FEDERAL GEOTHERMAL RESEARCH PROGRAM UPDATE FISCAL YEAR 1995

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EXECUTIVE SUMMARY

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OVERVIEW

The Department of Energy (DOE) and its predecessors have conducted research and development (R&D) in Geothermal Energy since 1971. To develop the technology needed to harness the Nation's vast geothermal resources, DOE's Office of Geothermal Technologies (formerly the 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 Office of Geothermal Technologies.

Mission

Sponsor research and development in advanced geothermal energy technology, and work in partnership with U.S. industry and electric utilities to provide a competitive energy option for meeting U.S. and worldwide energy needs.

Vision

- ☐ *A fully competitive U.S. geothermal industry in domestic energy markets.*
- ☐ *Expanded leadership for the U.S. geothermal industry in world energy markets.*
- ☐ *Broad 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) 1995. The information contained in this *Research Program Update* illustrates how the mission and vision of the Office of Geothermal Technologies are 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 serves 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. energy sector.

The five categories of work used to distinguish the research activities of the Office of Geothermal Technologies 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 focusses 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.

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 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.

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 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 geothermal reservoir in California 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 since 1960; 2) Flash steam plants, favored for liquid-dominated or two-phase resources when the resource temperature is over 180°C (360°F); and 3) Binary cycles, favored for moderate resource temperatures in the range of 100° to 180°C (212°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 are being refined.

A nearly-completed assessment of U.S. low-temperature geothermal resources will facilitate increased use of these abundant resources for direct use applications.

Environment

This category covers aspects of environmental, health, and safety research.

Construction of the Southeast Geysers Effluent Pipeline and Injection Project began in October 1995. This project will contribute to sustaining power capacity at The Geysers. In another project, new applications are being found for silica wastes from geothermal power plants.

The Department of Energy and other partners initiated the Geothermal Heat Pump Consortium (GHPC) in late 1994. The GHPC is a partnership of utilities, geothermal manufacturers, HVAC vendors, and public agencies whose objective is to overcome market barriers to the widespread deployment of geothermal heat pumps.

MAJOR RESEARCH ACCOMPLISHMENTS IN FY 1995***Exploration Technology***

- Research continued on improving Self-Potential (SP) exploration techniques. A new SP survey was initiated at the Cove Fort-Sulphurdale, Utah, geothermal area. One experiment measured small SP differences during flow tests of a production well to resolve permeability channels between the hot water reservoir and the small steam cap. Also, detailed numerical modelling was performed on SP surveys for the Meadow-Hatton and Abraham Hot Spring areas (both in Utah), using codes that run on small computers. A major review of the cost-effectiveness of the SP method was published.
- Work on electromagnetic surveys (magnetotelluric (MT) and controlled-source MT (CSAMT)) concentrated on improvements in high-impedance field instrumentation and improvement of algorithms for data reduction. MT surveys show striking differences between the quiescent central Great Basin and the active eastern Great Basin (EGB). The EGB shows a thick high-conductivity layer in its lower crust correlated with high-temperature brines and partial melts over regional distances. A CSAMT survey of the Vale, Oregon, field was completed.
- Refinements are being made in the analysis of gas geochemistry of fluid inclusions in geothermal reservoir rocks. These measurements are likely to provide better, early estimates of reservoir compositions and temperatures, and thereby help industry reduce drilling costs during exploration.
- Ongoing research identified generic relationships among characteristics of geothermal reservoirs. For example, the hotter the system, the larger the volume of rock through which the hydrothermal fluids circulate. This larger volume is correlated mostly with the area of the system, since the depth to which fluids circulate tends to decrease as the bulk temperature increases. This research incorporates data from both U.S. and worldwide reservoirs.
- Another major continuing effort involves the data basing, using Geographical Information System (GIS) methods, of extensive characteristics of a large number of geothermal reservoirs and prospects. This should speed the search for improved signs of hidden reservoirs, especially through correlation of ground truth with many types of data available from Thematic Mapper satellite images. Correlated exploration data-basing efforts include details of core samples, heat flow, and thermal gradient measurements.
- Inevitably, elaboration of exploration methods requires detailed analysis of specific sites and of sub-regional geologies. Studies of these types are currently ongoing with respect to:
 - a) Details of reservoir geology of the Coso, California, geothermal reservoir and the surrounding area.

- b) Broad survey work for geothermal resources in frontier areas of southeastern Oregon.
- c) Completion and archiving of surveys conducted on Ascension Island in the Atlantic Ocean.

Drilling Technology

- Technology development of synthetic-diamond bits for high-temperature drilling continues to be conducted cooperatively with five firms, based on the capabilities and current product interests of each company. The work concentrates on adapting polycrystalline diamond cutters to high-temperature conditions. This research is expected to double both bit life and penetration rate, thereby reducing the cost of geothermal wells in hard rock by 15 to 20 percent.
- 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 consideration. 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 Engineered-Lithology Test Facility (ELTF, packer demonstration facility) needed for the next phase of testing and development of the drillable straddle packer was completed and put into operation during FY 1995.
- Development of memory-based tools for downhole measurements continues to progress rapidly. Field tests of the pressure/temperature tool continued. Calibration of the spectral gamma tool continued; the tool is now ready for use in most geothermal environments. A steam/gas sampling tool was built and subjected to extensive tests above ground.
- An exploratory slimhole was drilled at Vale, Oregon, and tested extensively. Drilling of another exploratory slimhole at Newberry, Oregon, was started. It is expected that the use of slimholes will substantially reduce the cost of geothermal exploratory drilling.
- Research on acoustic data telemetry concentrated on equipment development and continuing field tests. The prototype transmitter for the production monitor has been fabricated and tested on the surface. Data from two field tests were used to design a new passive monitoring system, which is expected to be deployed in drilling operations in Indonesia. A new monitor for line shaft pumps was also designed. 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, adaptation of a retrievable whipstock to geothermal well conditions, development of rotating drilling head rubbers, testing of cementitious muds for lost

circulation control, and development of an improved mud hammer to increase geothermal drilling rates.

- Plans were made to turn over the Long Valley, California, deep exploratory well to the U.S. Geological Survey, for continued study and possible future drilling to learn more about the geology of the depths of this caldera.

Reservoir Technology

- Progress continued on a number of fronts with respect to measuring and understanding chemical reactions and relationships that affect geothermal reservoirs and power systems:
 - a) Origins of HCl in geothermal steam. It appears that the amount of HCl in steam from dryer regions of The Geysers reservoir may be more related to ammonia concentration than to that of sodium chloride. Other indications suggest that the HCl may be arising from the continuous degassing of a relatively recent magmatic intrusion under the Northwest Geysers reservoir.
 - b) Effects of salts on partitioning of deuterium-tagged water between steam and water. These are being measured, and efforts are underway to construct simple empirical equations for predicting the isotope-salt effects in natural complex brines over a wide range of temperatures.
 - c) Geochemistry of aluminum minerals in high-temperature brines, to develop a model for predicting changes in permeability and brine chemistry associated with fluid/rock interactions.
 - d) Water associated with granitic melts, to help determine plutonic origins of some geothermal fluids.
- Development of tracer compounds for measuring flows in reservoirs continued. Possible new liquid phase tracers evaluated during FY 1995 included lissamine FF, pyranine, and amino G. Liquid-phase studies included analyses of using up to three tracers at a time. Work on gaseous phase tracers concentrated on SF₆, as a possible substitute for the use of chlorofluorocarbons.
- The suite of user-friendly computer-simulation models of geothermal fluid chemistry, developed at the University of California, San Diego, were further improved by advances in simulating chemical and thermodynamic conditions in geothermal fluids, including: completion of models of the Na-H-Ca-Cl-HCO₃-SO₄-SiO₄-CO₂-H₂O and the Na-K-Ca-Mg-Cl-SO₄-H₂O systems. These are significant to the industry in analyzing and predicting calcium carbonate, calcium sulphate, and amorphous silica scale-forming minerals, as well as CO₂ solubility. Modelling of H₂S and NH₃ reactions are now included in the systems. Other features added during FY 1995 include: reliable simulation of phase equilibria in complex systems, thermodynamic properties of supercritical fluid mixtures, liquid density brines, and improvements in user interfaces to the models. These models are also being calibrated and field-tested extensively at specific geothermal reservoirs.

- Improvements of Lawrence Berkeley National Laboratory's geothermal reservoir simulation model, TOUGH2, also continued. TOUGH2 now can model > 10,000 grid blocks on personal computers, and includes treatments of dissolved solids, non-condensable gases, improved modeling of multiphase flows in heterogeneous media, and more details of how water interacts with the surface of reservoir rocks. An inverse version, ITOUGH2, was developed to perform automatic history matching of geothermal reservoir performance.
- Other advances in reservoir numerical simulation work included:
 - a) Efforts to apply linear optimization techniques to estimate the natural state of geothermal reservoirs.
 - b) Work to develop an improved matrix-fracture interaction term for simulating naturally fractured reservoirs.
 - c) Conceptual simulation studies of the possible initial formation and long-term behavior of the "high temperature" reservoir in the Northwest Geysers area.
- Advances in measurements of primary rock and reservoir properties included:
 - a) Continuing work to measure the relative permeabilities of vapor and liquid water in real reservoir rocks.
 - b) Measurements of details of how water behaves in fractures in real rock.
 - c) Continued improvement of measurements of adsorption of water on reservoir rock, especially with respect to how adsorption would affect steam returns from injected water.
 - d) Initial work to prepare an atlas of well-characterized faults relevant to geothermal systems, to provide better ground truth about geological settings and the characteristics of productive fractures.
 - e) Continuing work to detail the composition and history of the hydrothermal mineralogy of The Geysers reservoir. This included substantial analysis of core samples from relatively deep in the reservoir.
- Advances in geophysical methods continued along a number of lines of research:
 - a) Characterization of subsurface fracture patterns in the Coso reservoir by analysis of shear-wave splitting from microearthquakes.
 - b) Continuation of microseismic monitoring and analysis at The Geysers, now with sufficient data to begin to understand some of the complex relationships between microearthquakes and injection/production well arrangements and flow histories.
 - c) Heat flow studies in the areas surrounding The Geysers reservoir, to determine if The Geysers/Clear Lake region might contain additional significant hydrothermal deposits.
- Detailed case study analyses of real reservoirs continued, including:
 - a) The start of a survey of geochemical conditions during early stages of development of the Steamboat Springs, Nevada, reservoir.

- b) Use of lead and strontium isotope data to analyze the deeper roots of the thermal aquifer in the Twin Falls, Idaho, area.
- c) Use of production-decline type curves to better characterize details of controls on permeability at The Geysers.
- Hot Dry Rock research continued. The GEOCRACK reservoir numerical simulation model was improved based on data from the Long Term Flow Test (LTFT) of the Fenton Hill, New Mexico, reservoir. A series of Reservoir Verification Flow Tests (RVFT) in FY 1995 confirmed much of what had been inferred about the Fenton Hill reservoir from the LTFT. RVFT results indicate that hot dry rock reservoirs can be operated in a load-following mode to increase the amount of peak power extracted from the reservoir.
- Reservoir technology research teams continue with aggressive transfer of their technological advances. One example is the use of the TOUGH2-PC reservoir simulation code to model the Heber geothermal field in the Imperial Valley, California, in conjunction with staff of the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR). DOGGR staff have constructed a natural-state model of the reservoir, and are calibrating a TOUGH2-PC model of subsidence and uplift at the field by matching its results to field data.
- The Geothermal Technology Organization (GTO) continued to serve as a means through which the Office of Geothermal Technologies cost-shares research (other than drilling or conversion research) that industry deems of immediate urgency.
- On the international cooperation front, international agreements continue with Mexico and Italy, but at a relatively low pace due to funding constraints. U.S. researchers continued monitoring the geochemistry of the Cerro Prieto field, Mexico, and are studying ways to convert silica waste from that field to economically-useful products. An industry/DOE team worked with the Indonesian electrical utility PLN on a prefeasibility study of sites for small, rural, geothermal power. Other small studies and projects were conducted in or with Bolivia, Iceland, Italy, New Zealand, Nicaragua, and St. Vincent.

Conversion Technology - Electricity Conversion Systems

- Researchers refined 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 with limited supplies of water.
- Idaho National Engineering Laboratory (INEL) has largely completed its studies of improvements of binary power cycles. Supersaturated turbine expansions appear to be on the verge of being accepted by industry as an important improvement in this technology.
- The feasibility of retrofitting advanced direct contact condensers to one or more PG&E plants at The Geysers was analyzed. 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 results are being used to develop designs for the retrofit.

- Three 250-hour tests of a subscale Biphase turbine installed and operated at Coso Hot Springs, California provided valuable information and operating experience. The lessons learned have been incorporated into the design of the full size unit that is currently being constructed. The new unit will be tested at Cerro Prieto, Mexico, and is expected to generate approximately 1 MWe of electricity.
- DOE prepared an Environmental Assessment (EA) for the siting of a 12.5 MWe Kalina Cycle power plant at Steamboat Springs, Nevada. The State of Nevada is reviewing the EA. After DOE publishes a Finding of No Significant Interest, this project is expected to proceed to a power purchase agreement and detailed plant design and construction.
- The possibility of developing insulative corrosion liners that could be factory applied on the inside of pipe sections as a means of reducing the required amount of external insulation is being investigated. Industry-supplied metal coupons coated with BNL-developed polyaryl-based corrosion protection systems were laboratory-tested.
- Field test results indicate that thermally conductive polymer composite (PCL) tubes perform as well as AL-6XN stainless steel tubing. Both tubes experienced comparable heat transfer and pressure drop performance, and a similar rate of fouling and scale buildup. Antioxidant compounds will be added to a new PCL liner formulation to reduce the degree to which scale adhered to the tested version of the liner.
- At The Geysers, a series of field tests of polymer, polymer cement, and pre-ceramic coating systems to protect well casings from HCl was completed. Evaluations of coatings for surface pipelines and dry cooling towers were in progress. Coatings for turbine components are also being formulated and tested.
- The incorporation of inorganic and organic microsphere fillers into a calcium phosphate cement matrix (CPC) produced a lightweight, moderate strength, and highly durable cement. Continuing testing showed that chemically inert organic-type microspheres are promising fillers for use with calcium phosphate cements to produce lightweight, CO₂-resistant cements. Blast furnace slag and class F flyash combinations also were identified as promising cementing material additives.
- Research continued on the use of biochemical processes to clean up potentially hazardous wastes from geothermal power systems. New comparative studies of agitated tank vs. fluidized bed type bioreactors were completed. A first generation pilot plant has been constructed and is being automated. A process for the removal of radionuclides is being optimized. A preliminary economic evaluation was completed.

- The Office of Geothermal Technologies and industry representatives continued to refine the terms under which both could support the Geothermal Power Organization (GPO), a consortium similar in design to the GDO and the GTO, with emphasis on geothermal energy conversion research. A Memorandum of Understanding, approving a more structured organizational charter for the GPO is under review and expected to be signed in 1996.

Conversion Technology - Direct Heat Systems

- As a result of the Geo-Heat Center's continued geothermal direct heat utilization assistance since 1990, the thermal capacity of direct heat projects and geothermal heat pumps increased by 678 MWt in capacity and an annual energy utilization of 2,747 TJ/yr. This growth is the result of 18 direct heat projects in five states. It is the equivalent of installing 72,700 3-ton geothermal heat pumps.
- A spreadsheet model has been developed that allows users to quickly evaluate the capital cost and unit energy cost of accessing a geothermal resource for direct heat uses.
- State Geothermal Resource Teams in collaboration with the Geo-Heat Center have identified 48 high-priority resource study areas together with 150 new sites with high potential for near-term direct heat utilization. The ongoing collocation study has also identified 271 cities in ten western states that could potentially utilize geothermal energy for district heating or other applications.

Environment - General

- Ground breaking for the first segment of the Southeast Geysers Effluent Pipeline and Injection Project took place on October 6, 1995. Construction is expected to be underway concurrently at multiple locations throughout 1996, with completion and start-up expected in early 1997.
- Silica wastes from disposal ponds at Cerro Prieto, Mexico, were analyzed for potential commercial applications. Likely uses include both bricks for low-cost building construction and mixtures of silica and asphalt for paving low-volume roads.

Environment - Geothermal Heat Pumps (GHPs)

- The Department of Energy and a number of Government and industry partners initiated the Geothermal Heat Pump Consortium (GHPC) in late 1994. The GHPC is a partnership of utilities, geothermal manufacturers, HVAC vendors, and public agencies whose objective is to overcome market barriers to the widespread deployment of geothermal heat pumps (GHPs) in the United States. Subordinate goals include: improve GHP technology; create design tools, and substantially increase the number of architects, engineers, contractors, builders, installers, etc. who are familiar with the advantages of, and how to install, GHPs;

demonstrate the economic advantages of using GHPs; and develop and promote technology transfer mechanisms to hasten adoption of GHPs by vendors and users.

- Information on the performance of geothermal heat pumps was collected and analyzed in 256 case studies. For residential systems, the dollar savings from use of GHPs ranged from 18% to 54%, and the peak demand reduction ranged from 5.3 kW to 10.4 kW with a mean of 7.2 kW. For commercial systems, the dollar savings ranged from 31% to 56%.
- Research continued to reduce the cost of the ground loop portion of geothermal heat pump (GHP) space-conditioning systems. Sandia has managed many GHP installation projects at Department of Defense facilities. The data from these projects have proven invaluable for assessing the effectiveness of GHP systems and marketing them. An instrumented GHP vertical loop has been installed in Albuquerque, New Mexico. A draft GHP drilling handbook was completed. These activities are expected to help accelerate the use of GHPs nationwide.
- The GHP Consortium initiated a field demonstration of a patented, multi-loop configuration technology developed by Climate Master for both vertical and horizontal ground loops. The technology has potential for reducing loop installation costs by 25% or more.
- A ground loop heat exchanger model was integrated with a water loop fan system model (BLAST) to better compare geothermal heat pump systems with conventional systems. This will be one of the design tools promulgated to the emerging GHP industry.
- As part of an enhanced technology transfer effort, a series of brochures, case studies, and fact sheets on residential and commercial GHP systems was developed and distributed to assist in increasing public awareness. A training manual for architects and engineers was also prepared.
- Three new nationwide teleconferences on the state-of-the-art of geothermal heat pumps and their applications for residential and commercial buildings were developed and broadcast.

EXPLORATION TECHNOLOGY

GEOPHYSICS RESEARCH - SELF-POTENTIAL STUDIES

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KEY WORDS

self-potential, geophysics, field studies, hot springs, exploration.

