates, and the management of field testing. NREL also coordinates technology transfer activities.

The Magma Operating Company provides the field test site, operating personnel, and ancillary equipment at a plant at the Salton Sea. Tests in an environment typical of that in a bottoming cycle application in a flash process are being performed.

RESEARCH RESULTS

Work was performed at BNL to optimize the various process parameters for applying a composite liner on the inner surface of small-diameter tubing and to determine the minimum thickness required to assure corrosion resistance. Similar studies were conducted with PCLs containing anti-oxidants. The ability to centrifugally cast the modified formulations onto long lengths of tubing was verified. NREL completed heat transfer calculations and performed cost evaluations which confirmed the potential cost-effectiveness of the materials system. The first engineering-scale flow test at the Magma Operating Company was completed. Seventy-five of a planned 100-day field test were accomplished. Boroscopic examination of the tubes revealed no obvious corrosion of the carbon steel substrate or spalling of the PCL. However, all of the tubes, including the AL-6XN high alloy steel controls, were extensively scaled such that the flow area of the brine was very restricted. This flow restriction was suspected even before the boroscope inspection because of repetitive brine pump failure and low brine flow through the tubes. At the time of shutdown, the overall heat transfer and fouling coefficients for the PCL remained at essentially the same values as those for the AL-6XN. Post-exposure evaluations planned for the tubing include x-ray analysis for PCL delamination, ease of scale removal using hydroblasting, scale composition, PCL thermal stability and erosion resistance, carbon steel corrosion, depth of brine penetration into the PCL, and reaction products at the PCL/steel interface.

FUTURE PLANS

Laboratory R&D to evaluate the effectiveness of the use of anti-oxidants as a method for reducing scale accumulation on composite lined heat exchanger tubing will be completed. Optimization of the anti-oxidant concentration with respect to scale deposition and adherence will be made. Based upon the laboratory results, four 6-m lengths of PCL tubing containing anti-oxidants will be prepared for use in a second field test. The conditions for this test will be similar to those for the FY 94 test, and the results will quantify the benefits of anti-oxidant additions. Tubing samples will also be provided to heat exchanger manufacturers for use in work to define potential methods for the joining of PCL tubes to tube sheets in shell-and-tube heat exchangers.

INDUSTRIAL INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Magma Operating Company	CRADA participant. User of technology.
Babcock & Wilcox	Potential supplier of technology.

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FIELD TESTING OF THERMALLY-CONDUCTIVE, CORROSION-RESISTANT LINERS

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KEY WORDS

Materials testing, polymer concrete lining, heat exchanger

PROJECT OBJECTIVES

The goal of this activity is to reduce the cost of electricity generation from moderate-temperature geothermal resources by improving the performance and economic viability of binary geothermal power cycles. The objective of this task is to complete 100-day field experiments for quantifying heat transfer and anti-corrosion properties of polymer concrete lining. This task is important to the geothermal industry because it provides an alternative to the existing, expensive, high-alloy, stainless steel heat exchanger tubes.

Technical Objectives

- Collect field data for quantifying the anti-corrosion, anti-scaling, and heat transfer properties of the polymer concrete lining.
- Assess manufacturability of the polymer concrete lined heat exchangers.
- Assess economic advantages of the polymer concrete lined heat exchangers over the high-alloy stainless steel heat exchangers.

Expected Outcomes

- Obtain field test information that will help to establish the engineering data required for full-scale heat exchanger design for use in binary geothermal cycles.
- Develop new heat exchanger lining material that will lower the cost of electricity generation and extend the life of the primary heat exchangers.
- If successful, similar thermally non-conductive coatings could be used to reduce the cost of brine piping and well casing.
- The outcome of this project can help the development of appropriate coatings that could be used for extending the life of the plant's rotating equipment that must be periodically repaired because of corrosion and erosion damage.

PROJECT BACKGROUND AND STATUS

A major concern in utilization of geothermal resources for production of low-cost electricity is the scaling and fouling of heat exchanger surfaces used in binary geothermal power cycles. Brookhaven National Laboratory (BNL) has developed a low-cost Polymer Concrete (PC) material that, when applied to an inexpensive base metal (e.g. carbon steel), can protect it from corrosion. It is also believed that PC lining will provide less buildup of scale deposits. An industrial partner and NREL have been collaborating in conducting field experiments at a geothermal power plant to quantify the heat transfer and anti-corrosion properties of Polymer Concrete Lined (PCL) heat exchanger tubes provided by BNL. Recently, 75 days of field testing was completed and the tubes have been sent to BNL for post-test examination. The field testing of the PC lined heat exchangers started in late 1993 and continued through 1994. Following the post-test examination of the tubes, a final report on the results of the field tests and the performance of the PC lined tubes will be prepared by April 1995. In this report, the performance of the PC lined tubes will be compared to the performance of more expensive high alloy stainless steel tubes.

APPROACH

The approach taken in this task is to work closely with an industrial partner and BNL, where the polymer concrete lining was developed, to complete the field testing, and to aggressively promote the commercialization of the polymer concrete material as a tube lining. In preparation for field testing, NREL signed a Collaborative Research and Development Agreement (CRADA) with an industrial partner for utilizing brine in one of their geothermal power plants. The steps taken by NREL for achieving the objectives of this task include:

- The long-term field testing was completed that began in FY 93. These tests were completed on November 1994, and the tubes are in the process of post-test examination.
- Post-test examination (both destructive and nondestructive) was conducted of the fouling and corrosion in the tubes. Following the long term field testing, BNL and our industry partner are preparing the tubes for post-test examinations and measurement of the accumulated fouling and corrosion.
- An analysis was performed of the economic value of the PC lined tubes relative to the high alloy stainless steel tubes that it would replace. NREL's industry partner with the help of NREL will perform value analysis of PC lined tubes compared to high alloy stainless steel tubes.
- An assessment was completed of the manufacturability of the lined tubes in a full-size heat exchanger configuration. NREL will work closely with US firms knowledgeable in the areas of advanced materials and heat exchanger construction to assess and evaluate manufacturing issues related to PC lined heat exchangers.
- Plans were developed to test other linings of interest.

RESEARCH RESULTS

Early testing of the PC lining was conducted by researchers at BNL in laboratory environment using test coupons. The preliminary indications of laboratory tests were that the lining could provide protection

to pipes exposed to the aggressive brine environment. BNL researchers measured the thermal conductivity of the PC material as well. They reported a thermal conductivity of $k_{pc} = 3.7 \text{ Btu/hr } ^\circ\text{F ft}$. Based on this measurement, it is concluded that the effective thermal conductivity of a base metal such as carbon steel tube ($k_{cs} = 26 \text{ Btu/hr } ^\circ\text{F ft}$) with the PC lining is comparable to that of the more exotic and expensive stainless steel tubes ($k_{ss} = 8.2 \text{ Btu/hr } ^\circ\text{F ft}$), having the same wall thickness.

To evaluate and compare the performance of the PC lined tubes to that of high-alloy stainless steel tubes in an actual geothermal field, Idaho National Engineering Laboratory (INEL), an industrial partner, and BNL conducted a combination of base line and field experiments during FY 90. The study was supported by the Department of Energy's (DOE's) Geothermal Division. The base line tests were conducted using a relatively benign brine (with total dissolved solids (TDS) of 5000 ppm) with the objective of providing "clean" performance data. The field tests were conducted using a very corrosive brine (with a TDS of about 250,000 ppm). The base line experiments were successful and provided very useful information. However, the field tests were faced with numerous problems as a result of the high TDS of the brine used for field experiments. The post examination of the test tubes indicated that the primary contributor to the unexpectedly poor performance of the PC lined tube was a non-uniform and overly thick PC lining that varied from 0.025 inch to 0.120 inch. The high total dissolved solids content of the brine with silica particles suspended in the solution caused plugging of both the AL-6XN and the PC lined tubes in less than 30 hours of operation. During FY 93, INEL completed a technical report (1) describing the results of both base line tests and field experiments. This report is currently being reviewed by DOE and the industrial partner who provided the brine for field tests and will be released shortly.

During FY 93, NREL assumed the performance evaluation of PC lined heat exchanger tubes by preparing for a new round of field experiments on a new set of PC lined tubes provided by BNL. As initial step, NREL carried out a simple thermal and value analysis of PC lined tubes. The purpose of this analysis was to provide information to BNL about the minimum requirements for a PC lined tube to be comparable in performance to the expensive AL-6XN tubes. In this study, the thermal performance of two heat exchangers, one with AL-6XN tubes and the other with PC lined carbon steel tubes, was simulated and compared under similar conditions. In order to study the effect of the thickness and thermal conductivity of the PC lining on the overall performance of carbon steel tubes, these parameters were varied over a wide range. The results of this study were communicated to both DOE and BNL in two short reports in early FY 93.

The thickness of the lining and its resistance to scaling have been identified as critical factors in determining the thermal performance of the liners, while the uniformity of the lining is critical in providing corrosion protection. NREL identified a non-destructive technique, taking cross-sectional x-ray photographs of the tubes, for measuring the thickness and uniformity of the PC lining of carbon steel tubes. This technique is employed by a variety of shops and is customarily used for non-destructive testing of welds. From these images the thickness of the tube wall and the lining can be clearly distinguished and measured. This technique can be equally applied for post examination of the tubes for measuring the thickness of any scale buildup.

NREL utilized a test skid originally designed and built by INEL for conducting the field experiments. The test skid consists of two parallel heat exchanger loops where one loop contains the PC lined tubes and the other loop contains the AL-6XN tubes. Each loop consists of four 20 ft long heat exchangers connected in series that provides a total heat exchanger length of 80 ft. This total length is similar to the length of the commercial heat exchangers with similar residence time for geothermal brine. Each loop is a double pipe counter flow heat exchanger with brine flowing through the inner tube and cooling water

flowing through the annulus between the tube and outer pipe. For more details about the test unit please refer to previous reports (2) submitted by INEL.

The carbon steel tubes (used as base metal) were 1" o.d. with 0.049" wall thickness. The thickness of the PC material was 0.030" resulting in total wall thickness of 0.079". The AL-6XN tubes were 1" o.d. with 0.065" wall thickness. AL-6XN tubes with 0.079" wall thickness could not be purchased readily and required a manufacturing period of up to four months causing a serious delay in conducting the field tests.

All the PC lined tubes were x-rayed before the field tests and they showed that the lining in all the tubes was uniform and had a thickness of about 0.03 inch. This thickness was chosen based on the simulation results conducted at NREL. NREL's simulations showed that the lining thickness below 0.030 inch will provide better heat transfer, however, it is not clear if thicknesses below 0.030 inch would protect the base metal from corrosion. Following the completion of the field tests, x-rays of all tubes were taken again for the post test examination and comparison.

During the field tests, data were recorded over ten-minute intervals. Each leg of each loop of the test skid was instrumented to record the inlet and outlet temperatures of the brine and cooling water as well as the pressure drop. Using the field data, the pressure drop, friction factor, and overall heat transfer coefficient for each tube were calculated. Unfortunately, due to the nature of the collaborative agreement between NREL, and its industrial partner, field test data cannot be released at this time. A complete report will be prepared on this task by April 1995 and will be submitted to DOE and our industrial partner for their review and evaluation. However, it is safe to say that the field tests indicate that the performance of the PC lined tubes is similar to that of high-alloy stainless steel tubes under the same operating conditions.

The information gathered from this field testing will help to establish the engineering design data for full-scale heat exchanger design for use in binary cycles in conjunction with electric power generation.

FUTURE PLANS

Post-test examination of the tubes is planned to be completed by March 1995. Although the field test results obtained to date are very encouraging and show comparable hydraulic and thermal performance, additional field operation are planned for an improved PC lining that is expected to have better resistance against scale buildup. In addition, a value analysis exercise is planned to prove that PC lined tubes (or heat exchangers) are economically advantageous. There also remains the question of manufacturability of the PC lined heat exchangers. It is not clear yet if the PC material will be applied to the heat exchangers as a whole or it will be applied to each individual tube. If so, questions related to forming the tube joints need to be addressed. An industry partner will be identified for collaborative work related to the question of the manufacturability of PC lined heat exchangers. Also the thickness of the PC lining needs to be optimized such that it protects the base metal while providing good heat transfer.

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ADVANCED HIGH-TEMPERATURE, CO₂-RESISTANT LIGHTWEIGHT CEMENTS

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KEYWORDS

Calcium aluminate cements, phosphate containing compounds, acid-base reactions, mechanical properties, carbonation, lightweight, pumpable, well completions

PROJECT OBJECTIVE

The quality of the cementing phase of a geothermal well completion often establishes the life expectancy of the well. Poor cements can result in blow-outs and casing corrosion or collapse. The conventional use of normal weight (approximately 1.7 g/cc) slurries can contribute to the formation of lost circulation zones when attempts are made to cement in weak unconsolidated rock zones with very fragile gradients. Therefore, lightweight (approximately 1.2 g/cc) slurries that cure to form hydrothermally durable materials are badly needed.

Technical Objectives

The technical objective of the project is to develop and field test non-portland based cementitious materials which can be used for geothermal well completions. Specific design criteria are as follows:

- Slurry density, approximately 1.3 g/cc;
- Pumpability, 4 hr at 100°C;
- Carbonation rate, <5 percent after 1 year in brine at 300°C containing 500 ppm CO₂;
- Compressive strength, >5 MPa at 24-hour age;
- Bond strength to steel, >0.07 MPa; and
- Water permeability, <0.1 m Darcy.

Expected Outcomes

Attainment of the project objectives will result in the following:

- Decreased costs for well completions due to reductions in lost circulation control episodes;
- Increased well life to >20 years;
- Reduced environmental concerns regarding blow-outs; and
- Permit development of higher temperature, higher CO₂ content brines.

PROJECT BACKGROUND AND STATUS

During the period 1978-84, BNL under sponsorship of the Department of Energy, Geothermal Division, organized and conducted an R&D program to develop and test advanced normal weight cement formulations. This international effort coordinated through the American Petroleum Institute, which involved universities, private industry, and government laboratories, culminated in the field testing under downhole flowing brine conditions of several cement formulations cured in-situ. The CO₂ content in this well was low, therefore carbonation resistance was not evaluated. The results from this effort currently serve as the basis for the selection of cements used for geothermal well completions throughout the world. All of the cement slurries evaluated that had densities < 1.6 g/cc failed to meet the test criteria, identifying a research goal that, based upon recent work, appears attainable.

A more recently identified problem that is severely reducing well life, and has increased costs and environmental concerns, is cement deterioration due to alkali metal catalyzed reactions between CO₂-containing brines and the calcium silicate hydrate (CSH) compounds and calcium hydroxide present in conventional well cements. In the former, 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 CaCO₃ and Ca(HCO₃)₂ leads to rapid reductions in strength, increased permeability, and corrosion on the outside surfaces of the well casing. Cement failures attributed to CO₂ are occurring in less than five years, and in one case, resulted in a collapsed well casing within 90 days. Solving these materials problems is the goal of the current cement research activity.

As of October 1994, two cement formulations that meet most of the design criteria have been developed. Laboratory characterization is nearing completion. Industrial collaborators (Halliburton Services and Unocal) have been identified and they are participating in ongoing engineering-scale tests. Plans for field testing in a variety of geothermal fluids are being made.

APPROACH

The project is organized into five phases: 1) fundamental cement research; 2) mix design; 3) property characterization; 4) placement technology; and 5) downhole evaluations. Phases 4 and 5 are conducted as cost-shared efforts with industry to insure the practicability of the materials and technology transfer.

Phase 1 consists of fundamental work to synthesize non-portland, cement-based materials and to elucidate the interactions that occur between them and a number of aluminosilicate-based microsphere fillers. State-of-the-art surface science analytical techniques are used in all parts of this phase. Phase 2 consists of the development of cement-filler mixtures and curing conditions to yield the desired properties. In Phase 3, the mechanical, physical, and chemical resistance characteristics of promising formulations are determined before and after autoclave exposures to CO₂-containing hydrothermal fluids. The technical feasibility for use of the cement slurries in well completions using conventional placement technology is determined in Phase 4. This work includes the selection of retarding admixtures to extend pumpability, and verification of this by the performance of consistometer testing in accordance with American Petroleum Institute standards. Industrial assistance in the selection of retarders is contributed by a well service company. In Phase 5, which is a cost-shared activity with a well service company and a well owner, the ability to mix and place the cements on a large-scale is verified, and the long-term durability of samples cured in and exposed to downhole geothermal environments is determined.

RESEARCH RESULTS

Materials that yield a cementing matrix produced by acid-base reactions between calcium aluminate cements and phosphate-containing compounds can be mixed with lightweight fillers to produce pumpable slurries with densities as low as ~ 1.1 g/cc. Upon curing for 20 hours in hydrothermal environments up to 300°C , high strength, durable, and CO_2 -resistant cement pastes are produced. Four different commercially available calcium aluminate cements were used as base reactants, and it was determined that the reactivity and resistance to carbonation were dependent upon the chemical composition of the base ingredient. The presence of monocalcium aluminate (CA) and gehlenite (C_2AS) accelerated the setting of the cement and reduced carbonation. All of the cement pastes exhibited compressive strengths > 58 MPa after hydrothermal curing at 250°C for 20 hours. Subsequent exposure to an 0.05 M Na_2CO_3 solution at 250°C for 120 days indicated strength changes over the first 28 days due to the growth of crystalline phases, after which the compressive strength remained constant. Measurements of the CaCO_3 concentrations produced during the 120 days indicated values of < 0.4 percent by weight (wt%) for all of the cements except the one rich in CA. A conventional portland cement-based well completion material will form approximately 10 percent by weight CaCO_3 after only seven days exposure to the same environment.