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 reduces confidence in, and use of, the method in geothermal resource exploration and development. Theoretical studies support the occurrence of both positive and negative anomalies over geothermal upflow zones, and these are reported throughout the world over geothermal areas.

SP studies were initiated as a geophysical research topic at ESRI (then University of Utah Research Institute, UURI) in 1990 following a successful survey at Newcastle, Utah in support of the DOE-GD State Cooperative Program studies at this resource area. Subsequent surveys showed the promise of the method in exploration for covered geothermal systems. Self-potential studies as a research topic is perhaps 75 percent completed, with additional field studies, documentation and interpretation methodology yet to be completed. We anticipate completion of SP research in FY-98 although field surveys and interpretation will continue in support of exploration and development efforts as needed.

PROJECT OBJECTIVES

The objectives of this project are to evaluate and demonstrate the use of the 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 to improve confidence in SP surveys as a 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.

APPROACH

The objectives will be obtained by completing detailed SP surveys while obtaining high-quality data, 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. The studies are being conducted in collaboration with investigators of the Utah (Utah Geological Survey - UGS) and New Mexico (New Mexico State University - NMSU) state geothermal resource teams, who contribute their time and field expenses. Industry (Oxbow Power Corporation and Utah Municipal Power Agency) has contributed access to resource areas, interface with regulatory agencies such as the BLM, and supplemental data.

RESEARCH RESULTS

Recent studies by ESRI (UURI) and state teams have mapped well-defined minima in close association with fluid upflow in Utah, New Mexico and Nevada. Several systems have been mapped in detail (Newcastle, Wood's Ranch, Thermo, Meadow-Hatton and Abraham Hot Springs, Utah; Rincon and Radium Springs, New Mexico; Carson Lake, Nevada) and survey results presented at the Geothermal Resources Council meetings and the World Geothermal Congress (see references). The dominant expression of these resources, using station spacings of 60 m, 30

m, or smaller, is an SP low. Some surveys show both positive and negative (dipolar) anomalies (Ross et al., 1993).

A major effort for FY-95 was the preparation of a technical paper "The Self-Potential Method: Cost-Effective Exploration for Moderate-Temperature Geothermal Resources" (Ross et al., 1995), which was presented at the World Geothermal Congress in Florence, Italy. The paper summarized recent SP survey results and called attention to more detailed papers presented at the GRC in earlier years. Table 1, from that paper, summarizes anomaly magnitudes, polarities, and extents for ten thermal areas in the western United States.

The only new field survey initiated in FY-95 was at the Cove Fort-Sulphurdale geothermal area in Utah. Acquisition of the resource leases by the power producer, Utah Municipal Power Agency (UMPA), provided an opportunity for ESRI to renew studies of this resource after ten years of power production. The University of Utah and UMPA completed a "Right of Entry for Technical Data Gathering" agreement in June which provides the formal background for cooperative studies. The Utah Geological Survey (UGS) is also a participant in these studies. The principal new survey element is a high-quality SP survey. During FY-95 16 profiles totaling 20 line-km (65,700 line-ft.) of data, at station spacings of 30 and 60 m, had been completed. The survey is about 70 percent complete. Plans to reproduce key profiles during the flow test of a hot-water well were canceled due to delays in pipeline construction and pump emplacement. We hope to measure small SP differences during the flow test period which may indicate permeability channels between the hot water reservoir and the small steam cap. Measurements during pumping will be attempted during FY-96. Survey results to date show a small negative anomaly in the producing steamfield and another anomaly peripheral to this area. Some soil types in the survey area exhibit a slow recovery to normal voltage levels after wetting of electrode stations, perhaps a result of high clay and zeolite compositions in the soils. This has required prewatering of electrodes and the repeating of several profiles to obtain acceptable data.

A third effort during this year has been a cooperative study with researchers Susan Schima and Michael Wilt, of Lawrence Livermore National Laboratory. Howard Ross submitted detailed SP data and supporting geologic and geophysical information for the Meadow-Hatton and Abraham Hot Spring surveys to Schima and Wilt for detailed numerical modeling. After smoothing the data, Schima and Wilt completed several iterations to geologic and physical property models proposed by Ross to arrive at a reasonable fit to the observed SP data. The results were presented at the 1995 Annual Meeting of the Geothermal Resources Council in Reno, NV in October (Schima et al., 1995). Numerical modeling of other SP data at the University of Utah suffered a setback when visiting scholar Dr. Wang Jung Yoon had to return to South Korea without completing his modeling projects.

FUTURE PLANS

Plans for FY-96 include the completion of the Cove Fort-Sulphurdale studies, including comparative measurements during flow testing or production from the hot water well. This effort will be part of an integrated study of other remote sensing, geologic, geochemical, and geophysical data which will update our geologic model of the geothermal system. We anticipate

one additional field survey in an area of possible development interest. Geologic and quantitative interpretation efforts and presentation of the data will also receive priority.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Oxbow Power Corp.	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 Univ.	Possible power and greenhouse development at Rincon, NM; resource delineation at other areas.
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
Utah Municipal Power Agency	Geothermal reservoir model for the Cove Fort-Sulphurdale resource

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Table 1A: Data Summary for Self-Potential Surveys of Geothermal Areas.

Area	Temperature (°C)		Depth (m)	Surface Manifestations
	Res*	Obs#		
Newcastle, UT	>130	98	100	none; hot wells
Woods Ranch, UT	>110	36	30	none; hot wells
Thermo, UT	130	90	0	domes; seeps
Meadow-Hatton, UT	200?	-	0	----
Meadow (hot pools)	-	32;41	0	hot pools
Hatton (hot springs)	-	63	0	domes; springs
Crater (Abraham), UT	140?	55-87	0	springs; pools
Carson Lake, NV	>100	>50	100	none; hot wells
Rincon, NM	>140	88	128	alteration; hot
Radium Springs, NM	>100	70	<75	wells
Tortugas Mtn., NM	-	>50	90	hot springs;
				wells
				none; hot wells
*Estimated reservoir temperature; #Temperature in springs or shallow wells.				

Table 1B: Data Summary for Self-Potential Surveys of Geothermal Areas.

Area	SP Survey		Anomalies (mV)	Anomaly Size (km)
	Area(km ²)	Line-km		
Newcastle, UT	1.5	9.8	-108,-44,-36	0.6 x 0.3
Woods Ranch, UT	8.0	25.0	-59,-43	1.8 x 0.9
Thermo, UT	10.4	45.0	-116,-40,-30	2.5 x 2.0
Meadow-Hatton, UT	6.5	29.5	----	----
Meadow (hot pools)	-	-	0(?)	----
Hatton (hot springs)	-	-	-120,-74,-72,+60	1.0 x 0.7
Crater (Abraham), UT	5.7	22.0	-46,-24,+14,-9	1.0 x 0.5
Carson Lake, NV	10.9	47.9	-96,-71,-61,-50	2.1 x 0.7
Rincon, NM	6.7	37.5	-122,-77,-74,-34	2.4 x 1.3
Radium Springs, NM	6.5	27.8	-146,-92,-42,-34	2.5 x 1.3
Tortugas Mtn., NM	4.2	20.2	0 to -40 (?)	2.0 x 1.0
*Estimated reservoir temperature; #Temperature in springs or shallow wells.				

MODELING SELF-POTENTIAL (SP) DATA IN THE ABRAHAM AND MEADOW-HATTON GEOTHERMAL SYSTEMS

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KEY WORDS

self potential, SP, fluid flow, field data acquisition, modeling

PROJECT BACKGROUND AND STATUS

Ross et al. (1993) collected SP data at Abraham and Meadow-Hatton Hot Springs, two of the largest thermal spring systems in Utah. In this paper, these data were modeled to determine upflow zones and source characteristics using a numerical code.

PROJECT OBJECTIVE

SP has long been a promising method for geothermal exploration because the measured anomalies are directly related to subsurface heat and fluid flow. The technique has not been widely used because of uncertainties in data quality and the lack of interpretation methods. As part of our research effort in SP we are examining data collection issues and have developed interpretation techniques that are suitable for small computers. The two case studies below present examples of SP data interpretation.

RESEARCH RESULTS

Numerical Modeling of SP Anomalies

Computer code SPXCL calculates the electrical potential anywhere in a two-dimensional medium from thermal or pressure (flow) sources. It is the latest modification of a code written by Sill (1983). The two-dimensional model requires input of three sets of physical properties for every mesh point. The location and strength of the flow sources must also be specified. The resulting voltages, pressures, and temperatures can be used to fit field observations (see Wilt et al, 1996).

Information on the permeability distribution, resistivity structure, and cross-coupling coefficients are gathered to begin constructing a model. These are either known from site studies, or estimated from previous experience. Source characteristics are based on hot springs flow data or educated guesses. The code allows either a point or a finite line source. Data is interpreted via iterative forward modeling. That is, a model consistent with the known geology and hydrology is input

and then iteratively modified to fit the SP voltages and/or pressures and temperatures. Each forward model requires less than one minute to compute on a Sun workstation.

Case 1: Abraham Hot Springs

The thermal springs that issue at Abraham have temperatures as high as 87°C and flow rates up to 140 l/s. The hot springs lie 6 km east of Fumarole Butte, a Quaternary eruptive center that formed a broad basalt apron known as Crater Bench. A north-northwest trending fault within Crater bench probably provides the vertical permeability for geothermal flows emanating at Abraham Hot Springs.

A total of approximately 22.0 line-km of SP data were collected in 1991 and 1992 (Ross et al., 1993). Figure 1 is a map of the Abraham Hot Springs area showing SP contours in millivolts and data collection points. The contours show a general trend of negative values to the west of the fault and positive values to the east. The smoothed SP contours, overlaying the raw data in Figure 1, were used in the two-dimensional modeling.

To model a data set with SPXCL the geologic structure must be approximately two-dimensional and the data must be smoothed to remove short wavelength anomalies related to near-surface sources. For Abraham Hot Springs we applied a rough hand-smoothing of the data to accentuate large-wavelength anomalies and selected a profile (A-A'), perpendicular to the predominant NW-SE structural trend, for application of the 2-D model.

Our SP model, based on published geology and geophysics is shown in Figure 2 (Mabey and Budding, 1987; Oviatt, 1991). Two layers of Quaternary basalt overlay the alluvial sediments. These layers represent the basalt apron that makes up Crater Bench. The lower layer, weathered basalt mixed with Quaternary alluvium, is 75 m thick. The upper "fresh" basalt layer has virtually the same properties as the weathered basalt, except for a lower permeability due to less fracturing. The vertical unit, consisting of highly fractured basalt and alluvial sediments, is coincident with the fault and represents the passage for fluid to ascend.

A point pressure source was placed at a depth of 200 m near the contact of the vertical conduit and the alluvial sediments. The source strength was given as 300 l/s, about twice the observed flow rate at the surface. Physically, this point source represents the onset of open fractures.

Although the depth required for heating the fluids, suggested by Ross et al. (1993), is about 3 km, the actual source from which fluids are released from a high pressure conduit to a lower pressure layer in the subsurface is likely much shallower. A likely scenario is that geothermal waters are circulated by convection to an area of highly fractured rock. The high permeability of the fractured zone causes a decrease in pressure. This area is designated as the source location in the model. The flow then ascends along the fracture zone, encounters the basaltic overburden, and travels laterally until it discharges at the surface.

Our model is consistent with the known geology at Abraham Hot Springs, but it is clearly not unique; for this reason we did not strive for an exact fit to the observed data. We discovered that

the model was most sensitive to changes in the source depth and strength and to a lesser extent changes in the permeability and resistivity of model units. The location and strength of the source in relation to the fractured zones also played an important role for aligning the dipolar anomaly correctly with the observed SP data.

Case 2: Meadow-Hatton Hot Springs

Meadow-Hatton is located in the eastern Black Rock Desert, in the Basin and Range province of western Utah. Hatton Hot Springs issues from the edge of a 2 km long, northeast trending travertine mound with a temperature of 63°C and a flow rate of 0.1 l/s. Meadow Hot Springs, located 8 km northwest of Hatton, experiences variable flow rates, from no discharge to significant discharge.

Figure 4 is a map of the area with SP contour lines in millivolts and data collection points; the hand-smoothed SP data used in modeling is superimposed. The field studies by Ross et al. (1993) show three coherent anomalies with amplitudes of -70 to -120 mV located 300 to 1000 m north of Hatton Hot Springs, suggesting a possible upflow zone. No significant anomalies were observed at Meadow Hot Springs. Our smoothed profile, located across the voltage anomaly, indicates two adjacent negative anomalies reaching -50 mV.

The geologic model for Meadow-Hatton is shown in Figure 5. The dome of mixed alluvium and travertine is about 20 m high and extends laterally 600 to 900 m. Thermal fluids rise along fractures within the dome which cut valley fill sediments. Two pressure sources (190 l/s and 200 l/s) are located at 200 m depth each on the outside contacts of the conduits.

Figure 6 shows the fit of the observed and model-generated data. Like the model for Abraham Hot Springs, the highly negative anomalies (-50 mV) measured require large subsurface flow rates. The model suggests that geothermal waters, brought up from deeper convection, may have migrated laterally in the permeable travertine layer to outflow at Hatton Hot Springs where minor seeps occur, and probably northwest beneath conductive soils, to the Meadow-Hatton pools area. Although, at present, neither hot springs system produces significant discharge, the travertine mound indicates that there was significant flow in the past. The SP models suggest a high flow rate exists today but most of it remains subsurface.

CONCLUSIONS

We have shown through these two studies at Abraham and Meadow-Hatton Hot Springs that models consistent with known geology can locate the source depth, strength, and location. As with any geophysical technique though, SP modeling does not come without limitations. The solutions derived are restricted to a point or line source, the code cannot account for three-dimensional variations, and the solution is not unique. However, given enough background information, a model can be constructed that is both accurate and realistic.

FUTURE PLANS

We plan to continue our research in SP along several fronts. We are continuing to work on data collection schemes to improve reliability and isolate sources of noise. We are also improving our computer codes and developing better documentation for wide acceptance. In particular we are working on the following tasks.

An operations manual for program SPXCL is presently being written and the code will be modified for use on a PC. (Note that an older version of SPXCL, is available for PC through the U.S. Army Corps of Engineers, Wilt and Butler, 1990).

The main stumbling block to effective use of numerical modeling is the knowledge of SP coupling coefficients. Very little reliable data on this physical property is known and little new data is being acquired. We are presently working with Dr. Dale Morgan at MIT, the only active researcher in this area, to assemble known data and outline future needs.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

There is considerable new interest from geothermal developers in using SP and applying our two-dimensional modeling algorithm to field data. We have distributed our computer code to TransPacific Geothermal Inc. of Oakland Calif and to Geophysica of Golden Colo. We are presently examining SP data provided by Oxbow Geothermal.

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Figure 1. Abraham Hot Springs raw and smoothed surface voltages. The contour interval is 10 mV. Profile line A-A' is used in modeling the data.

Figure 2. Model used in the SP interpretation.

Figure 3. Plot of surface voltage values generated from the model compared to the smooth observed values.

Figure 4. Meadow-Hatton Hot Springs raw and smoothed surface voltages.

Figure 5. Model used in the SP interpretation.

Figure 6. Plot of surface voltage values generated from the model compared to the smooth observed values.

MT/CSAMT ELECTRICAL METHODS RESEARCH

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KEY WORDS

electromagnetics, magnetotellurics, CSAMT, instrumentation, algorithms

PROJECT BACKGROUND AND STATUS

ESRI (formerly UURI) has maintained a long-term (since the late 1970's) effort devoted to upgrading magnetotelluric (MT) data acquisition and interpretation, and has received support from the Department of Energy (DOE) and the National Science Foundation (NSF) for this effort. ESRI has developed and field-tested a wideband MT system which includes simultaneous, dual-site measurement with each site acquiring five channels of electromagnetic (EM) time series. Time series are transmitted in digital form via radio telemetry to the recording truck and processed in real time using coherence-based data quality sorting. 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. In addition to defining a platform for instrumentation research, our MT system has been intended as insurance against the often fragile stability of MT contractors in the unsteady petroleum and geothermal exploration markets.

ESRI also has taken a lead role in the development of more efficient, more accurate and more reliable algorithms for the interpretation of electrical and electromagnetic (including MT/CSAMT) data for the geothermal, petroleum and mining industries. Particular emphasis has been placed on developing two-dimensional (2-D) finite element and three-dimensional (3-D) integral equations methods for modeling and inversion, but 1-D methods remain useful and have been advanced also.

The anticipated benefits of this research are reduced drilling costs (through increased drilling success) and better evaluation of reservoir potential which reduces 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.

ESRI has achieved the state-of-the-art in MT field instrumentation but seeks new advances in data acquisition efficiency and field noise reduction. Instrumentation concepts to this time have proven highly successful based on survey results in diverse environments. Both 2-D and 3-D numerical interpretation developments are producing structural interpretations with detail and

reliability not achieved in the recent past. We will continue research which incorporates a significant component of field data acquisition because this has been very instructive as to interpretation needs.

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. ESRI has chosen to address the magnetotelluric (MT) method and its controlled source analog CSAMT in particular because of their importance in geothermal exploration.

Technical Objectives

- Improve interpretation of MT/CSAMT data through new algorithm development and response characterization.
- Improve the quality of MT field data through improved instrumentation and field techniques.
- Demonstrate the improved capabilities of MT and CSAMT through carefully selected field studies.

Expected Outcomes

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

APPROACH

ESRI 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. ESRI will continue to test existing methods, to improve techniques and equipment for gathering field data, and to improve interpretation algorithms and computer codes. Integrated geoscience interpretations will provide additional insight into these methods. Field surveys in varying field conditions identify method limitations and practical resolution limits. DOE research support for instrumentation and algorithm development has been complemented strongly by NSF support for MT field programs which test the methodology.

RESEARCH RESULTS

Significant progress has been made in the areas of MT field instrumentation, 2-D and 3-D numerical analysis methods, and in interpretation methodology for the CSAMT technique.

Magnetotelluric Instrumentation

A primary advance in our MT field system was completion and deployment of a custom electrometer for measurements in environments of very high contact impedance (e.g., young volcanic terranes), with support also from the NSF. A schematic diagram portraying key elements is given in Figure 1. The most important component was the buffering of electrodes individually with ultra-high input impedance (900 M-ohm) preamps incorporating high-performance FET input components. Preamp outputs are driven differentially about a quiet reference line and outputs combined at a central control module isolated optically from the second stage electronics and digital control. New low-impedance modules for integration with the electrometer setup have been designed and proto-types fabricated. These are being bench-tested at the time of this writing. Design and construction has been lead by J. Stodt.

Magnetotelluric Surveying

Substantial field trials of the MT field system took place in the last year in Central West Antarctica, and around the Ruby Mountains metamorphic core complex in central Nevada. These projects were supported by the NSF under its Polar Programs and Continental Dynamics offices.

With the high-impedance electrometer of our own design, we obtained the first high-quality MT soundings, twelve in all, over the thick interior ice sheet of central-west Antarctica (Wannamaker and Stodt, 1995). Contact impedances of our electrodes with the firm (amalgamated snow pellets) was on the order of 0.5 M-ohm, which actually was less than anticipated. Parallel electrometer channel tests yielded agreement on the order of ten bits, in the absence of noise-inducing wind, for full-scale signal ranges exceeding 10,000 bits. The profile of soundings implies lithospheric resistivity typically exceeding 1,000 ohm-m to depths of about 100 km (Figure 2), similar to ancient stable regimes (e.g., Wannamaker et al., 1995a). This negates the hypothesis that central west Antarctica is an active rift zone, a conjecture advanced previously based on aeromagnetics and radar surveying.

Fifty-four new sites in central Nevada allow comparison of deep thermal states of the quiescent central Great Basin (CGB) with the active eastern Great Basin (EGB) of western Utah, which we have been surveying with MT for several years (Johnston et al., 1995). The EGB shows a thick, high-conductivity layer in its lower crust correlated with high temperature brines and partial melt over regional distances (Wannamaker et al., 1995b). In contrast, the lower crust of the CGB is less in conductance by at least a factor of four and the conductor lies deeper (Figure 3). The latter results are consistent with fluid percolation models where fluid input from basaltic underplating ceased about 10 Ma when CGB rifting subsided.

Wannamaker presented an invited paper at the First International Symposium on Three-Dimensional Electromagnetics hosted by Schlumberger-Doll Research in Ridgefield, CT, October 4-6, 1995 (Wannamaker, 1995a). The paper is entitled "Magnetotelluric surveying one can afford: interpretation of MT profiling data in natural environments". The subject matter addresses the need for adequate sampling of the MT response both in space and frequency, but balanced by the need for the data to be reliably interpretable and affordable. The manuscript is published in the proceedings, which runs 642 pages in length. A select group of the papers, of which this is one, will undergo formal peer review and publication in the SEG Investigations in Geophysics series.

Algorithm Development

We have implemented the adjoint method (reciprocity) in obtaining parameter sensitivities (Jacobians) for the 2-D MT/CSAMT inversion problem (de Lugao and Wannamaker, 1995). The adjoint approach is necessary for regularized or minimum-structure inversion to curtail spurious model structure not demanded by the field data. The approach reduces the computational need for these derivatives to about the price of the original forward problem rather than several tens of forward problems, or more, which has been required by existing perturbational approaches (Figure 4). Results compare exactly with the original perturbation approach and within 1-2% with finite differencing of similar forward problems. The adjoint implementation is general and has been verified for both TM and TE modes including the vertical magnetic field and topography. It is programmed within the framework of program PW2D, which we literally have distributed hundreds of copies of, and which is the computational engine for the state-of-the-art Occam-2 minimum structure inversion code. Occam-2, however, utilizes the older perturbation method of derivatives and we will produce a new-generation inversion code which runs at least an order of magnitude faster.

Effort also was expended on our 3-D integral equations algorithm for simulating EM responses due to diverse sources (Wannamaker, 1995b). 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 were obtained 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 end-point terms rather than a potential field evaluation for cell-cell, source-cell, cell-receiver and source receiver couplings. Moreover, the algorithm has been augmented for central loop and short-offset loop-loop calculations including airborne and downhole EM arrays under support of the Consortium for Electromagnetic Interpretation (CEMI) of the University of Utah (Figure 5). The loop source calculations consider all three components of source and receiver and have been verified against published results and using reciprocity.

CSAMT Research

Wannamaker's comprehensive paper on tensor CSAMT surveying of the Sulphur Springs thermal area, Valles caldera, NM (Figure 6), has been provisionally accepted by Geophysics (Wannamaker, 1995c,d). Data acquisition was funded by DOE/OBES but a substantial amount of the interpretation has been supported by DOE/GD. Two-dimensional modeling of the plane-

wave regime CSAMT data augmented by sparse MT soundings and layered earth, tensor CSAMT inversion was carried out for four data profiles. Modeling revealed that almost all fault displacement in the area lies on the NE-trending Sulphur Creek fault. Toward the SE side of the prospect, surveying also discovered a major, down-to-SE normal fault here named the Redondo Border fault. No especially high resistivities are associated with an inferred shallow vapor zone in the thermal area.

Existing MT soundings and the resistivity model allow us to understand controlled source effects in the CSAMT data (Wannamaker, 1995d). Modeling with our 3-D code shows that small-scale heterogeneity local to the transmitter does not cause an overprint effect on the observed CSAMT ρ_a and ϕ . Modeling the observed E and H fields shows that an effective regional layering appears to control the magnetic field amplitudes and the far- to near-field transition in this survey area. The regional setting of conductive Paleozoic sediments over resistive basement seriously reduced depth of exploration within the plane wave regime to about 1/20th of the transmitter-receiver separation, rather than the traditional 1/3rd to 1/5th based on half-space models. When heterogeneity is important, significant departures between scalar and tensor CSAMT data can be expected, and are exacerbated when the source field is poorly coupled to the sensors.

FUTURE PLANS

Continued upgrade of the MT system is anticipated as new limitations of noise suppression and field efficiency are identified. In addition, the second-stage analog components are more than five years old now and are suffering fatigue failures. The analog filter cards, power delivery, and digital control have been redesigned and will be rebuilt with partial support from the NSF. The new low-impedance electrometer components will be tested in our transect of the South Island of New Zealand this January and February.

With completion of the adjoint method for parameter sensitivities, we will produce a new regularized, 2-D inversion algorithm for MT/CSAMT data profiles. At present, we prefer regularization with apriori models because it allows ready incorporation of constraints. Three-dimensional model development will include improved high-frequency simulation as well as time-domain modeling through a discrete Fourier transform technique. Additional arrays of interest include gradient resistivity/IP, magnetic IP, and downhole galvanic sources.

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/CSAMT interpretation and equipment MT/CSAMT and finite-source
Mining, Petroleum and Geothermal Research Consortium	EM interpretation

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Figure 1. Key elements of electrometer design for high contact impedance measurements.

Figure 2. Example MT sounding taken over 2 km thick ice sheet of central-west Antarctica. High ρ_{yx} values at all periods show high resistivity lithosphere. Low ρ_{xy} values at longer periods show local mid-crustal conductor, probably representing graphitic shear.

Figure 3. Characteristic ρ_a and ϕ soundings from the eastern Great Basin (EGB) and central Great Basin (CGB) obtained by integration of TM mode impedance along each profile to remove effects of upper crustal heterogeneity. Solid response curves show fit of respective tabulated layered models.

Figure 4. Schematic subregion of finite element mesh showing interchange of source and receiver, and location of parabola coefficients for auxiliary field Jacobian.

Ground, Airborne & Borehole Loop-Loop EM Simulation

Figure 5. Schematic depiction of loop source modeling capability with integral equations code. This augments existing source capability for MT, CSAMT and dipole-dipole resistivity/IP.

Figure 6. Regional geological map of Valles caldera showing principal geological features and tensor CSAMT survey layout. Crossed-bipole transmitter antennae are about 13 km SSW of corehole VC-2B and Sulphur Springs (SS). Receiver layout in local inset box is shown in detail in Figure 2.

ELECTROMAGNETIC METHODS FOR GEOTHERMAL EXPLORATION

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KEY WORDS

magnetotelluric (MT), controlled-source magnetotelluric (CSMT), source effect, geothermal, electrical conductivity

PROJECT BACKGROUND AND STATUS

In the fall of 1993, Trans-Pacific Geothermal Inc. (TPGI) consulted with LBNL in evaluating the CSMT data collected near Vale, Oregon. LBNL interpreted the data provided by TPGI using a state-of-the-art, two-dimensional MT inversion code (INV2D) developed at LBNL. The inversion code is capable of handling the topography, which is of great importance when dealing with data from rough terrains. The results were very successful. There was one concern however. At low frequencies the impedance data appeared to have been affected by the source effect. So we could not be certain of the interpreted result at depths.

TPGI is now engaged in a few ambitious field exploration projects in Central America (Tsvi Meidav and Bill Teplow, personal communication, 1995). The first field site to be investigated is the El Hoyo-Monte Galan field in Nicaragua. The depth of investigation at this site ranges from 4000 to 5000 ft and the major field technique considered is the CSMT method. To support TPGI's effort in the exploration, and possibly in the reservoir characterization stage later, LBNL proposed to investigate the source effect in the CSMT method and design and direct survey specifications using CSMT methods at the El Hoyo-Monte Galan field. Upon completion of the survey according to the specification, LBNL will make corrections for the source effect and interpret the data using the inversion code INV2D mentioned above.

PROJECT OBJECTIVES

Technical Objectives

- Evaluate current magnetotelluric (MT) methods for: (a) use in exploration of geothermal fields, and (b) characterization and monitoring of production processes in regional scale.
- Demonstrate the utility of the controlled-source magnetotelluric (CSMT) method when used in conjunction with the MT method, and identify source effects and make corrections to CSMT data.

Expected Outcomes

- Provide improved means for interpreting MT and CSMT data.
- Help establish guidelines for efficient and economic CSMT survey design.
- Improved general reservoir characterization.

APPROACH

There is an essential difference between MT and CSMT methods in terms of the nature of the source field. The MT source is natural and the resulting electromagnetic field is a plane wave with zero horizontal wavenumber for all frequencies. The CSMT source field is man-made consisting of a wideband wavenumber spectrum. Wideband wavenumber effects in CSMT result in deviation from plane wave impedance responses in regions near the source.

We approximate the controlled source fields by terms at a few appropriately-chosen horizontal wavenumbers. The objective is to develop a simple correction of near-source effects.

RESEARCH RESULTS

The finite wavenumber approach leads to an asymptotic expression between the impedance and the various field components. Initial results using a few chosen wavenumbers to approximate fields by finite sources have been very promising.

FUTURE PLANS

We are now investigating which part of the wavenumber spectrum can best approximate the correct impedance. This will be a function of frequency and source-receiver geometry. Of particular interest is the use of high horizontal wavenumbers for this approximation. With this method, one may be able to achieve better asymptotic relationship between fields and impedances.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

CSMT methods have been widely used in geothermal exploration in hostile environments. Presently, this project is a joint TPGI and LBNL effort (In the future, other companies might also participate.) TPGI will provide field support, CSMT data, and other relevant geophysical and geological information. Meetings are held periodically to discuss research directions and priorities.

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GAS GEOCHEMISTRY OF FLUID INCLUSIONS

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KEY WORDS

fluid inclusions, gases, exploration

PROJECT BACKGROUND AND STATUS

Fluid inclusions are used by the geothermal community to determine the temperatures and compositions of the fluids that have circulated through a reservoir. During exploration and development, fluid inclusions can provide estimates of reservoir temperatures shortly after drilling and before equilibrated measurements can be obtained. When stabilized well bore temperatures become available, comparison with the fluid inclusion data can provide information on system heating or cooling over time. Similarly, changes in fluid composition can be characterized, although the interpretation of apparent salinities obtained from routine fluid inclusion measurements can be complicated by the presence of dissolved gases. Nevertheless, the composition, distribution and abundance of these gases can provide insight into the geometry of the reservoir, the importance of boiling and mixing, and the origins of the fluids (Moore et al., 1992; Norman and Musgrave, 1994; Norman and Moore, 1994).

Fluid inclusion investigations have been an integral part of the geothermal program at ESRI since the late 1980's. Detailed investigations have helped characterize the thermal and chemical structure of reservoirs at Coso, Heber, Los Azufres, Zunil, (Guatemala) and The Geysers, among others. Studies are currently underway at Tiwi (Philippines), Steamboat Springs, and The Geysers. These studies are approximately 50% complete.

PROJECT OBJECTIVES

The overall objective of the work described here is to develop new techniques for characterizing the chemical and thermal structures of geothermal reservoirs. This work places particular emphasis on the role of fluid inclusions because they provide quantitative information that is not available from other techniques. The project has several technical objectives.

Technical Objectives

- Complete detailed microthermometric measurements on fluid inclusions and conduct supporting petrographic and chemical studies of geothermal systems in selected magmatic and nonmagmatic environments.

Technical Objectives (continued)

- Assess the applicability of quadrupole mass spectrometry and Fourier transform infrared spectroscopy (FTIR) for determining the gas compositions of fluid inclusions in geothermal systems.
- Develop approaches needed for the interpretation of the resulting data and establish the limitations of the methods.
- Characterize the thermal and chemical structure of the geothermal systems being analyzed, establish the origins of the fluids within the reservoir (including the impact of magmatic activity), and characterize the processes affecting them.

Expected Outcomes

- Reduce drilling costs by providing information on the geometries of geothermal systems under exploration and development.
- Provide better, early estimates of reservoir compositions and temperatures.
- Determine the origin of the reservoir fluids and the extent of mixing and boiling.

APPROACH

The approach is to integrate the results of geochemical, petrologic, and fluid inclusion heating and freezing studies from well-characterized geothermal reservoirs. Data on the temperatures and compositions of the reservoir fluids will be obtained from the field operators to characterize the present-day conditions within the geothermal systems being studied. Samples of cores and cuttings provided by the operators will be studied petrographically and by X-ray diffractometry to determine the distribution and age relationships of the various secondary minerals in the rocks. Where practical, the stable isotope composition of vein minerals will be determined so that the compositions of the waters responsible for mineralization can be estimated. Fluid inclusions in these samples will be studied petrographically and their homogenization temperatures, salinities and gas contents will be determined. These data will allow comparison of present thermal and chemical conditions with those recorded by the fluid inclusions.

The work will be conducted in collaboration with several other investigators. Field related studies will be conducted through efforts between ESRI and Unocal Geothermal, Calpine Co., Oxbow Power Corp, CCPA, and California Energy Inc. We will use the quadrupole mass spectrometer in Dr. David Norman's laboratory at New Mexico Tech and the FTIR in Dr. Roger Ainge's laboratory at LLNL for the gas analyses. Both of these researchers will collaborate in the interpretation of the data.

RESEARCH RESULTS

In FY 95, we initiated geochemical analyses of fluid inclusions from The Geysers, and Steamboat Springs. Petrographic investigations and heating and freezing data had shown that the present vapor-dominated regime at The Geysers had developed from a larger, liquid dominated system related to the emplacement of the granitic intrusion (felsite) that underlies the field (Moore and Gunderson, 1995). These studies had indicated that fluids of three different origins were present. Fluids with salinities in excess of 40 weight percent NaCl equivalent were found in the intrusion and in the overlying graywacke at distances of up to 600 m from the contact. The high salinities and temperatures recorded by these inclusions suggest that they trapped fluids exsolved from the granite. At greater distances from the intrusion, the maximum salinities of the inclusion fluids typically range from 5 to 10 weight percent NaCl equivalent. These fluids are believed to represent connate waters. Meteoric waters are found in the upper parts of the system. Inclusions that contain these waters are characterized by low salinities and low homogenization temperatures.

Fluid inclusion gases were analyzed in 12 samples from 9 wells and from one sample of a pregeothermal carbonate + lawsonite vein from Elk Mountain by quadrupole mass spectrometry. The gases were released from the inclusions by thermal decrepitation at temperatures of 400° to 500°C. Figure 1 shows the relationships between Ar, He, and N₂ in the samples studied. According to Gigganbach (1986), high He values are typical of crustal or connate waters while high Ar concentrations characterize meteoric waters. Magmatic gases are characterized by high N₂ contents.

The gas data shown in Figure 1 indicates that most of the reservoir samples and a few from the caprock plot near the N₂ corner, suggesting that these gases have a magmatic origin. The presence of hypersaline brines with salinities exceeding 26 weight percent NaCl equivalent in some of these samples supports this conclusion. However, some of these N₂-rich samples contain only low- to moderate-salinity waters, suggesting that the movement of the gases was not coupled to that of the liquids in all cases. The remaining samples display a much larger range of gas ratios and are dominantly from the caprock. These samples may contain varying proportions of magmatic, connate, and meteoric gases.

For comparison, the gas compositions of the fluid inclusions and those of representative analyses of the present-day steam from The Geysers and springs located outside of the productive portions of the field are shown in Figure 2. In this plot, CH₄ substitutes for He as a possible indicator of crustal fluids. Variations in the gas ratios of the steam indicate that the percentage of air-saturated water increases from the northwest to the southeast. Truesdell et al. (1987) showed that the stable isotope compositions of the steam also indicated that recharge was greatest in the southeast portion of the field.

The fluid inclusion gas ratios are very similar to those of the steam, with the majority of the fluid inclusion compositions plotting near steam from the northwest part of the field. These inclusion fluids are characterized by relatively low Ar contents, and thus, show little evidence of a meteoric component. The spring data and the sample from Elk Mountain also plot in this region of the

diagram, supporting the conclusion that the fluid inclusion gases are dominantly crustal or connate in origin. A significant meteoric component only appears to be present in two fluid inclusion samples, both of which are from the caprock in the southeast part of the field. In addition to these data, we have tested the possibility of using FTIR techniques on a large vapor-rich inclusion from the caprock encountered in SB-15. This inclusion consists dominantly of trapped steam. The analysis indicates that H_2O , CO_2 , and an unidentified hydrocarbon that may be CH_4 , is present.

The Tiwi geothermal field, in the Philippines is a volcanic hosted system in an island arc environment. Our work here has focussed on samples from a deep scientific core hole, Matalibong-25, drilled by the Unocal Corp. The well was drilled to a depth of 8000 ft and continuous core was collected below 2586.5 ft. The results of fracture and petrologic studies that include homogenization temperatures and apparent salinities on more than 500 fluid inclusions is reviewed by Nielson and Moore (1995).