The incorporation of inorganic and organic microsphere fillers into the calcium phosphate cement matrix (CPC) produces a lightweight, moderate-strength, and highly durable cement. An aluminosilicate-based hollow microsphere, with a density of 0.67 g/cc and a particle size of 75 to $200\mu\text{m}$, produced the most suitable results, a low slurry density of approximately 1.3 g/cc and a compressive strength greater than 6.89 MPa. The slurry did not segregate after storage for 24 hours at 25°C due to chemical interactions between the microspheres and the cementing matrix formulation. Upon curing, this microsphere-filled lightweight CPC exhibited the following characteristics: 1) after autoclaving at 200°C , amorphous ammonium calcium orthophosphate (AmCOP) salt and $\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$ gel phases, formed by the reaction between calcium aluminate cement and an $\text{NH}_4\text{H}_2\text{PO}_4$ -based fertilizer, were primarily responsible for the development of strength; and 2) at a hydrothermal temperature of 300°C , the microsphere shell moderately reacted with the CPC to form an intermediate reaction product, epistilbite (EP), while crystalline hydroxyapatite (HOAp) and Boehmite were yielded by the phase transformations of AmCOP and $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, respectively.

Only short-term data on the carbonation resistance of LCPCs containing aluminosilicate microspheres are currently available. After exposure to 0.05M CaCO_3 solutions for 10 days at temperatures between 100° and 300°C , < 0.4 percent by weight CaCO_3 was produced. Acceptable compressive strengths and water permeabilities were also produced. Longer-term exposure data are needed before field testing can commence.

The use of hollow acrylonitrile microspheres covered with a calcite sizing layer results in CBCs with slurry densities as low as 1.1 g/cc which when cured yield properties which appear suitable for use in wells at 200°C . At this temperature, the compressive strength is 3.7 MPa and the water permeability is 0.05 m Darcy. Unfortunately, hydrothermal decomposition of the microspheres occurs at approximately 300°C , thereby eliminating higher temperature applications.

FUTURE PLANS

Fundamental and applied research leading to the identification of reaction paths yielding advanced high temperature lightweight CO_2 -resistant cements will be continued. Promising materials will be

characterized and then introduced into the cooperative program with the geothermal industry for scale-up and downhole evaluation.

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CHEMICAL SYSTEMS FOR LOST CIRCULATION CONTROL

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KEY WORDS

Lost circulation control, calcium phosphate cements, blast furnace slag, thickening time, strength, permeability, hydrothermal stability

PROJECT OBJECTIVES

Correcting lost circulation episodes is the single most costly problem routinely encountered during well drilling and completion operations, and may constitute 10 to 20 percent of the well cost. This project is to yield advanced cementitious materials which can be used in conjunction with placement technology under development at Sandia National Laboratories. The overall goal is to reduce geothermal lost circulation costs by 30 to 50 percent.

Technical Objectives

The technical objective of the work is to develop advanced chemical formulations which can be used to rapidly plug lost circulation zones. Specific design criteria are as follows:

- Viscosity of mixed reagents, < 40 Bc for four hours at 300°C;
- Compressive strength, > 3 MPa at two-hour age;
- Permeability to water, < 10⁻² Darcy;
- Volume increase upon curing;
- Durability in brine at 300°C > 30 days;
- Compatibility with organic and inorganic particulates; and
- All constituents environmentally benign.

Expected Outcomes

When utilized in conjunction with advanced placement technologies, the materials systems under development will result in:

- Reductions in geothermal lost circulation costs by 30 to 50 percent; and
- Reductions in fluid production costs by 10 to 13 percent.

PROJECT BACKGROUND AND STATUS

Lost circulation is the loss of drilling fluids to pores or fractures in a wellbore during drilling or of mix water during well cementing. This loss of fluids is expensive and causes problems related to hole stability and wellbore completion. When loss zones consist of major fractures, as is common in geothermal drilling, rapid setting cements are required. Conventional oil well cements have excessive set-up times

(around eight to 24 hours) and may not withstand harsh geothermal environments. In order to decrease the time period between placement of a lost circulation control cement and resumption of drilling, it is necessary to decrease the set time of the cement and increase the rate of strength development after setting.

As of October 1994, several promising calcium aluminate-blast furnace slag formulations have been developed which meet many of the design criteria. Engineering-scale field testing of the materials at Sandia National Laboratories and possibly downhole evaluations as part of a Geothermal Drilling Organization Project, are scheduled for FY 95. Unfortunately, the Department of Energy, Geothermal Division, budgetary constraints which resulted in termination of the BNL effort at the end of FY 94 will severely impact these plans.

APPROACH

The work was being conducted in four phases. In Phase 1, cementitious formulations were selected for evaluation. Emphasis was placed upon chemical interactions occurring between the cementing matrix and reactive fillers, and identification of the reaction phases formed. Mechanical, physical, and chemical durability characterization was conducted in Phase 2. Optimization of the formulations for use with the advanced placement techniques identified by Sandia was conducted in Phase 3. Contingent upon these results, larger-scale engineering and downhole field tests were to be performed in Phase 4.

RESEARCH RESULTS

Calcium phosphate cements produced by reacting calcium aluminate cement with sodium phosphate compounds exhibit potential as lost circulation control materials for geothermal drilling. Rapid set and strength development can be achieved. The calcium phosphates show low permeability and good durability under hydrothermal conditions. Thickening time can be controlled by the addition of borax. The type of phosphate used also controls thickening time and compressive strength. Use of ground granulated blast furnace slag as a partial replacement for calcium aluminate cement results in thickening time extensions, particularly at elevated temperatures, and has the added benefit of cost reduction.

FUTURE PLANS

BNL materials development work was terminated at the end of FY 94 due to budgetary constraints. Above ground engineering-scale and downhole testing is scheduled for FY 95 as Sandia National Laboratories coordinated activities. Both tests will be severely impacted by the lack of BNL participation.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Halliburton Services	Materials evaluation. Potential supplier for chemical systems and field placement services.
California Energy Company, Inc.	Possible Geothermal Drilling Organization participant in downhole evaluation of materials. Well owners, potential users of technology.

Organization(s)	Type and Extent of Interest
Schlumberger	Potential supplier for chemical systems and field placement services.
Unocal	Well owners, potential users of technology.

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ADVANCED BIOCHEMICAL PROCESSES FOR GEOTHERMAL BRINES

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KEY WORDS

Biochemical processing, decontamination, metal recovery, brines, sludges

PROJECT OBJECTIVES

Geothermal hydrothermal systems in the U.S. currently provide about 2,500 MW of electric capacity and can play a significant role in providing additional capacity. Moderate- to high-temperature hydrothermal resources are found in many areas of the United States, while low temperature hydrothermal resources can be used for direct heating.

Geothermal energy is a major, clean energy resource. However, disposal of toxic leachable solid waste in an environmentally and economically acceptable way may be a major impediment to large-scale geothermal development. Hypersaline brines lead to the generation of geothermal solid wastes in power plants. Currently, the disposal of these wastes can cost over \$1 million per year for a 50-MW geothermal power plant. High disposal costs and the long-term liability associated with hazardous waste disposal provide the incentive for this study in which cost-efficient processing of geothermal wastes is being developed.

The overall objective of the Advanced Biochemical Processes for Geothermal Brines effort is to develop economic and environmentally acceptable methods for disposal of geothermal wastes and conversion of by-products to useful forms.

Technical Objectives

Develop biochemical processes which:

- Solubilize, separate, and remove environmentally regulated constituents of geothermal sludges and brines;
- Produce a treated sludge which may be used as a feedstock for the production of revenue generating materials, for example, as fillers and construction materials; and
- Recover economically valuable trace metals and salts. The residues from such processing can be reinjected and/or converted to highly reduced volumes for disposal in the conventional manner.

Expected Outcomes

- The high disposal costs and the long-term liability associated with hazardous waste disposal will be reduced significantly. Assuming adequate funding, it is anticipated that at least a 25 percent or more reduction in disposal costs will be accomplished by FY 95/96. This will greatly enhance the rate at which U.S. hypersaline brine geothermal resources are developed.
- Conversion of geothermal sludges and brines into environmentally acceptable feedstocks, together with the metal salts recovery option, will offset the costs of initial investments associated with the installation of the biochemical processing plant(s).
- Integration of the biochemical processing recovery and recycling options into a geothermal power producing plant, may lead to a financial net gain with a concurrent satisfaction of regulatory requirements.

PROJECT BACKGROUND AND STATUS

In 1987, an R&D program was established at Brookhaven National Laboratory (BNL) to identify methods for the utilization and/or low-cost, environmentally acceptable disposal of toxic geothermal residues. Laboratory work has shown that a biochemical process would meet the cost requirements and produce environmentally acceptable end-products. In this work, micro-organisms which can interact with toxic metals (including trace radionuclides) found in geothermal residual brine sludges, and which can convert them into soluble species for subsequent reinjection or concentration, have been identified. The biochemical activities of these organisms served as models for the development of technically and economically feasible detoxification processes leading to advanced biotechnology for geothermal waste treatment. The new biotechnology reduces significantly the cost of surface disposal of sludges derived from geothermal brines. Concurrent processes for the concentration and recovery of valuable metals and salts is also being developed. Currently, the process removes better than 80 percent of total metal concentration in less than 24 hours. Economic and regulatory significance of the new biotechnology can be clearly defined by the following information.