FUTURE PLANS

During FY-96, we will complete gas analyses of fluid inclusions from The Geysers, and continue our investigations of the geothermal systems at Steamboat Springs and at Tiwi. Petrographic, isotopic, and fluid inclusion studies of rocks from Matalibong-25 at Tiwi are underway and will be finished. These data will be integrated with the gas analyses and the composition of the production fluids. It is anticipated that our work on the gas geochemistry of fluid inclusions from The Geysers will also be completed. We will present our initial findings on Matalibong-25 at the 1996 Stanford Workshop on Reservoir Engineering and more detailed results on its hydrothermal alteration and geochemistry at the 1996 GRC meeting. In a separate paper at the Stanford Workshop, the application of fluid inclusion gas data to the evaluation of geothermal and fossil hydrothermal reservoirs will be discussed.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Several organizations have demonstrated an interest in the fluid inclusion investigations we are currently conducting. California Energy Co. Inc., Calpine Co., CCPA, Oxbow Power Corp., and Unocal Corp. have provided samples and data for study. Dr. Shiro of the Geological Survey of Japan has also expressed an interest in the work we are doing, particularly with respect to deep, high temperature resources like those at The Geysers.

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Figure 1. Ternary plot showing $N_2/100$ - $10He$ - Ar ratios of fluid inclusions from the caprock, normal vapor-dominated reservoir (NVDR), high-temperature vapor-dominated reservoir (HTVDR), and from a calcite-lawsonite vein of Franciscan age from Elk Mountain. ASW represents air-saturated water.

Figure 2. Ternary plot showing $N_2/100$ - $CH_4/500$ - Ar ratios of fluid inclusions, steam, and springs, from The Geysers and adjacent regions. Steam analyses from Truesdell et al. (1987); spring data from Goff and Janik (1993). Abbreviations as in Figure 1.

MODELS OF HYDROTHERMAL SYSTEMS

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KEY WORDS

brittle-ductile transition, depth of circulation, circulation volume

PROJECT BACKGROUND AND STATUS

This project was initiated by a review of existing models of the geometry and size of active geothermal systems. Brooke et al. (1979) noted a direct relationship between geothermal system volume and the temperature of the system; that is, the hotter the system, the larger the volume of rock through which hydrothermal systems circulate. Nielson (1993) re-evaluated the relationship using information that had been established by drilling since the Brooke et al. Study. In general, the relationship was confirmed. In an additional paper, Nielson (1994) recognized that the larger volume was a function of the area of the system, since the depth to which fluids circulate decreases as temperature increases. This phenomena results largely from the transition from brittle to ductile response of rock to an applied stress (see also Smith and Bruhn, 1984; Sibson, 1984; Fournier, 1991). In the ductile regime, rocks will not sustain open fractures and fluids cannot circulate freely.

This project is on-going and is updated as new information becomes available. Current interest in the deep geothermal resources, particularly in Japan (Yagi et al, 1995) means that more data will become available. The research well WD-1 at the Kakonda geothermal field has recently reached temperatures of 500°C or greater (M. Yagi, NEDO, written communication).

PROJECT OBJECTIVES

The objective of this project is to evaluate recent data and update geothermal system models.

Technical Objectives

- Determine the circulation volume of geothermal systems.
- Determine the depth of circulation of active systems and investigate the character of the brittle-ductile transition which is though to determine the depth of circulation.

Technical Objectives (continued)

- Determine how geothermal systems cool naturally and brittle fractures are superimposed on formerly ductile rocks.
- Formulate a tectonic classification of geothermal systems.
- Determine the character of fracture permeability in active systems.

Expected Outcomes

- Increased efficiency of reservoir exploration and development.
- Development of new techniques for the recovery of heat through injection.

APPROACH

The approach in formulating models uses information from review of literature on both active and fossil geothermal systems as well as published papers in the topic of tectonics. Subsurface data from the Geysers, Tiwi, Philippines and Awibengkok, Indonesia systems were collected in the past year and have been integrated into system models. This project is integrated with other research activities at ESRI, including The Geysers and Tiwi reservoir studies and determination of fluid flow characteristics of fault zones (see other summaries in this volume).

RESEARCH RESULTS

The circulation volume of active geothermal systems increases as temperature increases. The depth to which fluids circulate decreases with an increase in temperature resulting in an increase in the area occupied by convection. The depth to which fluids circulate is thought to result from the transition from brittle to ductile behavior of the host rock; however, the character of this lower boundary is one of the least understood aspects of geothermal systems. Natural analogs suggest that heat extraction from the deep portions of systems may be practical (Nielson, in press).

Detailed studies of core from SB-15D at The Geysers (Hulen and Nielson, 1995) and Matalibong-25 at Tiwi (Nielson et al., in press) show that permeability is controlled by steeply dipping fractures. In The Geysers system the permeability is closely associated with strike-slip faults, while in the Tiwi system, the permeability is associated with normal faulting. Also, at Tiwi the fracture frequency decreases dramatically below 6500 feet to the bottom of the well at 8000 feet. Information such as this can be very useful in determining the depth to which production wells should be drilled.

FUTURE PLANS

- Investigate the character of brittle-ductile transition zones now exposed in metamorphic core complexes.
- Propose a tectonic classification of active geothermal systems.

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DEVELOPMENT OF A REGIONAL DIGITAL GEOSPATIAL DATABASE FOR GEOTHERMAL MODELING

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KEY WORDS

remote sensing, GIS, geospatial data, database, geothermal exploration

PROJECT BACKGROUND AND STATUS

This project is a component of a larger study testing the use of remote sensing in geothermal exploration. Initially only regional remote sensing techniques were to be tested. However, early in the study it became apparent that, to optimize the use of the remote sensing data, additional ancillary data needed to be integrated with the remote sensing data in a GIS environment. Therefore, a search was initiated to find applicable regional data for the study area.

Throughout the study several criteria were kept in mind regarding efficiency, as the technical transfer of the methodology would be useless to industry if certain conditions were not met. These criteria included (1) that the data was readily available, (2) that the data and processing procedures were cost effective, (3) that the data could be analyzed with off-the-shelf image processing/GIS software and equipment, (4) that tried and true processing techniques could be used and, (5) that useful information could be generated in a time-frame that would be expedient enough to allow the use of remote sensing in commercial projects within typically tight scheduling parameters.

The project is currently near completion. Data sets are now being compiled into mosaics for modeling. The model will be created through a weighted digital overlay technique.

PROJECT OBJECTIVES

The objective for this project was to build a digital geospatial database containing items pertinent to the development of a regional geothermal exploration model for the central Great Basin, U.S.A. This was done through the collection and GIS input of data from disparate sources.

Technical Objectives

- Collect data relating to geothermal exploration.

Technical Objectives (continued)

- Reformat data for input into a GIS environment, using a standard projection and coordinate system.
- Develop a geothermal potential GIS model.

Expected Outcomes

- Initial completion of a regional geospatial database for the study area using digital geospatial data relating to geothermal exploration.
- Use of the regional digital geospatial database in a GIS environment to develop a geothermal exploration model.

This database is nearly complete and the GIS geothermal exploration model is expected to be generated by 30 December 1995.

APPROACH

The approach has two components: (1) the processing and interpretation of remote sensing data, and (2) GIS development.

The remote sensing component consisted of standard preprocessing techniques followed by processing for hydrothermal alteration enhancements and fault/lineament mapping. Landsat Thematic Mapper (TM) data were used for these purposes. This was due to several factors including (1) a wide area of coverage (185 x 185 km² per scene), (2) relatively high spatial resolution (30x30 m), (3) spectral bands that are conducive to geologic investigations, (4) relatively low cost per unit area, (5) good availability, and (6) a proven track record.

The TM data were first rectified to a Universal Transverse Mercator projection and coordinate system. The rectified data were then subjected to a dark object subtraction technique for haze reduction (Chavez, 1988).

Hydrothermal alteration was then mapped. It has been shown that both band ratio (Prost, 1994; Ebel et al., 1993; Sabins, 1987) and Feature Oriented Principal Component Selection (FPCS) (Laughlin, 1991; Crosta et al., 1989) images are useful for processing TM data to enhance hydrothermal alteration. It was found by Nash et al. (1994) that the use of both methods can often lead to better hydrothermal alteration maps. Both methods were used in this study. The results were integrated into the GIS database.

Another key GIS component derived from the TM data was fault and lineament information. Testing was done to find the most effective method of mapping these features in the most

expedient manner. A principle components method of combining multiple spatially enhanced images was tested first (Chandra, 1984). This method, although effective, is relatively time consuming.

A TM false color composite image was tested next. Optimum contrast exposing most lineaments in the TM image was found using combinations of bands 4,5,7 and bands 7,4,1 when represented on the computer screen as red, green, and blue (Mah et al., 1995; Karpuz et al., 1993). The key advantage with the two false color composites is the speed in which they can be displayed to map lineaments, since no spatial enhancement processes are required prior to interpretation. The drawback is that some subtle lineaments may be missed. However, geomorphic relationships are more apparent on false color composites than in most spatially enhanced imagery.

We found that the differences, in both the number and the spatial association of faults and lineaments mapped, using the two above techniques, was minimal at the regional scale. Therefore, the majority of fault/lineament maps were derived from false color composite images, which proved to save a great deal of time.

We used the second component of the study, GIS, extensively throughout the project. GIS allows the smooth integration of remote sensing and ancillary data sets. Ancillary data were gathered and processed throughout the project. During this process several problems and obstacles were encountered. These included the following:

1. Lack of data availability and coverage of the study area
2. Data inaccuracy (both spatial and thematic)
3. Inconsistent data formats
4. Lack of metadata.

GIS is a powerful analytical tool for many disciplines including those in the earth sciences. However, many facets of GIS are still in their infancy, hence the problems listed above. These problems, with the exception of availability, can be surmounted at a cost of time.

The following data sets were successfully compiled and added to the digital geospatial database (1) earthquakes since 1968, (2) known geothermal locations, (3) heat flow, (4) mines and mining districts, (5) geologic units, (6) total field aeromagnetic data, (7) gravity data, (8) geochemical data, (9) lineaments/faults, and (10) areas of high hydrothermal alteration probability.

RESEARCH RESULTS

Both remote sensing and GIS are useful in digital geospatial database generation for geologic exploration. As far as expediency and cost effectiveness are concerned, the utilization of TM data meets both of these criteria. It was found that an entire TM scene could be utilized to generate a CRC image and to map lineament/faults in a period of about three weeks (using standardized techniques). This amounts to a coverage of approximately 34,000 km². The use of TM data met all of the criteria listed in 2.1 above.

The addition of ancillary GIS data, although an important factor in modeling, was time-consuming and costly (primarily in staff-hours). Therefore criteria 1, 2, and 5 from above, were not fully met in the GIS component.

As more digital geospatial data becomes available, problems relating to availability and cost of digital geospatial data will be ameliorated. GIS is a very powerful tool, and its use will not only help provide the answers to many questions in the earth sciences, but also help create more digital geospatial data to increase its availability. It is up to all GIS professionals in the private and public sectors to support and help fill the centralized geospatial data clearinghouses with high quality data.

It is anticipated that the digital geospatial database created for this project will be very useful in the development of a regional geothermal exploration model. However, the time/cost may currently be prohibitive for some private exploration projects in generating similar GIS coverage for this type of analysis.

FUTURE PLANS

It is planned that the data created in this project will soon be utilized to generate a geothermal potential model for the study area. With the available data, it will be somewhat rudimentary initially. However, as the digital geospatial database grows and is enhanced, new models will easily be created that will more accurately reflect the probability of geothermal occurrences.

It is planned that the data created in this study will be archived on CD-ROM for future use. It is hoped that this will be the beginning of a geothermal geospatial database that will someday be readily accessed over the Internet.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Although no specific companies have been contacted regarding the above work at this time, the data will be useful to any organization doing geothermal exploration in the study area. One of the goals of this project is to present the concept of a centralized geothermal database to both the governmental and private sectors. The geospatial data generated in this project could act as a pilot. The centralized database could include data covering all aspects of the geothermal industry with data being made available to users through a point-and-click interface via the Internet.

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DEVELOPMENT OF A COMPREHENSIVE CORE DATABASE UTILIZING GIS FOR ANALYSIS AND ARCHIVING

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KEY WORDS

core, GIS, image processing, spectroscopy, x-ray diffraction, Ferron

PROJECT OBJECTIVES

The objective of this project was to develop a comprehensive database of rock core information using geographic information systems (GIS) for the purposes of analysis of core imagery and archiving of core data sets. This study has used several different commercially-available software packages such as ERDAS™ for image processing and ESRI Arc/Info™ and ArcView™ for GIS updating, manipulating, and viewing the core database. As a case study, digital images of drill core from the Ferron Sandstone Member of the Mancos Shale from central Utah were used in the GIS database. After digital photography of the core, a clustering algorithm in ERDAS Imagine was used to identify lithologies. High resolution VisNear/SWIR spectroscopy and x-ray diffractometry were employed to further quantify the core lithologies and provide additional inputs for the GIS core database.

Technical Objectives

- Determine rock core lithology based on image processing, spectroscopy, and x-ray diffractometry.
- Create a GIS database of the core information including the above data sets as well as ancillary information such as digitized lithologic logs and photomicrographs for analysis and archiving purposes.

Expected Outcomes

- A GIS database containing Ferron core information such as natural color core images, classified core images, ancillary images (lithologic logs and photomicrographs), and tables of information and images from spectroscopic and x-ray results.

Expected Outcomes (continued)

- An easy-to-use, point and click software program which has been customized to fit the core imagery and text files.
- A means of archiving and retrieving high-quality digital images of rock core and associated data sets, which negates the need of the researcher to travel to the core repository for in-person viewing. All core images and associated files will be stored on CD-ROM.
- A methodology by which the same type of database could be created for other rock core and other types of associated data sets.

It is expected that the results of this study will provide a methodology by which a core database can be created and used by a wide variety of people of differing backgrounds (related to GIS and image processing), quickly and efficiently. It also will demonstrate the utility of image processing software to automate the process of lithologic identification, as well as VisNear/SWIR spectroscopy and x-ray diffractometry in lithologic determination.

PROJECT BACKGROUND AND STATUS

Imaging technologies have now reached a point where it is possible to accurately display annotated digital images of rock core in a manner that is both cost-effective and user-friendly. This study focuses on a relatively new technique of archiving and analyzing rock core obtained during a drilling program. Recent studies have shown the utility of imaging spectrometers or hyperspectral scanners in determining the mineralogy of rock core (Kruse *et al.*, 1994). The authors state that automated, laboratory-based, hyperspectral scanning of rock core should be possible in the near future. Additional work by Nielsen *et al.* (1995) has shown that image processing software can be utilized as an inexpensive and timely means of identifying differing lithologies in rock core. They also discussed the use of GIS software as a means of archiving the core images and ancillary images such as digitized lithologic logs, photomicrographs, hyperspectral images, and other data.

The Ferron core used in this study was from a research well cored by the University of Utah Research Institute (now Earth Sciences and Resources Institute) in 1991 under a contract from the Gas Research Institute. The well (UURI #1) was drilled in the Muddy Creek Canyon area of central Utah to a total depth of approximately 450 ft (137 m). Continuous core of 6-inch (15-cm) diameter was collected from the 8-inch (20-cm) borehole (Nielson and Lutz, 1993). Core was prepared for imaging by slabbing with a rock saw. This step required some care in that the saw marks could potentially cause difficulties in later analyses. After preparation of the core, the project proceeded in several steps: (1) Core imaging, capturing, and archiving, (2) Image processing and analysis, (3) Spectroscopy and x-ray diffractometry, and (4) Customization of the GIS interface for using the end product.

APPROACH

Core imaging was performed using a Sony ProMavica MC-7000™ Professional Still Video Camera. This camera produced natural color images with a horizontal resolution of 500 + TV lines during recording and playback. Images were stored on floppy disk inside of the camera, and then played back and captured using a Matrox Video Presentation Plus™ board and software. Enhancements to rotate, adjust brightness and contrast, and stitch the images together were done using Adobe Photoshop™ software. Due to inherent limitations in the camera's field of view in order to obtain high resolution images, only pieces of each core run could be photographed at one time. The pieces were then reconnected using Photoshop software to rebuild the core run to its original dimensions. A scale bar was constructed along the side of the core, in both English and metric units, to aid in identifying the core with respect to the lithologic logs and subsequent spectroscopic and x-ray images and tables. The rock core images were ultimately archived using ESRI ArcView GIS (geographic information system) software. ArcView presents GIS coverages in a user-friendly manner, yet provides the author of the database with a means of customizing the ArcView end product (using the Avenue™ programming language) to suit the needs of the user when he/she is accessing the database.

Digital image analysis was applied in an effort to characterize and analyze the core according to lithological differences. The methodology involved using the natural color digital image of the core in the ERDAS image processing system ".lan" form, which was necessary for classification. In ERDAS, the classification step is accomplished using CLUSTER, a sequential clustering algorithm that creates a raster GIS file consisting of unnamed spectral classes. This algorithm measures the spectral distance between pixels based on the brightness values of the red, green, and blue bands. This procedure tests the homogeneity of the data. After determining the number of classes desired, which in this case was 60, the algorithm required a decision to be made by the interpreter regarding the minimum spectral distance that separates the means of the clusters, a distance parameter that is used when merging clusters, and a cluster elimination threshold percentage (ERDAS, 1991). Those pixels that exceeded a predetermined threshold were placed in new classes. The resulting classes represented pixels grouped according to likeness of spectral value. In order to define what the class type was, the GIS file was superimposed onto the ".lan" image, and the classes were highlighted one at a time. Those that represented the same lithology were then grouped together using the algorithm RECODE.

The addition of VisNear/SWIR spectroscopic and x-ray diffraction data also provided important inputs to the database. Core sample chips were gathered during the core photography process. The chips were then ground to a fine powder for both spectral and x-ray diffraction analysis. The spectra were then acquired using a GER 2100™ spectroradiometer. This instrument has a spectral bandwidth of 10 nm across the 400 nm to 1000 nm region and an 8 nm bandwidth across the 2000 nm to 2500 nm range. These were the critical spectral ranges for the identification of a great number of minerals. The samples were illuminated with a 1000 watt quartz/halogen lighting system. The spectral data were then analyzed using MSI SpectralFocus™ spectral analysis software. This software package allows for the incorporation of spectral data into a database which then can be searched by a number of methods for spectra comparisons. Algorithms are also included for spectral addition/subtraction as well as many other useful

functions to aid in the identification of minerals as well as other substances. One of the outstanding features of SpectralFocus™ is its curve matching algorithm. This algorithm allows a relatively rapid search of a spectral database which generates correlation coefficients to allow comparisons between spectra.

X-ray diffraction was done on about 1/6 of the samples for comparison and accuracy assessment of the interpreted spectral data. X-ray results allow the immediate inspection of the spectral curve to check the accuracy of the spectroscopic analysis for specific minerals. It also gives information needed to build an accurate spectral database within SpectralFocus software for future use. The x-ray diffraction data serves to enhance the mineralogic information for the GIS database. The data generated from the x-ray diffraction was stored in the GIS database in an Xbase .dbf format for use in the ArcView project for both visual and statistical analysis and for use in future comparisons with the VisNear/SWIR spectral data.