In 1985, the graded cost for type II-I disposal was \$200.00 per ton and \$75.00 per ton for non-hazardous waste. The non-hazardous waste was defined as that not exceeding the total threshold limit concentration (TTLC) and soluble threshold limit concentration (STLC). For example, for chromium, STLC is 5 mg/L, which becomes 0.25 mg/L after the biochemical treatment, while the corresponding TTLC of 500 mg/L becomes 100 mg/L. Thus, an 80 percent removal of the metals represented a 60 percent saving. It is to be understood, that the cost of disposal and the long-term liabilities are continuously increasing, while the available space for disposal is diminishing. For example, at BNL, disposal of a similar sludge cost \$500.00 per ton in 1991. The corresponding non-regulated waste disposal cost was \$100.00 per ton. If the sludge contains in addition to chromium and lead, say radium, then it has to be shipped at a cost of \$400 per cubic foot. On the other hand, removal of the metals leaving radium alone produces waste costing \$76 per cubic foot to dispose of or \$10,800 and \$2052 per ton, respectively. This represents a five-fold saving already achievable on a laboratory scale.

Further process cost savings may be achieved by (a) reactants recycling, (b) metal and salt recovery, and (c) adjusting to specific needs as demanded by different chemistries of geothermal sludges and brines.

The benefits that result will be both environmental and economical. Not only will the detoxification be less expensive, but the end products will be useful. Recovered metals will have market value. The detoxified sludges can have such uses as landfills. The emerging biotechnology could find applications in other industries, for detoxification of wastes or recovery of metals.

APPROACH

(a) Selection Criteria:

Brines from the Salton Sea geothermal area in California may contain total dissolved solids up to 350,000 ppm. These hypersaline brines lead to the generation of regulated geothermal solid wastes in power plants. In other areas, major contaminants may be only a few metals, such as arsenic and mercury. Development of cost-efficient, flexible processes which meet regulatory requirements is the determining factor in the selection of geothermal waste processing technology.

(b) Rationale:

The major thrust of this program is to develop low-cost processes for the concentration and removal of toxic materials and valuable metals from geothermal residues. In addition, methods and materials for the utilization of environmentally acceptable storage of these waste fractions are also investigated. The results from this effort will reduce significantly the high disposal cost and the long-term liability associated with hazardous waste disposal. This will greatly enhance the rate at which U.S. hypersaline brine geothermal resources are developed.

(c) Experimental Approach:

The experimental strategy used at BNL for the development of detoxification biotechnology for geothermal waste is based on the use of biochemical methods for dissolution of toxic elements found in geothermal residues. Thus, the produced solution containing toxic and valuable metals can be reinjected or used for concentration and recovery of metals and salts. In the recovery mode, both chemical and biochemical methods are being developed.

Technical and economic feasibility of a technology based on biochemical processes for the conversion of geothermal wastes from hazardous to non-hazardous wastes has been demonstrated. Laboratory-scale studies have shown that biotechnology for detoxification of geothermal wastes is versatile and is applicable to a variety of geothermal sludges containing few or many metals, including radionuclides such as radium, whose concentrations may exceed limiting threshold values as recommended by regulatory agencies. Metals such as chromium, copper, manganese, and others, can be removed with 80-90 percent efficiencies. A laboratory-scale pilot plant has been constructed and is being used for the optimization of processes used in the emerging biotechnology. The data generated in these studies serve as a basis for the design of full scale processing scenarios and projections for field applications. In terms of the latter, there are several Cooperative Research and Development Agreements (CRADAs) and collaborative arrangements already in place. (See section below on Industry Interest and Technology Transfer.)

RESEARCH RESULTS

Tasks completed previously include:

1. Identification of process type, i.e., chemical or biochemical. Biochemical identified as best candidate.
2. Determination of system and choice of microorganisms. Development of thermophilic microorganisms which operate at 50°-60°C and pH 1-2.
3. Multi-element kinetic studies. Bench-model bioprocesses.
4. Comparison of bioreactors. Choice of bioreactors for scaling-up.
5. First generation of scaled-up fluidized bed and agitated tank bioreactors, and first full process design. Economic and technical feasibility studies based on expertise gained in 1-4 above, indicate cost-efficient, environmentally acceptable processes. In hand.

Current research tasks include:

6. Process variables: Identification and optimization including automation.
7. Parallel studies for metal recovery technology and production of clean water.
8. Construction of a batch process pilot-plant. Partially completed. A block diagram of this plant is shown in Figure 1. The block diagram does not include biocatalyst production plants.
9. Removal of radionuclides. Secondary biochemical process defined and tested. Optimization of process variables needed.
10. Removal of radionuclides. Process optimization studies.
11. Bacterial culture recycling.
12. P.G.&E. Waste Stream: Bioprocess defined. Field application under a CRADA with CET Environmental approved.
13. Processing of samples from Magma Power company.
14. Hot Dry Rock Fluids. Analysis and Bioprocessing: Phase I completed.
15. Metal and salt recovery potential: Integrated processing.
16. Educational programs have proven to be successful and are continuing as part of the ongoing R&D under the auspices of BNL and DOE, Geothermal Division educational programs.

FUTURE PLANS

Collaboration with industry will be expanded, e.g., cost-shared ventures. Verification of process variables will be completed. The best results from optimization studies will be used for operating and field construction cost analyses.

Quality Control will be continued based on lessons learned from the Salton Sea experience. Additional and continuing attention will be given to the environmental requirements and management of trace radionuclides. This aspect of the R&D is particularly important in view of the anticipated "NORM" regulations.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Magma Power (now part of California Energy Company, Inc.)	One on one collaborative effort. Confidentiality Agreement signed. BNL assists Magma Power in their analytical chemistry needs and selected technical studies. Magma Power consults and exchanges materials and information. Field trials of a prototype biochemical process will be conducted by Magma Power.
CET Environmental/ PG&E Services, CA	A CRADA between BNL and CET Environmental Services has been approved. Under this arrangement, CET will scale up a modified version of BNL's biochemical process specifically geared to the type of wastes generated by the type of operations at The Geysers. PG&E's management at The Geysers Geothermal Field have already agreed to allow field testing of this process on their sludge waste stream.

Spin-offs from "Advanced Biochemical Processes for Geothermal Brines" have led to other CRADAs and collaborative ventures particularly in the processing of Fossil Fuels and hydrocarbon wastes. These include:

EER, Inc., CA
ENSOL, Inc., CA
 LILCO
 EXXON
 CHEVRON

CRADA
 CRADA
 Collaboration. CRADA being negotiated.
 Collaboration
 Collaboration

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Biochemical Process for Geothermal Sludge

(Batch process, 8 hr/batch)

Figure 1. Biochemical Process for Geothermal Sludge

GEOTHERMAL POWER ORGANIZATION

Ellen Morris, John Anderson
National Renewable Energy Laboratory

KEY WORDS:

Industry advisory group, geothermal energy conversion

PROJECT OBJECTIVE

The objective of the Geothermal Power Organization (GPO) is to provide industry-driven research objectives and guidance to improve energy conversion systems for geothermal applications supported by the Department of Energy (DOE).

Technical Objectives

- Assemble a coalition of management and technical staff from all facets of the geothermal electric power industry to identify both long- and short-term research targets for the energy conversion program.
- Provide critical analyses of the technical aspects and direction of the energy conversion programs in the DOE Geothermal Division.

Expected Outcomes

- Develop and promote priority areas through cooperative research partnerships.
- Increase industry's participation in joint ventures, state energy initiatives, and utility/industry cost-sharing opportunities.

PROJECT BACKGROUND AND STATUS

The GPO is a combination of two previously formed working groups, the Energy Conversion panel (ECP) and the Technical Advisory Group (TAG). Since the focus and membership of these two organizations are similar, they have been merged under the umbrella organization of the GPO so that it can be a more effective mechanism for industry interactions and to prevent possible duplication of efforts. To date, there have been three GPO meetings.

APPROACH

The coordination and management of the GPO is done by the National Renewable Energy Laboratory (NREL), with oversight provided by the DOE Geothermal Division. The primary means for industry input into the DOE energy conversion program is through the GPO. To solicit feedback from industry, NREL will continue to organize and conduct the GPO meetings, which are held twice a year, and maintain communication with the industry members on pertinent issues.

RESEARCH RESULTS

The GPO has provided ongoing industry-driven research objectives and guidance to improve energy conversion efforts supported by the DOE. An outcome of the GPO has been a prioritized list of research areas that are important to the industry. Using a consensus-building (team) approach, a number of high priority research goals have been identified by the members of the GPO. A summary of these critical areas that should be part of an energy conversion program is shown in Tables 1 and 2.

FUTURE PLANS

Continue to plan and carry out bi-annual meetings that coincide with the Geothermal Resources Council annual meeting (Fall) and the DOE Geothermal Program Review (Spring).

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The members of the GPO are drawn from a cross-section of the geothermal community who are working on geothermal energy conversion technologies and equipment. The following sectors are represented in the GPO: plant operators, plant owners, equipment manufacturers, equipment and project developers, utilities, and environmental constituents.