The first data set to be brought into the ArcView GIS software environment were the 79 Ferron core images representing rock from 53.0 ft (16.2 m) to 412.7 ft (125.8 m) at the bottom of the Ferron sandstone sequence. These images included the core, as well as a scale bar which had been created in the preprocessing step described above. The graphics file format for each core image had to remain in the ERDAS image processing system ".lan" form in order for the images to be "attributed". In ERDAS, a simple four-sided polygon was drawn around each image. These polygons were then saved as separate files, and brought into the Arc/Info GIS environment where topology was built for each polygon. Topology was necessary so that the polygon (and by proxy, the core image) could be "attributed" with other image files in the ArcView environment. An initial ArcView project file was created by opening up the image data source (a core image) and a feature data source (the image's polygon). The polygon was then sent "behind" the image, so that it would be essentially invisible to the user. As previously mentioned, the polygon's primary role was to take on attributes from other image files. Using a predefined script in ArcView, the core image was then hot linked to another image file (in this case a TIFF image of a portion of the digitized lithologic log corresponding to the core run). The user could now simply point and click on the core and another image would immediately appear showing a detailed lithologic log corresponding to the section of core that they were looking at. Initially, the photomicrographs were treated in a similar manner, however it was determined that as more data sets became available, it would not be feasible to construct many separate polygons with reference to the single core image. Also, the screen size of the ArcView window limits the number of drawings referring to a polygon (and another image file) outside of the core image. It was decided that future data sets, including photomicrographs, spectra, and x-ray results would be available to the user as point-and-click buttons created in the graphical user interface (GUI) of ArcView by using the Avenue programming language. Figure 1 shows a version of the ArcView core database with a corresponding lithologic log and photomicrographs. The left side of the image shows the main core image view with the scale bar and the hidden polygon behind the core image. To the right of the core view, is a digitized version of the corresponding lithologic log, and below that are two photomicrographs (unpolarized on the left and polarized on the right) from a thin section made at a depth of approximately 200 ft (61 m).

RESEARCH RESULTS

The procedure used to identify lithology based on image processing was first tested on a small segment of the core. The test area corresponded to a section at a depth of approximately 61.4 m (201.4 ft) to approximately 62.9 m (206.4 ft.). The lithology consisted of massive medium-grained sandstones. In the top section of the test area, there were abundant laminated carbonaceous shale clasts, about 9.1 cm (0.3 ft) long. The classification was able to discriminate these two types quite successfully. In order to achieve a high level of accuracy, the core had to be classified in sections due to the fact that much confusion existed between several classes. Following the recoding step, the classes were assigned different colors to allow them to be easily distinguished on the screen or color output. As a final step, statistics were generated in order to view the percentage and area of each class. This technique can be further refined by applying different texture and filtering algorithms to highlight distinct features in the lithologies.

Although no statistically rigorous study has been done at this time, preliminary results of the spectroscopy portion of this study indicate that the use of the curve matching algorithm will allow the rapid and relatively accurate correlation of lithologies and mineralogies across individual and multiple cores or cutting sets. Spectral curves were incorporated into the ArcView project as TIFF image files and as Xbase .dbf formats. This allowed immediate visual inspection or data queries through several PC based spreadsheet and database programs. The x-ray results for the sample used to generate the spectral curve were:

1. Quartz: 15%	6. Chlorite 1%
2. Plagioclase: 3%	7. Kaolin: 12%
3. K-Feldspar: 4%	8. Illite + mica: 3%
4. Dolomite: 2%	9. Mixed layer illite/smectite: 45%
5. Pyrite 2%	10. Amorphous/below detection limit: 13% (probably coal)

The ArcView programming language, Avenue, was used to customize the GIS to better suit the Ferron core information. Avenue is an object-oriented database language that allows the user to edit the GUI of ArcView, and write and compile scripts which tell the software how to perform a certain task. The GUIs consist of buttons and tool icons which appear at the top of the ArcView window after the program has been opened. By pointing and clicking on one of the buttons, ArcView performs a task that is associated with that button which was preprogrammed using an Avenue script (ESRI, 1994). New buttons were created in the ArcView GUI to allow the user to point and click on a button and open up a table of additional data set names. By pointing and clicking on the desired data set name, an image window was opened containing that data set (photomicrograph, spectroscopic data, or x-ray data). Multiple images could also be opened and viewed side by side for ease in comparison. Once the ArcView GUI was customized to meet the needs of the end user, the project file was saved. Reloading the project file brings up the customized GUI and access to the special buttons necessary when viewing the other available images. Zoom and display dragging features are also available on the ArcView GUI.

FUTURE PLANS

Through creation of the core database in a GIS environment, it is possible to update the database through the addition of data sets as they become available. Further enhancements to the database will include such things as more detailed lithologic analysis using image processing software, formation microscanner imagery, and digitized well logs and SEM imagery. Obviously, the inclusion of more data sets will increase the utility of the core database to the end user, resulting in a better understanding of the core properties. The technique can provide a fast and easy way of viewing and interpreting the rock core to the analyst who is unable to travel to the site of the core repository.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	Core Imagery and Archiving

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NEVADA GEOTHERMAL GRADIENT-HOLE DATABASE

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KEY WORDS

temperature-gradient drill holes, slim holes, exploration, Nevada, temperature logs.

PROJECT BACKGROUND AND STATUS

In March of 1994 the Geothermal Resources Council sponsored a Basin and Range Geothermal Resources and Exploration Symposium in San Francisco. The meeting was attended by about 30 representatives from industry, government, universities, and research groups. At that meeting, in addition to brief presentations on a variety of research projects in progress, there was considerable discussion about ways that ongoing and future investigations could benefit the geothermal industry. One such discussion centered on the large volume of industry geothermal exploration data that are known to exist but are not readily available. There was a consensus that some attempt should be made to preserve, archive, and categorize at least some part of this information. Specifically, such data include gradient- and slim-hole information (including temperature logs and water chemistry). It was noted that Nevada represented a good example of an area where considerable geothermal exploration effort had been expended during the 1970s and early 1980s, and should be a useful area for a demonstration project to evaluate the feasibility of collecting and making such data available for use by future geothermal explorationists.

The project was started in May of 1995 and is scheduled for completion in the Spring of 1996. It is less than 40 percent complete as of the time of this summary. For a comprehensive database, more donated data are needed from industry and individuals.

PROJECT OBJECTIVES

Technical Objectives

- Develop a database of geothermal temperature-gradient holes for Nevada in a dBase-compatible format.
- Integrate the Nevada database with a GIS visualization software product (ArcView, marketed by Environmental Systems Research Institute, makers of ArcInfo) that will allow interested users to easily query the database.

Expected Outcomes

- Provide a base of temperature gradient information that will be of assistance to future Nevada exploration efforts for both low- and high-temperature geothermal resources. Future exploration costs will be reduced as a result.
- The final product is expected to be made available as a digital publication of the Nevada Bureau of Mines and Geology (NBMG), to be on-line for interactive search in NBMG's Information Office, and eventually to be available on the Internet.

APPROACH

The first project priority was to develop a database having categories (fields) that will be useful for computerized search, especially by geographic area. Industry experts were informally queried regarding the utility of various fields. The latitude/longitude location is particularly important because future users are likely to need to search in specific geographic areas of interest. Location information is necessary to allow interactive computer search by potential data users. A system to display gradient-hole locations on a computer monitor using a GIS (Geographic Information System) will be developed and evaluated.

Concurrently, a search will be conducted of published information, especially "gray literature," for any information of geothermal gradient drill hole information. Files of various regulatory and research agencies will be examined as well, and any data obtained will be collected in hard-copy files. From these files, the pertinent data will be entered into the database, and drill hole locations will be plotted on 7.5-minute topographic maps for later digitization of longitude and latitude.

A variety of methods will be used to solicit individuals and companies to donate or permit copying of available gradient-hole information. Information will be collected on any existing gradient-hole data, even if the data can not be obtained at the present time, or if only partial information (for example, only location) can be obtained. Thus, a complete Nevada database should also include information on gradient holes for which no temperature-gradient data could be obtained. Such partial information may allow the relocation and remeasurement of existing drill holes; or, if the present owner and location of the data are available in the database, potential users can contact data owners directly. All these options can produce considerable cost savings by preventing needless recollection of data.

RESEARCH RESULTS

We have developed a preliminary database having approximately 40 categories (fields) that are likely to be useful for computerized search or preliminary evaluation by explorationists. The most significant of these fields include information on the following: operator and well name (and number), legal location, longitude and latitude, accuracy of location, well status, total depth, maximum temperature, completion and measurement date, water level, site elevation, and additional data available - logs, water analyses, drill samples.

Gradient-hole information from published sources has been entered in the database, as well as data from geothermal files in the public information office of the Nevada Bureau of Mines and Geology. At this time, about 650 records are in the database. Solicitations by letter, on-line computer services, newsletter announcement, flier, and verbally indicate a large volume of existing data. However, it is not certain how much can be obtained without purchase. General information on individuals or companies that hold such data is also cataloged and will be available to interested users.

FUTURE PLANS

The search for more Nevada gradient-hole data is a continuing effort. The most significant future additions to the database will be contributed by industry.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Industry input was the motivation for the project. To date, more than a dozen geothermal companies have been contacted, with a favorable response to the project goals. Much of the gradient-hole data were collected in the search for high-temperature resources. Most geothermal industry experts believe that preservation of such data is important and will eventually save money during future exploration efforts for such resources. Because of the virtual absence of such exploration in the United States at the present, potential users of low-temperature geothermal resources may be more likely near-term beneficiaries of a gradient-hole database.

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RESERVOIR GEOLOGY AND HYDROTHERMAL ALTERATION OF THE COSO GEOTHERMAL SYSTEM, CALIFORNIA

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KEY WORDS

Coso, Basin and Range, hydrothermal alteration, fluid inclusions

PROJECT BACKGROUND AND STATUS

Coso Hot Springs is the largest geothermal system in the Basin and Range Province with a generating capacity of 240 MW. It is also one of the few associated with young volcanic activity. Because of the extensive drilling program that has been undertaken, and the availability of core and cuttings from depths in excess of 3 km, this field has proven to be an important natural laboratory for studying the geologic and geochemical characteristics of geothermal systems.

ESRI has been involved at Coso since the late 1970's when geothermal exploration was first beginning here. Our efforts have included geologic mapping (Hulen, 1978), interpretation of geophysical data (Wright et al., 1985), and the development of hydrogeochemical models based on production and fluid inclusion data (Moore et al., 1989; 1990). Examination of the subsurface geology and hydrothermal alteration at Coso have been limited, however, to the shallow and marginal parts of the system (Fiore, 1981; Echols et al., 1986; Bishop and Bird, 1987; Nielson et al., 1990). In contrast, this study focusses on the distribution of rock types and secondary minerals within the deeper parts of the reservoir. Developing an understanding of the hydrothermal alteration throughout the field is of particular significance because the reservoir is developed in granites and metamorphic rocks that have been affected by multiple thermal events.

Our investigations of the cuttings and cores from Coso are currently approximately 75% complete. We anticipate completion of the present study in FY 96.

PROJECT OBJECTIVES

The primary objective of this project is to develop better conceptual models of granite-hosted geothermal reservoirs associated with young volcanism.

Technical Objectives

- Characterize the alteration mineralogy associated with recent geothermal activity and establish criteria for distinguishing it from earlier hydrothermal events.
- Integrate the mineralogic data with the results of fluid inclusion measurements to evaluate the effects of mixing and boiling on the distribution of the secondary minerals.
- Complete lithologic logging of boreholes throughout the field to assess the distribution of faults and fractures and their relevance to fluid movement.
- Determine the relationship between the secondary mineralogy and the thermal structure of the system, with emphasis on the caprock and upwelling center.

Expected Outcomes

- Assist explorationists and developers in targeting geothermal wells in granite-hosted geothermal systems by developing better conceptual models of these systems. This will reduce the number of dry holes and development costs.
- Develop an improved understanding of the reservoir in its natural state which will allow better prediction of the changes resulting from exploitation.

APPROACH

The objectives of this study will be attained by careful petrographic and geologic logging of the cores and cuttings. The samples will be studied in thin section to determine rock type and the distribution and paragenetic relationships among the secondary minerals. X-ray diffraction techniques will be used to characterize the fine-grained sheet silicates and determine the percentage of mineral phases within the rock. Fluid inclusion temperatures and salinities are available for many of the wells being studied. These temperatures will be compared with mineral based geothermometers and downhole measurements to assess the evolutionary changes that have occurred since the secondary minerals were formed. Temperature-salinity relationships will be used to establish the processes (e.g. boiling, mixing) responsible for mineral deposition.

These studies represent a collaborative effort between ESRI and California Energy Co. Inc., the operator of the field.

RESEARCH RESULTS

The geology and mineralogy of more than a dozen wells has been determined (Figure 1). These observations have defined a succession of mineral assemblages that vary systematically with depth and temperature. Within the interior of the system, where fluid inclusions record temperatures ranging from 235°C to 340°C, secondary minerals include calcite, quartz, illite, chlorite, epidote, pyrite, and wairakite (Figure 2). At lower temperatures, between about 200°C and 220°C, the mineral assemblages are characterized by calcite, quartz, and interlayered illite-smectite, and chlorite-smectite. In the outermost zone, where fluid-inclusion temperatures are less than about 200°C, the common minerals include smectite, stilbite, kaolin, calcite, and dolomite. Although the rocks at the surface appear to be pervasively fractured, rocks within the outermost zone are characterized by conductive thermal gradients. We conclude from these relationships that clay deposition has effectively reduced the shallow permeabilities of the reservoir rocks, restricting the upward movement of the thermal fluids. Mixing between the thermal fluids and low salinity groundwaters that are no longer present appears to be the primary cause of clay deposition.

Fluid inclusion homogenization temperatures and inferred formation temperatures of the alteration minerals indicate that the central parts of the system are still heating up while rocks on the margins of the system have cooled (Figure 3). In Figure 3, cooling is indicated by fluid inclusion measurements and temperature estimates based on illite-smectite interlayering. Progressive heating in the lower part of the well is demonstrated by the presence of stilbite which is stable up to 125°C, chalcedony, which is stable to 180°C, illite-smectite temperatures, and by fluid inclusion temperatures up to 250°C. These fluid inclusion temperatures are several tens of degrees lower than the present measured temperature.

FUTURE PLANS

We plan to complete our petrographic and lithologic investigations of the Coso geothermal field in FY 96. The results of these studies will be presented at the Stanford Workshop on Geothermal Reservoir Engineering in January, 1996. A more detailed paper, describing the results of the fluid inclusion and geologic studies will be prepared for publication in a journal.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The work we are conducting will be of benefit to several organizations. California Energy Co. Inc., developers of Coso and Roosevelt Hot Springs (UT), Caithness Corp. and Far West Capitol, who operate Steamboat Springs (NV), CFE (Mexico), Unocal Corp., and the Japanese Geological Survey have shown strong interest in this work because of its focus on granite-hosted systems.

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Figure 1. Location of wells and surface features in the Coso geothermal system.

Figure 2. Mineralogic and temperature relationships in well 10. The generalized distribution of rock types is shown in the lithology column. Interlayered illite/smectite is designated by I/S. The heavy solid line on the temperature-depth plot shows the boiling point to depth curve for a 0.0 weight percent NaCl solution. The thinner solid line shows the present measured temperatures.

Figure 3. Mineralogic and temperature relationships in well 16. The thin and heavy solid lines on the temperature plot represent measured temperature and boiling point curves, respectively (see Figure 2).

MAPPING AND GEOLOGIC INTERPRETATION IN THE COSO GEOTHERMAL AREA

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KEY WORDS

geologic studies, extensional features, strike-slip faults, Coso Range, paleomagnetism

PROJECT BACKGROUND AND STATUS

The Coso Range is located within the Mesozoic magmatic arc of the western Cordillera (Figure 1). Because of this, the bedrock geology of the region is dominated by Jurassic and Cretaceous plutonic rocks containing remnants 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 140 Ma suggesting that deformation was protracted over a period of at least 45 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 August of 1996. Fieldwork during the 1995 season was focused on the northern half of the study area. More samples were collected and are currently being processed for age determinations. Samples will also be collected for further paleomagnetic analysis on the basis of the mapping conducted during the 1995 field season. These samples will be analyzed in the paleomagnetism laboratory at the University of Kansas (KU) early in 1996. This data will be then be integrated with the existing paleomagnetic information in order to better understand the role of rotations and tilts that have been proposed for the Coso 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 3-D geologic modeling program.

PROJECT OBJECTIVES

The main aim of this study is to better understand the geologic development of the Coso Range, which is 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 not so well understood. In addition, there has been comprehensive study of the structural geology of the area that combines detailed structural investigations, geochronologic and thermochronologic age information, and paleomagnetic data.

Technical Objectives

- Identify important structural features within 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

- An understanding of the position of the Coso Geothermal Area relative to major Pliocene to Recent faults in the area. This is important for exploration models both within and surrounding the Coso Geothermal Area.
- Quantification of 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.
- Further understanding of 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 within the Basin and Range.

APPROACH

Field work follows normal practices of geologic mapping, such as 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 uranium-lead (zircon) geochronology. The cooling history of the area is being studied by use of Ar/Ar dating. Paleomagnetic poles are being determined for various igneous samples.

Mesozoic ductile deformation structures have been examined by normal petrographic techniques and polished slabs. Ages of deformation are being constrained variously by mineral isochrons, Ar/Ar thermochronology, or have been established by the cross cutting relations discovered through mapping within the study area. Conditions of deformation and pluton emplacement will be determined through studying the petrofabrics and mineral assemblages within various units.

Information concerning the offsets among Cenozoic faults is being gathered 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 KU 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 KU. Paleomagnetic analyses are being performed in the Phillips Paleomagnetic Laboratory at KU. Other studies are being conducted at Institutions where the necessary equipment is available (i.e., University of Missouri, Columbia for microprobe work and M.I.T. for Ar/Ar studies).

Most of the study area has now been examined, according to the 8 month time frame that was initially proposed. A substantial portion of this time was spent on the Coso area, because the bedrock geology and structure is of critical importance toward understanding the location of the geothermal system.

RESEARCH RESULTS

Progress thus far has resulted in a good understanding of the magmatic and deformational history within the Coso Range. In general, there are four major plutonic units (Figure 1) that contain inclusions of various metasedimentary and metavolcanic strata. The geochronology in progress will make clear the absolute age relations among these intrusions. This data, along with the ongoing paleomagnetic and rock fabric studies, will be used to address the problems related to the Mesozoic and Cenozoic development of the area.