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Table 1. Specific Activities Within Each General Category That Should be Pursued

	Team 1	Team 2	Team 3
Metastable Binary Turbine Expansion	<ul style="list-style-type: none"> - long term testing - economic studies - keep HCRF open 	<ul style="list-style-type: none"> - long term testing - steps to commercialization - expand to use of other working fluids - tests w/radial outflow 	<ul style="list-style-type: none"> - demonstrate no long-term problems - erosion, corrosion, isotrop. efficiency, system efficiency, prove efficiency gains - fluid property of crit. pt. - escape of hydrocarbons
Low Temperature Geothermal Plants	<ul style="list-style-type: none"> - new turbine design for lo-T flash plants - coordinate w/ other studies 	<ul style="list-style-type: none"> - control silica dep. in HX - study of geochem. - lo-T effect on ppt. of elements in brine - lo-T heat rejection - turbine devel. for binary cycles 	<ul style="list-style-type: none"> - kalina cycle demo. - concepts study - staged expansion - boiling cycle w/ mixed hydrocarbons - reduce water use - reduce footprint - dry cooling for mixtures - improved turbine generator equip.
Dry Wet/Dry Cooling Systems	<ul style="list-style-type: none"> - review EPRI study - economic analysis - evaporative pre-cooling - coordinate w/ other studies - ground-loop heat reject. - demo of hybrid system 	<ul style="list-style-type: none"> - reduce cost & size - reduce water use - corrosion problems - performance improvement of wet/dry systems for binary & flash systems 	<ul style="list-style-type: none"> - optimize wet cooling to incl. injection - demo. fin fan for Geysers - lower cost - improve materials - coatings-material - lo-quality makeup water - optimize dry-coolers for mixtures - minimize drift - low profile - minimize plume - reduce noise - improve NCG removal

Table 2. New Ideas--Top priorities for each group (number of votes)

Team 1	Team 2	Team 3
<ul style="list-style-type: none"> - NCG gas removal (4) - Improved pumps (3) 	<ul style="list-style-type: none"> - NCG gas removal & steam conditioning (5) - Coatings for heat exchanger and turbines (3) - Hybrid (gas/GT, solar/GT) power plants (3) 	<ul style="list-style-type: none"> - Steam driven compressor (5) - DCC Research (5)

GEOHERMAL HEAT PUMP CASE STUDIES AND UTILITY PROGRAMS

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KEY WORDS:

Case studies, ground coupled, ground source, groundwater, heat pump, performance, utilities, national assessment

PROJECT OBJECTIVES

The objectives of this program are to provide information on geothermal heat pump (GHP) performance and the status of electric utility companies in promoting the technology. Specific technical objectives are:

Technical Objectives

- Determine what existing monitored data are available on geothermal heat pump performance, energy savings, and demand reduction for residential, institutional, and commercial systems.
- Determine the most effective and successful utility marketing and incentive programs to expand geothermal heat pump markets, barriers to market entry, the number of installations in utility service areas, and benefits to utilities.

Preliminary results:

- Established a database of monitored GHP systems for residential, institutional, and commercial applications.
- The mean energy savings of residential GHP systems compared to air-source heat pump systems were 33 percent and electrical resistance heating systems were 52 percent. Winter demand reduction of GHP systems ranged for 3 to 7 kW compared to air-source heat pump units and summer reductions were 0.5 to 1.5 kW. The mean residential GHP system simple payback was 4.3 years. Commercial GHP system energy savings had a mean value of 50 percent over electric resistance heat with air-conditioning equipment.
- Annual energy costs for natural gas heating were less than GHP systems in four out of seven residential case studies.
- Determined the status of electric utility and rural electric cooperative programs to implement geothermal heat pumps into demand side management programs.

PROJECT BACKGROUND AND STATUS

Geothermal heat pump systems are a promising new energy technology that has shown rapid increase in usage over the past ten years in the United States. These systems offer substantial benefits to consumers and electric utilities in energy (kWh) and demand (kW) savings.

The Department of Energy (DOE) and the Environmental Protection Agency (EPA) are rapidly expanding their involvement in programs to promote increased use of both renewable-energy resources and energy-efficient technology. Federal implementation of the Clean Air Act Amendments of 1990 and the Energy Policy Act of 1992, and other regulations still under development, are a result of increasing worldwide environmental consciousness. Further, the environmental and efficiency aspects of energy production and use are expected to remain top priority items in President Clinton's Administration. Geothermal heat pump (GHP) systems can help meet the challenge by increasing our energy efficiency, with resulting benefits to utilities in better load management, to customers in lower utility bills and to society in a cleaner environment.

Electric utilities are the ultimate market targets for GHPs, especially utilities that are already committed to demand side management (DSM). Recommendations for implementation of geothermal heat pumps must be consistent with prevailing energy policies and supported by data. The data must show that the resource and technology are available, reliable, and cost competitive with other options. Concerns of utilities considering GHP technology as a DSM option include: (1) amount of demand and energy savings; (2) first cost of ground loop and wells; (3) effect of ground loop temperature increase for summer and long-term operation, especially for commercial applications; (4) utility rebates and other incentives; and (5) infrastructure availability of heat pump dealers and loop installation contractors.

The project was started in July 1992 and should be completed by September 1995. The project is estimated to be about 75 percent complete.

APPROACH

The Geo-Heat Center's approach is to compare as many types of like case studies, with monitored data, taken from as many sources as possible throughout the United States.

Oregon Institute of Technology provides a cost share of 10 percent on the project. Other participants in the project are the University of Utah Research Institute (UURI), primarily involved with technology transfer, and the Idaho Water Resources Research Institute, developing information on groundwater aquifer's that can be used for groundwater heat pumps.

RESEARCH RESULTS

In order to verify the performance of geothermal heat pumps, information from 217 case studies have been collected on residential, commercial, and school systems from primarily utilities throughout the United States. Sixty-five of these 217 case studies met the criterion that the system was compared to another energy source. These were compiled into a database. The database includes the startup date, location, GHP ground system description, application, capacity/demand, energy/economics, and data monitored.

Case Studies

Residential case studies represent systems located in north central, eastern, southern, and western U.S. climates. The systems were monitored for various parameters, ranging from only energy (kWh) input to the heat pump to eight other parameters. Unfortunately, there were very few case studies with a comprehensive set of monitored data available. Many testing techniques were used; but, ultimately the goal was to determine annual energy usage and peak demand savings for the homes.

The percent of GHP energy savings over air-source heat pumps (ASHPs) ranged from 13 percent to 60 percent with a mean of 33 percent. As shown in Figure 1, savings compared with electrical resistance systems with air-conditioning units ranged from 25 percent to 70 percent with a mean of 52 percent. In the case of GHP operating costs compared to oil and natural gas systems, natural gas costs were less in four out of seven case studies as shown in Figure 2. Figure 3 shows winter peak demand reduction which ranged from 3 to 7 kW compared to air-source heat pumps for typical homes. Summer reductions in demand only ranged from 0.5 to 1.5 kW. Utility coincident demand reduction with residential systems was, when monitored, about 33 percent less than the non-coincident demand.

GHP systems were analyzed for simple payback. The largest barrier to faster payback of GHP systems is the cost of the ground loop. The EPA (L'Ecuyer, et. al., 1993) has identified vertical loop costs for residential systems to be between \$200 to \$284/kW; while horizontal systems cost \$100 to \$142/kW. Costs are based on the experience of a U.S. north central utility in 1991. The lower costs are due to improved driller experience, economies of scale, and from design innovations (such as the spiral horizontal loop). Residential system simple payback ranged from two to 6.8 years with a mean of 4.3 years.

Figure 4 shows demand reduction (kW) of a vertical ground-coupled GHP system for a Virginia electric cooperative building. This is compared to a similar building with a variable air volume (VAV) electric heating system. A peak demand reduction of 46 kW occurred in March 1989 for the approximately 8,000 square-foot, ground-coupled GHP system over the VAV system. The total annual savings of the ground-coupled heat pump was \$4,783 or 55 percent compared to the VAV system.

Case studies documented for GHPs in commercial buildings ranged in capacity from 9 to 1,340 kW employing ground-coupled well fields of up to 370 boreholes for a 240-kW system to 3 wells for a 1,340-kW groundwater system. The percent energy savings ranged from 22 percent to 44 percent relative to air-source heat pump equipment and 40percent to 68percent over electric heat with air-conditioning equipment. Demand reduction for commercial buildings ranged from 32percent to 65percent with mean of 50percent.

Utility Programs

The geothermal heat pump is one of many technologies electric utilities are considering or implementing for demand-side management (DSM), especially aimed at improving the efficiency with which customer's use electricity. The results of DSM programs aimed at energy efficiency provide two benefits: they save energy and reduce peak demands. GHPs are one of the few DSM options that both save significant amounts of energy and reduce peak demands.

Information was developed on the status of DSM programs for about 60 utilities and rural electric cooperatives including: marketing programs, barriers to market penetration, incentive programs, number

of GHP units installed in service area, and the benefits to the utility. The most common marketing programs were newspaper and radio/TV advertisement, test and demonstration of GHP system performance, education programs, and home shows.