Mesozoic Geology

The four main plutonic bodies within the Coso Range are characterized as follows: (1) a foliated and compositionally mixed complex, including gabbro, diorite, and granitoids, which occupies the southwestern portion of the range; (2) an undeformed, light-colored granitoid complex that spans the Cactus Flats area in the west-central part of the range; (3) a foliated, hornblende granitoid complex that occupies much of the eastern portion of the study area; and (4) a distinct, undeformed hornblende granitoid intrusion in the northern portion of the range. Preliminary geochronology indicates that the mixed complex granite is of mid- to late Jurassic age (about 165 Ma), and was later intruded by other granitoids during the Late Cretaceous (approx. 70 Ma). A similar mid- to late Jurassic age is apparent within the foliated granitoids in the east, and field relations suggest that the Cactus Flats leucogranite post-dates this foliation.

Inclusions of Paleozoic-Mesozoic metasedimentary and metavolcanic units are found throughout the range. The compositions of these are varied, although they generally fall into one of several categories. These include siliceous metasediments (biotite±garnet schist, quartzite, and metaconglomerate), calcareous metasediments (marble, calc-silicate, and metaconglomerate), and metavolcanic-metasediment associations (metabasalt, metatuff, carbonate-clast breccia, and turbidite). The exposure of these included blocks is extremely limited and their position within the regional stratigraphy is unclear. Although, the metavolcanic units have yielded zircon that will be used to constrain the age of the associated sediments.

The range is transected by various dike swarms, which may be grouped into several categories. The southern Coso and Argus ranges are cut by numerous northwest-trending, subvertical dikes that are generally of intermediate-mafic composition. These are considered to represent part of an extensive late Jurassic swarm that provides an important structural marker throughout the region. A distinct group of felsic/microgranite dikes is recognized within the eastern part of the range. Field relations suggest that these are slightly older than the more mafic dikes, and preliminary zircon geochronology indicates an approximate age of 149 Ma. Another distinct group of dikes, composed of feldspar porphyritic granitoids, intrudes the northern part of the range. The age of these granitic dikes are unknown, although field relations indicate that they must be younger than the Cactus Flats leucogranite.

Precise geochronologic relations among the major intrusive units and the various dike swarms will be reported upon completion of the laboratory analyses. Ar-Ar thermochronology suggests that the entire Coso area was affected by a significant thermal event at approximately 90-100 Ma.

Furthermore, this may be related to a older phase of faulting that caused brittle deformation in the geothermal area at some time prior to 88 Ma. The significance of this thermochronologic data will become more clear when the U-Pb geochronology is completed.

At present, the field relations constrain the following sequence of major magmatic events during the Mesozoic:

1. intrusion of the South Coso mixed complex and the eastern granitoid complex (foliated)
2. " North Coso granite (unfoliated)
3. " felsic/microgranite dike complex
4. " intermediate-mafic dike swarm throughout region
5. " Cactus Flats leucogranite
6. " feldspar porphyry granite dikes

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. Intrusive contacts within the basement complex have been used to demonstrate various fault offsets that may pre-date the volcanic cover sequence. Tectonic stress within the range has been accommodated on several sets of faults. These include an old (possibly Mesozoic) WNW set, and two younger sets that trend NNE and NNW. The Geothermal Area is characterized by a complex interaction of the older WNW set with the younger NNE set. Displacements along the WNW faults are typically left-lateral strike-slip, whereas the other faults are typically extensional. One such WNW fault may, in fact, be responsible for the apparent strike-slip termination of an older ductile shear zone near Sugarloaf Mountain, and for partitioning more recent extensional deformation in areas farther south. This boundary may be one of the major structures that define the geothermal reservoir.

The age of these various faults is difficult to constrain, excepting the recent fault scarps along the west side of Coso Wash. However, the parallelism of late Jurassic dikes with the WNW faults suggests that faults/fractures of that orientation have existed since mid-Mesozoic time. Much of the cataclasite (brittle fault fabric) exposed along Coso Wash is probably related to the opening of the present basin, although thermochronologic analysis of white mica that post-dates the brittle fabric at one locality indicates that the cataclasite formed prior to 88 Ma. Such micaceous overgrowths are rare. This particular analysis does support the hypothesis that some of the brittle fabrics are pre-Cenozoic in age.

Less obvious effects of Cenozoic extension are recorded by the paleomagnetism analyzed in this study. For example, paleomagnetic poles within the area west of Coso (Rose Valley) are oriented much differently than poles within the range farther east. More specifically, the data indicate that the Rose Valley and Little Lake areas have been tilted a minimum of 36 degrees to the west. The timing of this deformation is also difficult to constrain, although it must post-date the units analyzed, which are of latest Jurassic or Cretaceous age. A similar 15-20 degree tilt of Coso Formation strata (since approx. 5 Ma) in the Haiwee Reservoir area may be used to further constrain the tilt history. This sense of tilting implies that the development of Cenozoic

structures of the western Coso Range may be related oblique slip along an extensional fault system within Rose Valley.

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

Additional sampling and mapping will be conducted during December 1995 and January 1996. Analysis of paleomagnetism will be completed early in 1996. The remaining time will be devoted to completing the geochronology and petrofabric analysis, and addressing the problems that have been outlined above.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

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

This project is supported by the Department of Energy (DoE) and the Geothermal Technology Organization (GTO). Funding is provided by GTO members and DoE.

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Figure 1. Major plutonic bodies of the Coso Range.

EXPLORATION FOR GEOTHERMAL RESOURCES IN FRONTIER AREAS OF SOUTHEASTERN OREGON

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KEY WORDS

southeastern Oregon, geothermal resources, blind hot springs

PROJECT BACKGROUND AND STATUS

This project began in 1993 as a joint project between Portland State University (Dr. Michael Cummings) and DOGAMI (Dr. George Priest). Phase I of the project was funded by the Bonneville Power Administration, augmented in 1994 with funding from DOE through the Idaho National Engineering Laboratory (INEL), and a small grant from Portland General Electric Company. Phase II has been funded by DOE 1995 and 1996 with a contract extension. Phase II should be complete in the summer of 1996.

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 was 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 old hot springs activity.

Technical Objectives (continued)

Field-check target areas located by the above techniques to look for structural settings favorable to hot spring activity and alteration associated with old hot springs.

Use detailed geochemical studies to characterize past geothermal activity.

Recommend areas for future geothermal exploration.

Expected Outcomes

Identification of several new areas of geothermal resource potential which have minimal land use conflicts or environmental concerns and reasonable proximity to power transmission facilities.

Development of a suite of indicators for blind or recent hot spring activity.

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 work included 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.

In Phase II, five additional study areas were mapped with air photos and reconnaissance visits. Detailed soil mercury sampling was performed at two sites. Landsat (Thematic Mapper) is being examined to look for anomalies associated with known active hot springs area and to search for similar anomalies in areas without known hot springs.

RESEARCH RESULTS

North Lake Abert: The area north of Lake Abert was mapped in detail, to look for evidence of Quaternary hot springs mineralization in addition to tufa deposits previously located. No additional areas of Quaternary geothermal mineralization were located, and the tufa mounds were shown to be roughly concordant in elevation, suggesting a relationship to playa lake level and chemistry. Tufa mounds were sampled for oxygen isotope geothermometry (Jellinek and others,

1996) and the results will be published in Oregon Geology in January of 1996. Temperature logging of a single shallow well near the area provided marginal evidence of relatively low heat flow. Soil mercury samples were collected along several transects crossing the faults associated with the tufa mounds. None of the samples had measurable free mercury (detection limit approximately 20 ppb). With the exception of the tufa mounds and modern warm spring (17°C) there is little evidence of Quaternary geothermal activity, and the area probably does not warrant further evaluation.

Valley Falls: A single 130 m deep well located at Valley Falls in 1994 was temperature logged in 1995. The hole was obstructed at a depth of 80 m, and the temperature profile shows a very low gradient, possibly related to groundwater flow. This study has found no further evidence of geothermal potential at Valley Falls.

Egli Rim: Egli Rim is the west facing fault scarp forming the east side of the Silver Lake basin. In the Picture Rock Pass area between the Egli Rim and the east facing winter Rim which forms the west side of the Summer lake basin, there is a complex zone of closely spaced faults. In 1994 we surveyed this area in detail and found numerous locations with silica and carbonate mineralization of Miocene bedrock, Pliocene to Quaternary channel gravels and Quaternary colluvium. The mineralization was sampled for oxygen isotope geothermometry and the results will be published in Oregon Geology in January of 1996 (Jellinek and others, 1996). The oxygen isotope data were encouraging for the prospect of a Quaternary geothermal system with significant (145 to 205°C) reservoir temperatures (see appendix 1). In 1995 the area was sampled in detail and tested for soil mercury. Essentially all of the samples had mercury levels below the limit of detection (about 20 ppb). We did identify an irrigation well in the area that was originally 190 m deep, and will work with the owner this winter and spring to determine whether it is feasible to use the well for a temperature profile. The evidence for geothermal potential at this area to date is significant, but the lack of soil mercury suggests that the system responsible for the mineralization may be dead.

Christmas Valley-Summer Lake: The highlands between the Christmas Valley and Summer Lake Basins are extremely complexly faulted, with intersecting sets of NE and NW-trending faults spaced as little as a kilometer apart. The area abuts the Egli Rim area, and includes at least one Quaternary Fault (Pezzopane, 1993). We mapped the faults over approximately eight quadrangles using air photographs. In 1995 these quadrangles were visited on a reconnaissance basis to look for evidence of Quaternary hot springs mineralization. Despite the extensive faulting the only mineralization we found was in playa beach bars of cobble gravel, along faults bounding the northern end of the Summer Lake basin. The gravels were extensively cemented with travertine, possibly due to interaction with mineralized spring water entering the Quaternary playa lake. Although the area is surrounded by numerous warm wells and springs there is no evidence within the eight quadrangle study area for significant Quaternary geothermal activity.

Drewsey: The Drewsey area is a region of faulted Miocene and Pliocene lake sediments, basalt and ash flows and rhyolite flows. In addition there are several warm wells and warm or hot springs in the area. We mapped faults over an eight quadrangle area using air photos, and reconnaissance mapped the area in the summer of 1995. There are numerous zones of intense

mineralization of bedrock units in the area, many staked or prospected, but we only found one area of mineralized Quaternary material adjacent to an uncatalogued warm (20°C) spring in the northwest corner of the Drinkwater Pass quadrangle. Bedrock mineralization is associated with rhyolite bodies, the active-Drewsey hot spring (74°C), and several zones of intense faulting. Although there was no clear evidence of widespread Quaternary mineralization associated with blind hot springs, we feel that this area warrants further investigation.

Antelope Valley: Antelope Valley occupies a graben south of Jordan Valley, Oregon. The area has several thermal wells and springs, and a few high heat flow data points, but in general data is quite sparse given the low population density. The southern boundary of the graben is an impressive fault scarp, marked by a broad zone of intense faulting. Similar east-west trending faults mark the southern edge of extensive Quaternary basalt fields at Jordan craters just north of the area of Figure 5, and many of those faults cut Quaternary Basalt flows. We mapped the northern half of the Parsnip Peak and Juniper Ridge quadrangles to locate faults and look for evidence of Quaternary hot springs mineralization. We found no evidence of mineralization in Quaternary units, although the Quaternary is largely represented by floodplain deposits and colluvium. Siliceous mineralization in Miocene rocks was commonly observed. One uncatalogued warm spring (17°C) was located at the intersection of a major north trending fault and the east-west trending graben boundary. Other springs in the area typically had temperatures of 8 to 10°C. The presence of numerous thermal springs and wells and sparse high heat flow data suggests that this area has significant potential. Further detailed mapping along the south side of the graben, and in the area of gold prospects northwest of Jordan Valley may be warranted.

Turpin Knoll: This study area was located at the north end of the Warner valley, in an area of complex northeast and northwest trending faults and Quaternary basalt cones. The southern end of the Warner basin has numerous thermal wells and springs located in the Crump Geyser KGRA. We mapped faults on eight quadrangles in the study area using air photos. Before visiting the area to look for evidence of Quaternary hot springs mineralization, we had a chance conversation with a geologist from a private geothermal exploration firm who reported that his company had looked at the same area in the past. He reported significant Hg anomalies which led the company to drill several temperature profile holes all of which were reportedly stone cold. Accordingly, we chose not to pursue further study in this area.

Satellite Imagery: DOGAMI has obtained Landsat TM imagery for a large swath of SE Oregon. We intend to use the data to look for signals associated with known areas of geothermal activity that might be used as an exploration tool for blind or recently inactive hot spring systems. To this end we have obtained 1:24,000 scale DEMs for quadrangles including the Alvord Hot Springs, Borax Lake, Mickey Hot Springs, Summer Lake Hot Springs and Easterday Hot Spring. We are using the DEMs and carefully georeferenced sections of imagery to calculate relative illumination for each satellite image and then normalizing each band with this information. We are then examining the normalized bands individually and in combination to look for anomalies associated with the hot springs. If any anomalies are found, we will search large areas for similar anomalies to define targets for further exploration.

FUTURE PLANS

For 1996 we intend to complete compilation of the geologic information collected to date, complete satellite imagery analysis and collect a temperature profile at Picture Rock Pass. If funds and weather allow, we will return to Antelope Valley and Drewsey for more field investigations.

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CASE STUDIES OF GEOTHERMAL SYSTEMS ASCENSION ISLAND, SOUTH ATLANTIC OCEAN

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KEY WORDS

geologic mapping, electrical resistivity, aeromagnetic survey, heat flow, volcanic rocks, exploration well

PROJECT BACKGROUND AND STATUS

The geothermal exploration of Ascension Island was conducted between 1982 and 1988 for the U. S. Air Force and the U. S. Department of Energy. The project included geologic mapping, an aeromagnetic survey, electrical resistivity surveys, temperature gradient hole drilling and the drilling of a deep exploration well. The project is no longer active; however, the information developed provides a good case study of geothermal exploration of a small volcanic island. The data is being developed into several papers that will be published in a special issue of the journal *Geothermics*.

Ascension Island is located about 80 km west of the Mid-Atlantic Ridge and about 50 km south of the Ascension Fracture Zone in the South Atlantic Ocean. Interest in the geothermal potential of this island was fostered by the relatively young volcanic activity and the abundance of felsic volcanic rocks. The oldest rocks dated on the island are approximately 0.9 Ma. Geochemistry shows a continuous sequence of rocks of basalt-hawaiite-mugearite-benmoreite-trachyte-rhyolite composition. Blocks of medium-grained syenite and granite in pyroclastic deposits suggest that felsic plutons, that could have been the heat source for a geothermal system, have formed.

PROJECT OBJECTIVES

Technical Objectives

- Technology transfer concerning geothermal exploration of a small volcanic island.

Expected Outcomes

- Increase the efficiency of geothermal exploration. Exploration case studies are high priority for companies interested in improving their ability to find high-temperature geothermal systems.

APPROACH

The geothermal exploration of Ascension Island applied a strategy based on the philosophy presented in our work on geothermal systems in the northern Basin and Range province (Ward, Nielson and Ross, 1981).

RESEARCH RESULTS

The exploration program discovered high temperatures but limited permeability at depth.

FUTURE PLANS

Papers are being reviewed and revised for the special issue of Geothermics. The publication of these papers will end work on this activity.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The USAF was originally interested in privatization of power generation on Ascension Island. They have apparently decided not to follow through on that initiative.

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

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KEYWORDS

eastern US, central US, geothermal potential, temperature, heat flow, thermal conductivity, heat mining.

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's 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. Publications on the status of the project are contained in Blackwell et al. (1993, 1994, 1995).

PROJECT OBJECTIVES

Technical Objectives

The technical objectives of this project are to:

Increase the precision and accuracy of geothermal resource estimates and assessments.

Regionalize geothermal resource quality in the United States.

These objectives are to be met by specific objectives:

Develop and make available for the process of evaluation 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.

Prepare heat flow and geothermal gradient data bases and maps based on published thermal data for the whole US.

Expected Outcomes

An updated heat flow data base.

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' (about 4 to 5 km).

A digital representation of the heat flow contours for the western US.

A specific application of the results to regional evaluation of the northern Louisiana area.

A preliminary data base of geothermal system specific gradient sites prepared as an addition to the regional heat flow data base.

APPROACH

This project is near the end of a multiyear effort to evaluate the geothermal conditions at depths of several kilometers in the US, focusing generally on the area east of the Rocky Mountains. Geothermal resource estimates and assessments by this and other projects are 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, first, 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). Second, statistics on the distribution of temperature at a depth of 4 km are illustrated 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 was updated as of the end of 1995 with an additional 353 heat flow sites that became available since compilation of the 1989 data list of 1735 sites. 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 a rationale, and a realization of that rationale, of a resource exploration and evaluation technique for HDR is demonstrated in this report and in more detail in Blackwell et al. (1995).

Calculation of the temperatures at depth requires a number of types of information available at the same scale as in the heat flow data (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. 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.

Temperature at 4 Km An example of the results for one major object of the study are illustrated in Figure 2. In Figure 2 the data sets for 1) heat flow, 2) mean thermal conductivity of the sedimentary section, 3) thickness of sedimentary rock, 4) geothermal gradient (from heat flow and thermal conductivity), and 5) surface temperature, have been combined to calculate temperature at a depth of 4 km. 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 US. 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 US, 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).

Application: Louisiana In the initial analysis an area that appeared to have unusually high geothermal potential, and that had not previously been identified, was outlined in northern Louisiana. The AAPG data base of Bottom Hole Temperatures (BHT) was used to examine in more detail the thermal conditions there. Petroleum well BHT data are often difficult to interpret, but that information was checked against ground truth well temperature logs and heat flow data. The resulting gradient map, based on the BHT data divided into 0.25 ° latitude and longitude bins, is shown on Figure 3.

The thermal gradients are indeed quite high in parts of northern Louisiana, with values of 30 °C/km (1.6 °F/100 ft) common. The data show that temperatures of 150 °C (300 °F) at 4 km are common over about 1/2 of northern Louisiana. The formations at the high temperatures are basement rocks and low permeability Jurassic sands and shales.

These temperature estimates are consistent with the Mosley well in northeastern Louisiana (Blackwell et al., 1993) where the measured equilibrium temperature is 130°C at 3 km (10,000 ft) and a projected temperature at 4 km is 150+ °C. These results demonstrate the existence of high temperatures over large areas in the tectonically stable eastern United States, given the combination of low thermal conductivity and high heat flow. These results also demonstrate the validity of the high temperatures shown in Figure 2 for the northern Louisiana area.