The primary barrier to marketing GHP systems according to a majority of the utilities is the incremental cost of installing the ground loop. Other deterrents to the implementation of GHPs cited by the utilities are: natural gas is inexpensive; lack of suppliers, dealers, and loop installers; and customer resistance to heat pump technology.

A total of 35 utilities reported installed GHP systems out of 60 contacted. More than 18,800 three-ton equivalent installed systems were reported, which probably represent about 9percent of the total installed across the United States.

Utilities have designed several incentive packages to encourage the installation of GHPs. In most cases, these incentives include cash rebates (average \$60/kW), low-cost financing, discounted energy rates, lease/purchase programs, and, in a few cases, ground-loop installations.

FUTURE PLANS

Documentation and monitored data continue to be collected and entered in a database for residential and commercial operating GHP systems throughout the nation.

Current and up-to-date information on the geothermal heat pump designs, especially those used in the commercial sector, are not easily found. There is a need to further document information on the operating experience with this technology and report on success and/or failure encountered at various locations in the United States.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The following are industries and institutions which have expressed an interest in the results of this project:

Organization(s)	Type and Extent of Interest
Electric Utilities	Energy and demand savings and installation costs
Rural Electric Cooperatives	Energy and demand savings and installation costs
California Energy Commission	Case study monitored data and utility programs

The Geo-Heat Center assisted UURI with the development of fact sheets by supplying data on specific case studies for technology transfer. In addition, information from this project was supplied to NREL for the development of a geothermal heat pump brochure. Papers on the preliminary results of the project have been prepared for the Geothermal Program Review XII and the 1995 World Geothermal Congress.

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Figure 1. Residential GHP energy savings (percent) compared to air-source heat pumps and electric resistance/air-conditioning systems.

Figure 2. Residential GHP annual operating costs compared to oil and natural gas systems.

Figure 3. Residential GHP non-coincident demand reduction compared to air-source heat pumps.

Figure 4. Demand reduction of a vertical ground-coupled GHP system for a Virginia electric cooperative building (CS-85) compared to a similar building with a variable air volume system.

GEOTHERMAL DIRECT-HEAT UTILIZATION ASSISTANCE

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KEY WORDS

Aquaculture, direct use, district heating, greenhouses, heat pumps, industrial, low temperature, silica waste, space heating, technical assistance

PROJECT OBJECTIVES

The objectives of this project are to provide assistance and conduct applied research and development to stimulate utilization of the nation's large low-to moderate-temperature ($<90^{\circ}$ to 150°C) "direct-heat" geothermal resource base. The success of this project will mean more rapid penetration of geothermal direct use into the energy sector.

Technical Objectives

- Provide technical assistance to developers of geothermal direct-use projects for space heating, geothermal heat pumps, greenhouses, aquaculture, and industrial applications.
- Perform appropriate R&D to reduce the cost of installing and operating direct-use projects.
- Publish information and educational materials and maintain a library to aid researchers and developers of geothermal direct-use projects.

Expected Outcomes

- Obtain energy savings and reduced emissions of airborne pollutants and greenhouse gases due to more geothermal direct-heat projects on-line.
- Improve design of downhole pumps.
- Compare costs of commercial geothermal heat pump systems.
- Increase awareness of geothermal direct-heat developments and opportunities by publication of Bulletins on geothermal projects, technical papers, software, tours, and other educational materials.

PROJECT BACKGROUND AND STATUS

The Geo-Heat Center located at the Oregon Institute of Technology (OIT) conducts research and provides assistance to users to stimulate utilization of the large direct-heat resource base in the United States. These users are typically small businesses, various types of local industries, communities, and individuals. They rarely have the technical expertise to determine the feasibility of a proposed application or to solve problems related to the operation of a geothermal heating system. Additionally, consultants for such systems often also require technical assistance. Technical information on project designs, technology advances, and new products is made available through a dedicated library and quarterly Bulletin. A handbook, Geothermal Direct Use Engineering and Design Guidebook, has been developed by Center staff and others to aid developers and engineers in the design of geothermal projects.

Geothermal direct-heat utilization assistance started in 1990; however, the technical assistance program was initiated in 1979. This program is a continuing effort to provide assistance to developers of low-temperature geothermal resources. Since 1990, the thermal capacity of direct heat projects increased by 51 Mw., representing an annual energy utilization of 524 TJ/yr (not including heat pumps). This growth is the result of 18 direct-heat projects in five states, ten of these are new projects and eight involved expansion. The Geo-Heat Center provided technical assistance to 14 of the 18 projects.

APPROACH

The Geo-Heat Center's approach is to provide technical assistance (TA) 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 14.3percent 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

The Geo-Heat Center provides assistance to those actively involved in geothermal development. Geothermal projects are allocated a limited number of man-hours (usually eight hours/project unless prior approval is received from the Department of Energy (DOE)) for analysis. 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 the process energy needs. During FY 94, the program handled 356 requests for technical and development assistance on geothermal direct-use projects and for various types of technical information. The program's R&D accomplishments included: (1) evaluation of lineshaft vertical turbine pump problems, and (2) capital cost comparison of commercial geothermal heat pump systems.

Downhole Pumps

A number of lineshaft turbine pumps used for producing geothermal fluids with temperatures ranging from 53° to 121°C have failed for various reasons. Specific pump failures have been summarized for

geothermal wells listed in Table 1. As the draft summary table shows, early failures appear to be related to variable-speed drives and pumps with extra lateral. Life appears to be only weakly inversely related to geothermal fluid temperature. Further investigation is indicating that life is related to system operation. Pumps in systems that have wide swings in flow rates (i.e., space heating systems where flows are low in summer and high in winter, which operate most the time at relatively low flow rates) seem to have most early failures. Pumps for these systems are typically specified for peak flow rates (considerably above calculated peak flows as a safety factor); therefore, are operating much of the time at 50 percent or less of design peak efficiency. This kind of operation has been related to early failures of large centrifugal pumps, failure being the result of vibrations caused by a phenomenon known as recirculation first documented in the early 1980s and not yet fully understood by pump designers or even known about by many engineers. This leads to a closer investigation into system operation as opposed to investigation of materials and bearing design that was at first suspected. The results of this investigation are being compiled into a report that will undergo a peer review by pump engineers in the industry. Also, a summary of this evaluation will be added to the pump chapter in the next edition of the Geothermal Direct Use Engineering and Design Guidebook.

Cost Comparison of Geothermal Heat Pumps

Commercial geothermal heat pump systems have been installed in a variety of configurations. Among the most common are groundwater, vertical ground-coupled, and hybrid ground-coupled (with cooling tower). Capital costs associated with installation of these three ground-source heat pump systems were compared for size ranges of 50 to 500 tons. Costs were also developed for three groundwater/soil temperatures: 10.0°, 15.6°, and 21.1°C representing northern, central, and southern climates. The basis for all calculations was a building loop temperature during the peak cooling load of 29.4°C supply water (to the heat pumps) and 35.0°C return water (from the heat pumps). Based on the assumption of equal building loop costs, a comparison was made of those costs associated with the ground-source portion of the system. Sensitivity of cost to a variety of factors including: well depth, system capacity, and soil (or groundwater) temperature were evaluated.

Figure 1 summarizes results for three types of systems for 15.5°C soil and the lowest capital cost conditions. The vertical ground-coupled system cost line is based upon \$16.40 per m and \$283.72 per kW. The two hybrid system curves are based upon loop length ratios (heating length/cooling length) of .30 and .40. These are the most favorable ratios for hybrid systems evaluated. The two groundwater curves are based upon 60 m wells and one production/injection well pair (lower curve) and two production/injection well pairs (upper curve). For this specific case, the groundwater system enjoys substantial capital cost advantage (for example a 500-ton capacity ground source system costs about \$1,000/ton for ground-coupled, \$600/ton for hybrid, and \$200/ton for groundwater) over the remaining two systems over the entire range of capacities (Rafferty, 1994).

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.

R&D activities will include geothermal district heating marketing strategies for several systems installed under DOE sponsorship and geothermal direct heat cost analysis to allow prospective developers to quickly bracket the range of probable costs for a project or site.

The Bulletin will be distributed quarterly, new software will be developed that will enhance the ability of design engineers on geothermal direct use projects, and information about geothermal projects and other related developments will be gathered and distributed.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The following is the number of requests for geothermal direct heat technical assistance during Fiscal Year 1994 from individuals, companies, and municipalities:

Type and Extent of Interest	Number of Requests
Space and District Heating	76
Geothermal Heat Pumps	71
Greenhouses	43
Aquaculture	9
Industrial	1
Resource/well	65
Equipment	32
Other	<u>59</u>
Total	356

Technology transfer activities included: publication of the GHC Quarterly Bulletin (v.15, n.2-4, and v.16, n.1), which includes technical articles and a geothermal progress section. A Geothermal Library of 5,100 volumes was computerized with the same software as used by the Geothermal Resources Council to enable compatibility through the GRC's on-line access system. A total of 781 publications were requested during the fiscal year, 14 technical papers were prepared (see references), 14 presentations were given at conferences, 15 tours of local geothermal facilities were conducted, and 17 geothermal progress monitor reports were prepared.

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Figure 1. Ground-source heat pump system costs (15.5°C water or soil - lowest capital cost conditions).

TABLE 1.

Name	Variable Speed	Extra Lateral	Bearing Material	Pump Setting	Pumping Level	Temp. °F	Average Rotating Life/Years	Comments
OIT #2	Yes	Yes	Brz.	360 ft	310 ft	192	6+ so far	Operated OK since new (1971) in same water conditions as other OIT pumps.
OIT #5 (July 1989)	Yes	Yes	Brz.	440 ft	350 ft	192	6+	Bowls had been in service 24+ years. Bearings replaced about every 6 years.
OIT #5 (August 1994)	Yes	Yes	Brz.	440 ft	350 ft	192	2 1/2	Lower 7 bowls and impellers worn beyond repair. Upper bowls and impellers worn. Lower bearing completely gone and shaft worn into bowl bearing housing. Upper bearings still in place but worn.
OIT #6	Yes	Yes	Brz.	600 ft	550 ft	192	6+ so far	Bowls in service 23+ years. Bearings and impellers replaced after 17 years.
Susanville (all in same well)								
Pump #1	Yes	Yes	Rubber	140 ft	-70 ft	174	5 1/2	Bowls, bearings and impellers looked like new. Rubber bearings had swelled.
Pump #2	Yes	Yes	Rubber	140 ft	-70 ft	174	16 mos.	
Pump #3	Yes	Yes	Rubber	140 ft	-70 ft	174	a few hrs.	No failure, not inspected. Pump is run at about 2/3 flow during heating season.
Naef	Yes	No	Brz.	160 ft	146 ft	158	9+ so far	No failure, not inspected. Pump is run at nearly full speed all the time during heating season.
Klamath County Shops	Yes	No	Brz.	165 ft	65± ft	128	10+ so far	No failure, not inspected. Pump is always run at full speed and very near best efficiency.
Wineagle	No	No	Brz.	140 ft	85± ft	231	7+ so far	Bearings and impellers worn at 4 - 5 year intervals. Bowls sometimes re-machinable.
Merle West Medical Center	Yes	Yes	Brz.	550 ft	300 ft	192	4	Strange wear pattern. Cause unknown. Possible imbalance of impellers.
Modoc High School	Yes	Yes	Brz.	320 ft	varies 25 - 280 ft	170	2 1/2	Not good example - poor engineering.
Colahan	No	No	Brz.	230 ft	?	230	1 - 2	Pump ok. Crooked well caused column brg. failure.
Bottling	No	No	Brz.	240 ft	55 ft	249	1 - 3 mos.	Improper alignment of lower column caused pump vibrations and failure. Possible critical speed problems?
CSI	Yes	No	Brz.	220 ft	100± ft		1	This pump is in an ex-artesian area and has a shallow (-90 ft) pump setting. The pump is turned on in fall and off in spring. No failure. Not inspected.
Klamath Union High School	No	No	Brz.	-90 ft	20 ft	165	12+ so far	Operated in shaft critical speed range.
Anonymous (Klamath Falls)	Yes	No	Brz.	90 ft	55 ft	172	10 days	

ENVIRONMENT

USE OF SILICA WASTE FROM THE CERRO PRIETO GEOTHERMAL FIELD AS CONSTRUCTION MATERIAL

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KEYWORDS

Direct use, silica waste, bricks, roads, Cerro Prieto, Imperial Valley, Mexico

PROJECT OBJECTIVES

A joint Department of Energy (DOE)/CFE research project was proposed to investigate the use of the waste silica from the Cerro Prieto geothermal field. The proposal included using the silica mixed with asphalt and cement to produce a suitable road surfacing material, and to combine the silica with various additives to be used as bricks for low-cost housing. It was thought that the low specific gravity of the silica and the proposed mixtures would give the bricks a high insulating value (low thermal conductivity), thus protecting the residents from high solar heating, typical of Baja California and the area around Mexicali. Also, since the geothermal fields of the area extend into the Imperial Valley of California, it was hoped that this research would also be applicable to the U.S. side of the border.

Technical Objectives

- Use mixtures of silica, lime, cement, pozzolan and fibers to mold bricks and cubes, and then cure them under various conditions of temperature and moisture.
- Test bricks in flexure and cubes in compression.
- Test dried samples for thermal conductivity and weathering.
- Test silica-asphalt mixtures for suitability as road surfacing materials by Marshall stability and immersion-compression.

Expected Outcomes

- Produce a brick using waste silica with a cementing additive that is suitable for low-cost building construction (i.e., has adequate strength, low thermal conductivity and resistance to weathering).
- Produce a mixture of silica and asphalt that would be suitable for a low-volume road surfacing (i.e., has adequate strength and stability, and resistance to traffic abrasion).

PROJECT BACKGROUND AND STATUS

The Cerro Prieto geothermal field produces approximately 11,000 tonnes of brine per hour that is disposed of in surface ponds. Approximately 1,300 tonnes of silica waste is the residual product from this hourly production of brine. At present, there is no use for this waste silica. Some experimental work has been undertaken by CFE to utilize this waste silica such as for surfacing roads with cement-silica mixture and making bricks with various additives. However, none of this research has been documented.

APPROACH

Approximately 35 kg of silica waste was shipped from Cerro Prieto in the Summer of 1994 to the Geo-Heat Center. This material was then used in two phases of research work: 1) to form bricks and cubes of various mixtures for strength testing; and 2) to produce asphalt mixtures for testing as pavement material.

The bricks were formed in 7.60 cm wide by 5.10 cm high by 15.2 cm long (2" x 3" x 6") molds with removable sides. These were cured under various conditions of moisture and heat and then tested in bending (flexure) by three point loading. Cubes were formed in 5.10 cm (2") square molds and then tested in unconfined compression. All mixtures were tested after seven, 14 and 28 days of curing. Three main additives were used to increase the strength of the silica: hydrated lime, portland cement, plastic fibers, and combinations of these three. Samples of all of the bricks were mailed to U.S. Geological Survey in Menlo Park for thermal conductivity testing. Finally, all samples were subjected to a simulated weathering test, consisting of a series of wet-dry tests, and then determining the weight loss after ten cycles. A summary of the sample mixtures is given in Table 1.

An asphalt cement (AR-4000) was mixed with the silica and tested by the Marshall stability method to determine if the material was suitable for use as an asphalt concrete structural pavement surfacing material. An emulsified asphalt (CRS-2H) was also mixed with the silica and compacted samples were tested in emulsion-compression to determine its suitability for surface treatment of roads in the form of a slurry seal.

RESEARCH RESULTS

The main conclusions from the testing are:

1. Silica-lime mixtures have low strength and weather resistance. However, they have high insulating properties, and thus can be used in non-bearing walls to insulate a building. The addition of plastic fibers to the mixture increases the strength and is the recommended mixture. A summary of the results is given in Tables 2 and 3.
2. Silica-cement mixtures have high strength and weather resistance. However, they have lower insulating properties. This mixture can be used in bearing walls with relatively light loads (i.e. single-story residences) and still provide some insulating properties. The addition of plastic fibers also increase the strength of the mixture. A summary of the results is given in Tables 2 and 3.

3. Asphalt mixtures are not suitable using silica, and thus should not be considered for any field construction.
4. Silica-cement mixtures appear to have application as a road surfacing material with the addition of an asphaltic chip seal for erosion protection.

FUTURE PLANS

Two projects are proposed for 1995/1996:

1. To test material from the large disposal pond at Cerro Prieto, as it is only about 70% silica. The 1994 testing used pure silica from one of the silencers.
2. To construct a building of bricks using both lime and cement with fibers as the additive. This building would be tested for thermal conductivity and weather resistance.
3. To construct a road using silica-cement and monitor its resistance to abrasion and weathering, and to determine its load carrying ability.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
CFE-Mexico UNOCAL Magma Power Co. Various cities in: Baja California, Mexico Imperial Valley, California	Building and road construction

REFERENCES

A more detailed report under the same title is available from the Geo-Heat Center, Klamath Falls (30 pages).