Discussion The temperatures illustrated in the map in Figure 2 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°C, 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 US 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

In the future we plan to make the data bases available by operating a home page on the Internet with the up-to-date information available. The data base of exploration data in the western US will be expanded. The regional resource and exploration methodology, with appropriate modifications, will be applied to the western US.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Geothermal Power, Inc. NY State Energy Office Dept. Geophys. and Astronomy U. of British Columbia Dept. of Geography, U. Ontario	Temperature in Northeast US Temperature in New York Paleoclimate, heat flow distribution GIS Comparison of heat flow and mineral resources Temperature for Heat Mining Economic Analysis Geothermal Exploration data in Nevada
Energy laboratory, MIT Barrick Gold Strike Mines	

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

Temperature (°C)	% Area
< 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

2 - 97

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 1995.

Figure 2. 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.

Figure 3. Geothermal gradients in Louisiana and vicinity contoured on AAPG BHT data gridded at 0.25° latitude and longitude intervals. 18.2 °C/km equals 1 °F/100 ft.

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 bits, impregnated-diamond bits, thermally stable polycrystalline (TSP), hard-rock drilling, geothermal drilling, single-cutter testing

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. An earlier 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.

A large number of companies were contacted and a comprehensive program proposal on synthetic-diamond drill bit technology development was written 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) Fossil Energy Division approved funding for the program under the Natural Gas and Oil Technology Partnership (NGOTP). This funding was received in August 1993. Joint-work, cost-shared contracts were placed with each company, and the program was begun at the end of October 1993. Additional funding was received from the DOE Geothermal Division funding in FY94. Overall funding for the program was shared equally by industry, DOE Fossil Energy Division, and DOE Geothermal Division in FY95.

At the conception of the program, it was anticipated that the initial effort would be completed within two years. Due to a variety of reasons (less funding than expected, the need to build new testing equipment, mergers and reorganizations of the companies) the projects were not completed in two years. It is now expected that an additional two years will be required to complete the ongoing projects and that additional work will be identified at the end of that period to further develop promising technologies.

PROJECT OBJECTIVES

The hard, abrasive, and fractured rock formations drilled to access geothermal 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 laboratory-industry cooperative research and development 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 above those currently attainable with roller-cone bits.

Expected Outcomes

- Develop an optimized claw PDC cutter design combining the abrasion resistance of diamond and the impact resistance of tungsten carbide.
- Develop advanced thermally-stable polycrystalline (TSP) drill bits capable of handling the higher temperatures associated with hard-rock geothermal drilling.
- 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.

APPROACH

Several drill bit and cutter companies have teamed with Sandia National Laboratories to work on four different 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 the capabilities and current product interests of each company. 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 TSP bits. The objective of each project is to develop drill bits

and cutters that drill faster and last longer in hard-rock formations. The development of these hard-rock bits would mean lower-cost and faster drilling in natural gas, oil, and geothermal reservoirs.

The companies that have teamed with Sandia to work on these projects are listed below with the corresponding projects.

- **Dennis Tool Company** is 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.
- **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-diamond 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 Laboratories provides technical program management, single-cutter wear testing, linear testing of cutting force and rock/cutter interaction, and numerical thermal and mechanical stress analysis.

A sixth project with Smith International and Megadiamond was dropped during FY95 because of corporate restructuring that left those industry partners without sufficient resources to participate in the program.

RESEARCH RESULTS

A conference paper summarizing the results of this project to date was written during FY95 (Reference 3). It is co-authored by Sandia and each of the participating industry partners. This work is summarized below.

Claw Cutter Optimization

A parametric numerical analysis of claw cutter design was initiated. Multiple claw cutter geometries employing various groove widths, groove spacings, groove depths, and diamond thicknesses were analyzed with a numerical stress code to determine cutter stresses under typical operating conditions. The analysis was divided into two steps, thermal and mechanical stress computations. The thermal stress calculations were completed in FY95. When the mechanical stresses are calculated in FY96, they can then be superimposed on the thermal stresses to determine the total stresses in each cutter configuration. This will allow the optimal configuration based on minimal stresses to be identified.

Development of a Cutter Wear Test Facility also continued under this project. This facility consists of a laboratory drilling machine designed to efficiently drill multiple holes in a large rock sample for comparative wear testing. The test cutter is mounted on a coring bit and experiences cutter interaction similar to that experienced by a cutter on an actual drill bit. Cutter speeds, forces, and a fluid environment typical of those that exist in downhole drilling will be possible to duplicate in this facility. During FY95, the facility was constructed and made mostly operational. Problems with the complex hydraulic system were encountered that had to be corrected. As the fiscal year came to an end, it was anticipated that the facility would be ready for cutter testing within the first half of FY96. After baseline cutter wear rates are established with a conventional PDC cutter, claw cutters of various geometries will be tested to verify the results of the numerical modeling.

Track-Set Bit Optimization

Linear, single-cutter tests are underway in support of this project. In these tests, three-axis cutter forces are measured as a function of cutter back-rake angle, side-rake angle, depth-of-cut, cut spacing, groove depth, lateral displacement in an existing groove, and rock type. This data is being obtained for use in a drilling model being developed for Track-Set bit design. During FY95, a large number of tests were completed in Sierra White Granite, Tennessee Marble, and Berea Sandstone. These rocks were chosen because they represent a wide range in rock strength and abrasive characteristics. The effects of repeatedly cutting in an existing groove were defined, as were the effects of displacing the cutter laterally within the groove. The results demonstrated that the groove provides very significant lateral stabilization to a cutter, thereby verifying the Track-Set bit concept. The effects of cutter back-rake and side-rake angles were also defined.

TSP Bit Optimization

Single-cutter wear tests conducted with a variety of TSP cutters on a vertical lathe were completed in FY94. During FY95, analysis of the test results was completed. TSP cutter configurations with the highest wear resistance were identified. In addition, one of these configurations, a TSP disk cutter, had the same geometry as a conventional PDC cutter and could, therefore, be compared directly against the PDC cutter. It was found that the TSP cutter wore at a much lower rate than the conventional PDC cutter. The conditions under which the testing was conducted were such that thermally accelerated wear of the PDC cutter occurred; however,

the TSP cutter did not experience the same effects under these conditions. This verifies that the thermally stable material can withstand much higher frictional temperatures than conventional PDC material. At a certain point in the wear process, however, the TSP disk cutters experienced catastrophic failure when the cutters fractured. These cutters had a very thin tungsten-carbide back-up layer. It is believed that a thicker layer will help these cutters withstand higher steady-state and impact loads.

Impregnated-Diamond Bit Optimization

Hundreds of feet of rock were drilled during FY95 in a laboratory drilling machine at Hughes Christensen in support of this project. A wide range of matrix materials, diamond grit size, diamond grade, and diamond concentrations was investigated. Bit wear rates were measured in several different rock types considered to be typical target formations for this type of bit, to identify bit characteristics that lead to reduced bit wear. Although not yet complete, this testing program has generated a large volume of data that will help optimize impregnated-diamond bit design for a given rock type. This optimization will also be guided by a mechanistic model being developed under this program. Work on this model proceeded during FY95.

FUTURE PLANS

The contracts with the industry partners have been extended for two additional years. This will allow the work outlined in the original program plan to be completed. At that time, the projects will be evaluated to determine the bit design approaches that have the greatest potential for improving hard-rock drilling. Additional work may then be initiated to further advance the technology related to those approaches.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Dennis Tool Company Maurer Engineering, Inc./Slimhole Int'l Security DBS Hughes Christensen Company	Cost-shared partner

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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 BACKGROUND AND STATUS

A reliable and accurate method for detecting and characterizing lost circulation zones is needed in order to reduce the downtime and costs associated with the loss of drilling fluid from the well during geothermal drilling operations. The current industry practice of monitoring drilling fluid pit levels to detect and quantify lost circulation zones is inadequate because of low resolution and slow response. A technique based on comparing the inflow and outflow rates of the drilling fluid would provide much faster response and more useful data. The goal of this project is to develop such a technique and the associated hardware and software.

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 of the rolling float meter for measuring drilling fluid outflow rates 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 (References 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 are discussed 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 ideal for this application because they are non-intrusive, having transducers that clamp onto the outside of the rig standpipe. Testing of a commercially available Doppler flow meter 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.

In 1994, a new type of Doppler flow meter became commercially available. This meter performs advanced signal processing in order to separate rig noise from the Doppler signal. This flow meter was tested with good success on four different geothermal drill rigs during the past year. These results are discussed in this report.

It is estimated that most development work related to the rolling float meter and the Doppler flow meter will be completed within the next year. It could take several years of low-level effort to fully transfer this technology to industry. In addition, an ongoing effort will be maintained in improving operating procedures and data processing algorithms for monitoring, recording, and analyzing flow data for the purpose of identifying and characterizing loss zones.

PROJECT OBJECTIVES

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, and reducing drilling costs and, therefore, 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 flow meters to accurately measure drilling fluid inflow rates in geothermal drilling. If feasible, develop procedures for the proper use of Doppler flow meters 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

- Reduced down time and costs associated with lost circulation are the expected outcomes 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, circulating to confirm a drilling fluid loss by monitoring mud pit levels, the standard practice, may require more than one hour of time for each loss zone, whereas the technology under development in this project is able to detect such fluid loss as soon as it occurs. This allows the location of the loss zone to be accurately determined if the loss zone is on bottom. 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 further when it is fully drilled through later.

APPROACH

The approach taken in this project has been: concept development, hardware design, and 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 have been obtained.

RESEARCH RESULTS***Rolling Float Meter***

Rolling float meters have been undergoing independent field testing and evaluation by seven industry participants for almost three years. 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 with 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; but 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 of which were found in our laboratory testing to affect meter performance.

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 and are enthusiastic about their potential. 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.

Because of the mixed industry experience with the rolling float meter, it was determined that further field evaluation by Sandia would be desirable. The opportunity arose when a Geothermal Drilling Organization (GDO) project on the field evaluation of a new cementitious mud was initiated. That project required accurate inflow and outflow measurements in order to evaluate the effectiveness of the cementitious mud. Over the past year, two geothermal wells were made available by California Energy Company for testing the mud, and Sandia was able to instrument the wells with the rolling float meter for outflow measurements and a Doppler flow meter for inflow measurements. One of these wells was in the Coso Geothermal Field, the other in the Newberry Known Geothermal Resource Area. In both cases, Sandia personnel performed the instrument installation and remained on-site to monitor and analyze the data.

Results obtained with the rolling float meter in these field tests were consistent with Sandia's previous lab and field tests: the meter is generally reliable and accurate. By correlating drops in outflow rate with fractures identified on borehole televiewer logs, it was shown that the rolling float meter can identify even very small fluid losses. Fluid losses can also be identified and quantified much more quickly than with mud pit level measurements.

Some of the problems encountered by industry in using the meter were, however, also experienced. Consequently, design modifications were identified late in FY95 that should make the meter more field hardy and user friendly. As the fiscal year came to an end, these modifications were being made to one of our rolling float meters to prepare it for further field testing in FY96.

Ultrasonic Doppler Flow Meter Testing

A new type of Doppler flow meter became commercially available from Peek Measurements, Inc., in late FY94. The new meter performs a fast Fourier transform on the received acoustic signal and isolates the transducer signal to achieve greater accuracy. The meter was designed primarily for industrial applications where flow and noise conditions are relatively constant. However, we recognized the meter's potential for drilling applications and embarked on a field testing program in FY95.

Over the past year, we tested the new Doppler flow meter on four different drill rigs: two wireline coring rigs and two large-diameter drilling rigs. All four tests were in geothermal fields. On three of the wells, more expensive (and generally less versatile) magnetic flow meters were used for comparison. It was learned that the meter provides a very accurate reading of flow rates under most drilling conditions. It is possible to identify the drilling and rig noise frequencies and to isolate them from the flow meter signal frequencies.

It was also found that problems are often encountered when the flow is stopped, such as when additional sections of drill pipe are added to the drill string. At those times, the signal strength drops to zero because of the no-flow condition, and the flow meter tends to "lock on" the drill rig noise and report a false, non-zero flow rate. This problem can be overcome by adding logic to the data acquisition routine that determines whether or not the pumps are actually rotating. If they are not rotating, the routine would report a zero flow rate instead of the signal received from the flow meter.

FUTURE PLANS

A field test of the modified rolling float meter is planned for mid-FY96 in conjunction with the next phase of the cementitious mud testing program with California Energy Company and Halliburton. Results of the test will be evaluated and transferred to industry. We will continue to identify and work with mud-logging companies to integrate the meter into their operations. We will also continue our effort to locate a company interested in marketing the rolling float meter.

We will also write a conference paper and a Sandia report on the testing of the new Doppler flow meter. We have worked closely with the manufacturer on our testing program, and they are very encouraged with the results and enthusiastic about the potential market in the drilling industry. Our work will help make the advantages and performance of the meter widely known.

Finally, we will continue work to integrate the rolling float meter and the Doppler flow meter into a stand-alone drilling fluid hydraulics measurement system. This system will also form the basis for a new "expert system" for geothermal drilling applications that may be developed under a new Geothermal Drilling Organization (GDO) project.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
California Energy Company Tecton Geologic, Inc. International Logging Japan, Inc. Epoch, Inc.	Rolling float meter testing, Doppler flow meter testing
Halliburton Services	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

downhole tools and materials for treating lost circulation zones

PROJECT BACKGROUND AND STATUS

This project to cut costs associated with lost circulation 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 results of this R&D were transferred to industry in 1988 and provide a basis for industry selection of LCMs for a wide variety of drilling applications. The design of LCM laboratory testing hardware and procedures were also provided to industry and were duplicated by at least two companies for use in their LCM development efforts.

The LCM testing and modeling also indicated that if the aperture of a loss zone fracture is very large (larger than the drill bit nozzles), it cannot be plugged with LCM materials that are simply added to the drilling mud. This, not temperature, is 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. The packer consists of an assembly that is attached to the bottom of an open-end drill pipe with two flexible fabric bags that straddle a loss zone and inflate as cement is pumped downhole. The bags provide low-pressure seals against the wellbore wall that confine the cement flow to the region between the bags. In this manner the cement is directed into the loss zone while at the same time restricting the flow of drilling fluid into the zone where it could dilute the cement. After a given volume of cement is pumped, the drillstring is withdrawn from the wellbore, leaving the packer assembly behind. The packer assembly is then drilled through after the cement sets. References 2-4 describe the drillable straddle packer concept and its development history.

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. All key component testing for the packer has now been completed, as reported in last year's *Federal Geothermal Research Program Update*.

Prior to taking the drillable straddle packer to the field, it is deemed necessary to test the packer under full-scale conditions with cement. Accordingly, an Engineered-Lithology Test Facility (ELTF) was constructed in FY94-95 for this purpose. This outdoor facility allows large-scale, simulated loss and production zones to be constructed in a clay bed that can be excavated after a cementing test to determine the location of cement and the effectiveness of any techniques or hardware (such as the drillable straddle packer) in directing the cement flow where it is needed. The facility became operational in FY95. In addition to drillable straddle packer tests, studies are being conducted with conventional cementing practices to learn more about the characteristics of cement flowing from an open-end drill pipe into a large-diameter wellbore.

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 5). 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 to treat lost circulation zones. Over the past year, this project was initiated with funding from the Geothermal Drilling Organization (GDO) and the industrial partners.

Most development work related to the drillable straddle packer has been completed. Testing of the hardware with cement in the ELTF will be completed within the next year, with a series of field tests 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 require at least one more year to complete.

PROJECT OBJECTIVES

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, as described above. The purpose of these tools and materials is to increase the effectiveness of the plugging operation. This would reduce or eliminate the need for multiple treatments in the same loss zone, thereby saving rig time and reducing drilling costs and, therefore, the cost 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.
- Foster the development of cementitious muds for lost circulation control by participating in laboratory and field testing of these materials.

Expected Outcomes

- Reduced down time and costs associated with lost circulation are the expected outcomes 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 greatly reduce geothermal drilling costs.

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

Initial development of the drillable straddle packer is essentially complete. The next step in the project is to test the prototype with cement in the Engineered-Lithology Test Facility (ELTF). It was anticipated that this testing would be completed in FY95; however, manpower limitations and ongoing field work on the GDO cementitious mud testing project prevented these tests from occurring. It is now expected that at least two tests will be completed in the ELTF with a drillable straddle packer in FY96.

Further laboratory tests will also be conducted to determine the self-centering capability of the packer assembly. These tests will allow us to ascertain the need to run a stabilizer or flexible hose above the packer assembly in a deviated wellbore. The test fixture for these tests was constructed in FY95. The fixture allows a side load to be imposed on a packer assembly inside a 15-inch diameter pipe while water is pumped through the packer bags to inflate them. The maximum side load the packer can withstand without becoming decentralized in the wellbore will be determined. This will provide guidelines for field use of the drillable straddle packer. It is expected that these tests will be completed in FY96.

Engineered-Lithology Test Facility

This facility will be used to test full-scale packer assemblies with cement at full-scale flow rates. The facility consists of a 15-ft concrete cube with an open top and one open side. An engineered loss zone is emplaced in the cube by alternating layers of clay and gravel, representing impermeable and permeable zones, respectively. Several 16-inch-diameter concrete tube sections are stacked vertically and placed in the center of the facility to simulate the wellbore into which the packer assembly will be emplaced. Vertical spacing between the sections of tubing creates simulated fractures of various sizes that permit fluid to flow between the wellbore and the permeable gravel layers. An extensive plumbing system exists with multiple pipe penetrations through the walls of the facility. Fluid can thereby be pumped into or out of any other permeable zones at rates up to 450 gpm. The fluid can be heated to temperatures up to the boiling point of water in Albuquerque (about 200°F). This allows temperature effects on cement setting to be studied.

Internal wellbore flows are 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 are 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 excavating 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 ELTF was completed in FY95 with installation of the plumbing system. Flow meters and pressure transducers were installed on the various flow lines and calibrated.

The first test in the ELTF was conducted in May, 1995. The purpose of this test was to serve as a baseline for conventional cementing practices, where the end of an open drill pipe is positioned near the suspected loss zone and cement is pumped into the open wellbore. In large-diameter wellbores typical of the upper sections of geothermal wells, density differences between the cement and drilling fluid in the wellbore often dominate over wall friction effects, causing the cement to settle to the bottom of the wellbore. Sufficient cement must then be pumped to fill the wellbore below the loss zone before any significant volume of cement will enter and plug the zone. It was expected that the first ELTF test would duplicate the large-diameter wellbore scenario.