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Table 1. Sample Types

SILICA/LIME

MIX A	1-S/1-L	Moist Cured
MIX E	2-S/1-L	Moist Cured
MIX I	1-S/1-L	Heat Cured
MIX J	2-S/1-L	Heat Cured
MIX N	3-S/1-L	Heat Cured

SILICA/CEMENT

MIX B	1-S/1-C	Moist Cured	IP Cement
MIX F	2-S/1-C	Moist Cured	I & II Cement
MIX H	3-S/1-C	Moist Cured	I & II Cement
MIX K	1-S/1-C	Moist Cured	I & II Cement

SILICA/CEMENT/LIME

MIX C	1-S/1-C/1-L	Moist Cured	I & II Cement
MIX D	2-S/1-C/1-L	Moist Cured	I & II Cement
MIX G	3-S/1-C/1-L	Moist Cured	I & II Cement
MIX L	1-S/1-C/1-L	Moist Cured	I & II Cement
MIX O	1-S/1-C/1-L	Heat Cured	I & II Cement

SILICA SAND/CEMENT

MIX M	1-SS/1-C	Moist Cured	I & II Cement
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POZZOLAN

MIX P	1-S/1-P/1-L	Heat Cured	
MIX 6	2-S/1-P/1-L	Heat Cured	
MIX 7	2-S/1-P/1-L/Fiber	Heat Cured	1.0% fiber total mix

FIBER

MIX Q	1-S/1-L/Fiber	Heat Cured	0.2% fiber total mix
MIX S	1-S/1-L/Fiber	Heat Cured	1.1% fiber total mix
MIX T	1-S/1-L/Fiber	Air Cured	0.8% fiber total mix
MIX U	2-S/1-L/Fiber	Air Cured	0.8% fiber total mix
MIX W	3-S/1-L/Fiber	Air Cured	0.8% fiber total mix
MIX X	1-GS/1-L/1-Fiber		1.1% fiber total mix
MIX Y	2-S/1-L/1-Fiber	Heat & Air Cured	1.0% fiber total mix
MIX Z	3-S/1-L/1-Fiber	Heat & Air Cured	0.9% fiber total mix
MIX YA	2-S/1-L/1-Fiber	Heat Cured	0.9% fiber total mix
MIX ZA	3-S/1-L/1-Fiber	Heat Cured	0.9% fiber total mix
MIX 5	1-S/1-C/Fiber	Moist Cured	0.9% fiber total mix

CLAY

MIX R	1-S/1-Cl	Heat Cured	Red Brick Clay
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PLASTER

MIX PL-1	1-S/1-PL	Air Cured
MIX PL-2	1-S/1-PL	Air Cured

STRAW

MIX 3	1-S/1-L/Straw	Air Cured	0.7% straw total mix
MIX 4	1-S/1-L/Straw	Air Cured	0.6% straw total mix

Table 2. Strength and Thermal Cconductivity Results

SILICA / LIME									
	MIX	COMPRESSIVE STRENGTH			FLEXURAL STRENGTH			THERMAL CONDUCTIVITY W/mK	DRY DENSITY kg/m ³
		7-DAY kPa	14-DAY kPa	28-DAY kPa	7-DAY kPa	14-DAY kPa	28-DAY kPa		
1	A	396.4	275.8	413.7	86.2	193.9	86.2	NA	656
5	E	172.4	NA	327.5	129.3	107.7	86.2	NA	615
9	I	672.2	655.0	586.1	387.8	258.6	86.2	0.36	635
10	J	327.5	241.3	379.2	129.3	86.2	86.2	0.35	576
14	N	172.4	NA	224.1	86.2	NA	43.1	0.29	485
SILICA / CEMENT									
	MIX	COMPRESSIVE STRENGTH			FLEXURAL STRENGTH			THERMAL CONDUCTIVITY W/mK	DRY DENSITY kg/m ³
		7-DAY kPa	14-DAY kPa	28-DAY kPa	7-DAY kPa	14-DAY kPa	28-DAY kPa		
2	B	1896.1	3275	2757.9	1292.8	1766.8	2283.9	0.37	873
6	F	2068.4	2154.6	2740.7	1508.2	1465.1	1809.9	0.36	729
8	H	775.7	948	1172.1	861.8	861.8	818.8	0.34	571
11	K	2137.4	5446.9	4895.3	2930.3	2973.4	2844.1	0.36	809
SILICA / CEMENT / LIME									
	MIX	COMPRESSIVE STRENGTH			FLEXURAL STRENGTH			THERMAL CONDUCTIVITY W/mK	DRY DENSITY kg/m ³
		7-DAY kPa	14-DAY kPa	28-DAY kPa	7-DAY kPa	14-DAY kPa	28-DAY kPa		
3	C	1982.2	NA	4860.8	2154.6	1723.7	2025.3	0.41	927
4	D	1379	2137.4	3085.4	2154.6	1465.1	1637.5	0.42	811
7	G	1516.8	2413.2	2671.7	1508.2	1077.3	1206.6	0.34	670
12	L	3102.6	5533	5619.2	3016.5	3059.5	3447.4	0.36	837
15	O	2533.8	2844.1	4567.8	172.4	172.4	137.9	0.40	835
SILICA / LIME / FIBER									
	MIX	COMPRESSIVE STRENGTH			FLEXURAL STRENGTH			THERMAL CONDUCTIVITY W/mK	DRY DENSITY kg/m ³
		7-DAY kPa	14-DAY kPa	28-DAY kPa	7-DAY kPa	14-DAY kPa	28-DAY kPa		
17	Q	586.1	603.3	NA	193.9	129.3	NA	0.36	576
19	S	896.3	939.5	NA	430.9	711	NA	0.34	567
23	T	327.5	NA	NA	172.4	NA	NA	NA	565
24	U	155.1	NA	NA	86.2	NA	NA	NA	517
25	W	120.7	NA	NA	77.6	NA	NA	NA	458
	X	NA	NA	NA	NA	NA	NA	NA	NA
26	Y	NA	115.1	NA	NA	43.1	NA	NA	474
	Z	NA	137.9	NA	NA	21.5	NA	NA	407
27	YA	1723.7	NA	NA	86.2	NA	NA	NA	490
28	ZA	1465.1	NA	NA	86.2	NA	NA	NA	440

Table 2. (continued)

OTHERS									
	MIX	COMPRESSIVE STRENGTH			FLEXURAL STRENGTH			THERMAL CONDUCTIVITY W/mK	DRY DENSITY kg/m ³
		7-DAY kPa	14-DAY kPa	28-DAY kPa	7-DAY kPa	14-DAY kPa	28-DAY kPa		
13	M	17236.9	17236.9	17236.9	10600	10557.6	9911.2	0.8	1948
16	P	603.3	551.6	775.7	387.8	301.6	193.9	NA	767
18	R	627.6	676.6	NA	204.6	230.2	NA	0.39	801
29	PL-1	NA	792.9	NA	NA	409.4	NA	NA	603
30	PL-2	257.1	NA	NA	111.8	NA	NA	NA	716
	3	NA	430.9	NA	NA	258.6	NA		581
	4	NA	69.0	NA	NA	86.2	NA		483
	5	12066.0	13790.0	14652.0	1939.2	2543.0	4007.7		983
	6	327.5	172.4	430.9	43.1	43.1	258.6		698
	7	2758.0	1723.8	6895.0	344.8	430.9	560.2		750

Table 3. Silica Mix Weathering Results

SILICA/LIME

MIX A	1-S/1-L	100.0% lost
MIX E	2-S/1-L	100.0% lost
MIX I	1-S/1-L	73.1% lost
MIX J	2-S/1-L	100.0% lost
MIX N	3-S/1-L	100.0% lost

SILICA/CEMENT

MIX B	1-S/1-C	3.3% lost
MIX F	2-S/1-C	9.5% lost
MIX H	3-S/1-C	7.7% lost
MIX K	1-S/1-C	3.7% lost

SILICA/CEMENT/LIME

MIX C	1-S/1-C/1-L	3.0% lost
MIX D	2-S/1-C/1-L	17.6% lost
MIX G	3-S/1-C/1-L	6.8% lost
MIX L	1-S/1-C/1-L	3.5% lost
MIX O	1-S/1-C/1-L	3.8% lost

SILICA SAND/CEMENT

MIX M	1-SS/1-C	8.2% lost
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POZZOLAN

MIX P	1-S/1-P/1-L	5.2% lost
MIX 6	2-S/1-P/1-L	13.2% lost
MIX 7	2-S/1-P/1-L/Fiber	13.9% lost

Table 3. (continued)

FIBER

MIX Q	1-S/1-L/Fiber	0.2% fiber total mix	90.8% lost
MIX S	1-S/1-L/Fiber	1.1% fiber total mix	8.4% lost
MIX T	1-S/1-L/Fiber	0.8% fiber total mix	77.3% lost
MIX U	2-S/1-L/Fiber	0.8% fiber total mix	100.0% lost
MIX W	3-S/1-L/Fiber	0.8% fiber total mix	100.0% lost
MIX X	1-GS/1-L/1-Fiber	1.1% fiber total mix	NA
MIX Y	2-S/1-L/1-Fiber	1.0% fiber total mix	100.0% lost
MIX Z	3-S/1-L/1-Fiber	0.9% fiber total mix	NA
MIX YA	2-S/1-L/1-Fiber	0.9% fiber total mix	100.0% lost
MIX ZA	3-S/1-L/1-Fiber	0.9% fiber total mix	100.0% lost
MIX 0	1-S/1-L/1-Fiber	1.1% fiber total mix	6.9% lost
MIX 1	1-S/1-L/1-Fiber	1.1% fiber total mix	22.9% lost
MIX 2	2-S/1-L/1-Fiber	1.0% fiber total mix	50.1% lost
MIX 5	1-S/1-C/Fiber	0.9% fiber total mix	12.3% lost

CLAY

MIX R	1-S/1-C		100.0% lost
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PLASTER

MIX PL-1	1-S/1-PL		26.4% lost
MIX PL-2	1-S/1-PL		100.0% lost

STRAW

MIX 3	1-S/1-L/Straw	0.7% straw total mix	37.7% lost
MIX 4	2-S/1-L/Straw	0.6% straw total mix	100.0% lost

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