For the first test, three permeable gravel layers were emplaced in the facility, sandwiched between impermeable clay layers. The middle layer was intended to simulate a loss zone, with the exterior plumbing leading out of the zone being open to the atmosphere. The upper layer was intended to simulate a production zone, with water being pumped from the exterior plumbing, through the gravel zone, and into the wellbore. The bottom layer was intended to simulate additional wellbore volume, with no outlet to the exterior plumbing. It was therefore expected that most or all of the cement would flow by gravity into the lower permeable zone, similar to the manner in which cement flows to the bottom of a large-diameter wellbore before it flows into the loss zone. Two pressure transducers and twenty thermistors were distributed throughout each gravel zone to measure pressure gradients and cement exotherm temperatures, respectively. Halliburton Services was contracted with to mix and pump cement using the same materials and procedures they use in a geothermal well.

Two problems occurred during the test. First, a major "blowout" occurred in the clay surrounding the lower permeable zone; thus, the lower zone became a simulated loss zone instead of a closed wellbore volume. When the cement flowed into the lower zone, it therefore could not be argued that this was due to density differences between the cement and the water in the wellbore. Second, a larger volume of cement was inadvertently pumped by Halliburton than was requested. Upon excavation of the facility after the test, it was discovered that the lower zone was completely filled with cement, but the middle and upper zones also had a significant amount of cement in them. Thus, although it is believed that the cement flowed into the middle and upper zones only after it had completely filled the lower zone, it could not be proven that this was the case. Consequently, the first test was considered a failure. We did, however, learn that the method for containing the gravel zones within the clay had to be modified and the volume of cement pumped had to be more closely controlled.

For the second ELTF test, each permeable gravel zone was encased in a plastic geomembrane box to prevent fluid leak paths from developing in the surrounding clay. By the end of FY95, the facility was ready for the second test, with the same objectives as the first test. The second test was scheduled for early FY96.

Cementitious Mud Testing Project with California Energy Company and Halliburton Services

Sandia's active participation in this project is considered to be part of the lost circulation project. Progress over the past year, however, is described under the Geothermal Drilling Organization section of this report.

Porous Packer

Due to the commitment of personnel to the other lost circulation projects, no progress was made on the porous packer project during FY95. It is anticipated that much of the packer technology developed for the drillable straddle packer will have applicability to the porous packer; thus porous packer development is still considered to be important, but the project is suspended pending the outcome of the drillable straddle packer project.

FUTURE PLANS

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

The cementitious mud field testing project will also 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 and drillable straddle packer
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, slim-hole tools, high-temperature tools, downhole measurements, memory tools, pressure, temperature, spectral gamma, fluid/gas sampler

PROJECT BACKGROUND AND STATUS

Sandia's involvement with downhole instrumentation dates from the mid 1970s when work was centered on the development of a high-temperature acoustic borehole televiewer, and the establishment of a list of high-temperature component parts such as resistors, microchips, and sensors. This work evolved into the development of memory logging devices for the U.S. Continental Scientific Drilling Program. These tools were of low cost, and very easy to use. Their deployment resulted in scientific advancement in understanding geothermal formations, and a thrust of the current program is to move memory tools from the scientific realm to the commercial environment.

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 features. 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 on-site 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 (est. 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 continue 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.

PROJECT OBJECTIVES

Downhole measurements 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 instrumentation that is:

- Low cost, yet possesses a pedigree for data quality.
- Two inches in diameter or less so suitable for slim, diamond-cored holes.
- Transportable by common air carrier.
- Operable to 400°C (750°F).
- Operable on a "slick line," not an electric wireline.
- Programmable for different operations and operating conditions.

Expected Outcomes

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

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 actuate the sampler at appropriate states in the borehole. The development of this tool was supported by the Department of Energy's Office of Basic Energy Sciences. The current fielding stage is supported by the Geothermal Division.

RESEARCH RESULTS

The pressure/temperature tool was used recently in industry demonstration exercises with Oxbow Geothermal at the Dixie Valley Field, and with California Energy at the Coso Field. In all cases, industry representatives were incorporated into the logging exercises so that they could benefit from the field experiences. Data were provided to the companies; unfortunately much of this information is proprietary and cannot be discussed in this note. Suffice it to say, the pressure/temperature tool located zones of fluid influx, and it aided in solving engineering problems. A paper detailing the design and construction of this tool may be found in the Proceedings of the U.S. Department of Energy Geothermal Energy Review XII.

The pressure/temperature tool was used, along with other tools including a German fiber optic temperature measuring device, in a test hole in Kansas. This effort was headed by David Blackwell from Southern Methodist University, and was intended to provide industry with a comparison with options for temperature measurement. A paper describing the results of the study is in preparation, and will soon be available to the geothermal community.

Calibration of the spectral gamma tool continued using the DOE test pits at Grants New Mexico, and Grand Junction, Colorado. Data were taken in holes of differing diameter. Some holes had steel casing; another variable was whether the holes were water or air filled. These data were incorporated into a model for tool calibration; the tool is now ready for use in most geothermal environments. Furthermore, signal processing techniques were used to enhance the signals obtained in holes with low count rates. It is envisioned that this tool will be used in drilling operations in FY 96.

The steam sampling tool was constructed and subjected to extensive tests in the Sandia steam plant. The heart of this tool is a vessel surrounded with a low-temperature melting alloy. As steam enters the originally evacuated vessel, it condenses there by allowing a large amount of specimen (steam) to be captured in a relatively small tool. Since the orifice to the vessel is small, once inside the vessel material cannot get out. It is felt that this design will overcome the difficulties with flow-through samplers that over sampled hydrogen chloride when it was attracted to condensate as gasses passed through the vessel. The sampler tool "triggers" on time, temperature, or pressure through appropriate programs introduced to the tool through a portable computer. The pressure and temperature of the trapped material is monitored for diagnostic purposes. A plot of sampler operation is part of this report. Field tests will be conducted in the Geysers at the first available opportunity.

FUTURE PLANS

FY96 will see a major thrust in industry interactions. A working agreement is in place with Southern Methodist University to augment field activities, targeted areas are Coso, the Geysers, and Dixie Valley. Extensive sampling activities may be seen in the Geysers if access to suitable wells can be negotiated (A difficulty with many Geysers wells is that hole slough precludes tool access.).

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
<i>Pressure/Temperature Tool</i> Unocal Cal Energy	Slim-hole measurements in remote locations, Reservoir evaluation Lost circulation evaluation
<i>Spectral Gamma Tool</i> Unocal California Energy Hydrocarbon Companies	Fracture identification, mineralogy Fracture identification, mineralogy Tracer studies using decaying isotopes
<i>Fluid/Gas Sampler</i> Unocal Calpine	Acid corrosion in the Geysers

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Sampler Test at the Sandia Steam Plant

Note: The eutectic melting temperature is 138 Celsius.

Figure 1. Sample pressure and temperature obtained in a test of the new sampling tool in the Sandia steam plant. Past flow-through samplers have overestimated the amount of hydrogen chloride by almost two orders of magnitude when this gas was scrubbed from the steam stream by water drops condensed on the walls of the sampling vessel. To overcome this difficulty, the new sampler utilizes an evacuated vessel which accepts steam through a small orifice. The steam is then condensed when it comes in contact with walls cooled by a melting alloy that has a very high effective specific heat.

In the illustrated test, the sampler valve was opened three minutes after being attached to the steam system. The sample temperature increased to the melting point of the alloy, then decreased as the rate at which steam entered the vessel decreased due to a lowering of the differential pressure across the orifice. The sampler valve was closed fifteen minutes into the test, and the pressure and temperature decreased as heat was removed from the system by flow to surrounding components. Many such tests were conducted, and the operation of the system in the clean environment of the steam plant is understood. Tests are being scheduled that will exercise the system when it is exposed to gasses in a flowing geothermal well.

SLIMHOLE DRILLING FOR GEOTHERMAL EXPLORATION

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KEY WORDS

geothermal, exploration, slimhole, drilling costs

PROJECT BACKGROUND AND STATUS

Geothermal development costs must be reduced for projects to be competitive in meeting the expanding requirements in the West for environmentally benign, alternative energy sources. An industry survey¹ 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 that 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 three exploratory slimholes: in the Steamboat Hills geothermal field near Reno, Nevada; in the Vale KGRA just south of Vale, Oregon; and in the Newberry KGRA south of Bend, Oregon. Data from these wells include drilling reports, core logs, and cost reports submitted daily, many temperature logs during drilling, and - in the case of the Steamboat Hills well - downhole PTS (pressure-temperature-spinner) 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 the Steamboat Hills data is complete, and a detailed report⁴ on the project has been published.

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. There are two crucial questions to be resolved: Can slimholes provide sufficient data to characterize a geothermal reservoir? What are the costs of slimhole exploration compared to conventional methods?

Specific tasks derived from that research objective include:

Technical Objectives

- Collect data from slimhole and production wells in existing geothermal fields, including international developments where available.
- 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 with slimhole flow data to yield a reservoir evaluation.

Expected Outcomes

- Acquire cost and performance data from exploratory slimholes.
- Analyze and compare these data with corresponding data from production-size wells subsequently drilled near the exploratory slimhole(s).
- Publish all results and transfer slimhole exploration-drilling technology to industry so that it becomes an accepted method for geothermal reservoir identification.

APPROACH

We have used a coordinated working group including personnel from Sandia, S-Cubed, Lawrence Berkeley Lab, Earth Sciences of Resources Institute (University of Utah), US 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

Principal activities during FY95 were analysis of data from Japanese geothermal fields which use slimholes and preparation and drilling for two exploratory slimholes. In partnership with Trans-Pacific Geothermal Corporation, well TGC 61-10 was drilled approximately four miles south of Vale, Oregon during April-May 1995 and well TCH 76-15 was drilled on California Energy Company's lease near the Newberry Crater, Oregon, beginning in July, 1995. Drilling operations on this latter well were continuing at the end of Fiscal Year 1995, with completion expected in November. Both of these drilling operations will be fully documented during FY96, but highlights of the projects are given below. The Japanese data were collected and analyzed by S-Cubed, a subsidiary of Maxwell Laboratories, under contract to Sandia.

Vale Exploratory Slimhole

This 5825' exploratory slimhole (3.85" diameter) is in the Vale Known Geothermal Resource Area (KGRA) near Vale, Oregon. The well's data set includes: 2714' of continuous core (with detailed log); daily drilling reports from Sandia and from drilling contractor personnel; daily drilling fluid record; numerous temperature logs; pressure shut-in data from injection tests; and comparative data from other wells drilled in the Vale KGRA. As part of their cost-share, TGC will release all data from the previous exploratory well near the slimhole, all geophysical logs of the area, and an explanation of how they used these data to choose the location for another exploratory well.

The exploratory slimhole was specifically designed evaluate the geothermal potential at this location, and to provide additional data on drilling practices, costs, and testing in slimholes. Principal objectives for this project were the following: development of slimhole drilling and testing methods, cost comparison with a recent, near-by, conventionally-drilled exploratory well, comparison of reservoir and performance data from this well with that from subsequent production-size wells, and evaluation of commercial geothermal potential at this location. Drilling was relatively continuous, with all testing (other than temperature logs) reserved until hole completion at 5825 feet. The following tests were then performed: injection tests into the complete open hole section, with pressure shut-in data; bailing from the bottom 500' of the hole, which was isolated with an inflatable packer, and then measuring temperature change in that section; repeated temperature logs in the hole, following well completion with a 3-1/2" liner from 3080' to 5814'.

A major objective of the slimhole program is to demonstrate not only that the smaller wells give sufficient data to evaluate a reservoir, but that they do it more cheaply than conventionally-drilled large holes. The Vale slimhole presented an ideal situation for cost comparison because a rotary-drilled exploration hole had been completed less than two miles away, to approximately the same depth, in February 1994. The table below gives a breakdown of costs for both wells, and helps to define where major cost differences occur.

Well Name:	A-Alt	TGC 61-10
Depth	5757'	5825'
Completion	14" line pipe to 62' 9-5/8" casing to 506' 7" casing to 3010' 5" slotted liner, 2902'-5723'	10" line pipe to 29' 7" casing to 510' 4-1/2" casing to 3111' 3-1/2" H-rod, 3080'-5814'
Rig days	31 + 5 standby	40
Cost/foot, excluding directional	\$153	\$110

There are several points to note in this comparison:

- Even though charges by the drilling contractor were 10% greater for the slimhole than for A-Alt, lower ancillary costs for the slimhole made the total project much cheaper.
- The only aspect of the earlier well which made it inherently more expensive was the directionally drilled interval. Beside the explicit costs of directional tools and services, there may have been additional rig days and bit costs, but even after deducting these items, there are clear savings for the smaller hole.
- The drilling-fluids expense for the slimhole was slightly greater than for A-Alt, but it was inflated by the complete loss of circulation in the lower part of the hole. A slimhole which did not lose total returns would have a much smaller mud cost.
- Even though more than half the total footage in TGC 61-10 was rotary-drilled, the smaller bits used in the rotary section and the less expensive core bits in the cored section greatly reduced the cost of bits and tools.
- Smaller sizes of the rig, pad, and sump reduced rig mobilization and site construction costs.
- Smaller casing sizes, with correspondingly smaller cement volumes, were less expensive for the slimhole.

Although this hole was geologically informative and drilling went well, unfortunately this location holds little promise for commercial geothermal development. Still, several useful conclusions can be drawn from this project.

- Drilling this hole to the same depth as a nearby rotary hole provided information of the same quality at substantially lower cost.
- With some refinement of techniques (hydraulics, etc.) used in the rotary part of the hole, cost savings for TGC 61-10 could have been even greater.
- Total well cost is sensitive to the ratio of rotary-drilled interval to core-drilled interval. For example, see the table below. If rotary drilling in TGC 61-10 had only gone to 2000', then the extra 1100' feet of coring would have increased the total cost by approximately \$32/foot for that interval. These costs are lower than the total well costs given above because they do not include mobilization, site construction, casing, cementing, and other fixed expenses.

Type of Drilling	Average Hole Advance/day (Feet)	Average Daily Cost (Dollars)	Average Cost per Foot
Rotary	289	14,408	\$50
Coring	129	10,573	\$82

Since neither the tests performed just after drilling nor repeated temperature logs over the following four months indicated that this hole was promising for geothermal development, the hole was plugged and abandoned during September, 1995.

Newberry Exploratory Slimhole

This exploratory well, drilled in cooperation with California Energy Company, Incorporated (CECI) is part of a development project which is expected to result in a 30 MW power plant. In addition to the slimhole cost-shared by Sandia, another slimhole and at least three production wells will eventually be drilled and tested in this immediate vicinity. Data from all of these wells will allow direct comparison between slimholes and production-size holes, and will be available under the contract with CECI. At the end of the fiscal year, this well was at a depth below 3,000 feet, with completion expected in November. Complete documentation of this project will be published during FY96.

Analysis of Japanese Data

Far more exploratory slimhole drilling has been done in Japan than in any other geothermal area, but access to this data set is extremely difficult. S-Cubed, in La Jolla, CA, has been able to acquire and analyze comparative slimhole/production data from three geothermal fields in Japan. Results of this analysis^{6,7,8} are strong confirmation of the concept that test results from slimholes can be used to predict output from production-sized wells. Further documentation of these results will be published during the coming fiscal year.

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 combines statistically-valid analysis of slimhole/production well data (such as that acquired from Japanese fields) and cost-shared drilling projects with domestic industry, which are invaluable for creation of guidelines on drilling practices and on potential technology developments.

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.
- Additional cost-shared drilling projects, if budget and industry opportunities allow.
- Comprehensive analysis of slimhole and production well test data to verify applicability.
- Complete documentation of cost-shared drilling projects.
- 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.

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, Steamboat Hills, NV (complete)
Trans-Pacific Geothermal Corp.	Cost-shared exploratory drilling, Vale, OR (complete)
California Energy Company, Inc.	Cost-shared exploratory drilling, Newberry Caldera, OR
Unocal Geothermal	Discuss Unocal slimhole drilling (foreign and domestic)

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ACOUSTIC DATA TELEMETRY

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KEY WORDS

acoustic telemetry, measurement while drilling (MWD), waveguides, communications, production monitoring, pump monitoring, core-tube monitoring

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 are 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 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.

PROJECT OBJECTIVES

Communications hardware is under development which will both transmit data and passively listen to acoustical signals in well tubulars. This includes new data communication links for measurement-while-drilling operations and for pump and production monitoring.

Technical Objectives

- Provide measurement-while-drilling technology with higher data capacity.
- Provide wireless data link for production-monitoring technology and geothermal line-shaft pumps.
- Provide passive listening device for wireline-core drilling.

Expected Outcomes

- **Reduced drilling costs** -- Mud pulse telemetry is the only commercial data telemetry system available to the drilling industry. It is slow, expensive, and limited to rotary drilling in liquid-filled wells. Our goal is to develop less expensive communication tools for a broader range of applications. Acoustic telemetry will work at 100 times the current data rate and does not require the use of drilling mud. It can also be used to passively monitor drilling operations. The potential savings offered by this technology is enormous. As an example, both banking and industry sources estimate that successful deployment of an MWD system with increased data capacity would double or triple the MWD industry's gross revenues 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.
- **Improved reservoir management** -- Currently, production monitoring tools are deployed with hardwire connections. The wireline represents 80% of the tool cost and 85% of the tool failure. Wireless telemetry can eliminate these factors. This work will result in less expensive tools available to a broader market.
- **Reduced pumping costs** -- Line shaft pumps are used extensively throughout the geothermal industry. These pumps are oversized to compensate for misalignment of the down-hole pump rotor. By providing measurement and active control of alignment, smaller and less expensive pumps can be used in deep wells.

APPROACH

In our past work, we augmented the empirical approach of industry with a more systematic program directed at the fundamentals of acoustic telemetry. We assembled computer simulations, experimental data, and field test results which demonstrated the existence of acoustic transmission bands strongly correlated to theoretical predictions. We also demonstrated transducer arrays which were capable of directionally projecting and measuring acoustic energy in a drill string. Several MWD devices have been designed, built, patented, and licensed to an industrial partner, Baker Hughes/INTEQ. Recently, our work has branched into several other applications of acoustic telemetry. We are developing a wireless telemetry tool with another industrial partner,

Baker Oil Tools. This tool monitors reservoir temperature and pressure. It is designed as an inexpensive, low-data-rate tool for monitoring reservoir parameters in a production well. Costs are being shared with the Natural Gas & Oil Technology Partnership (DOE) and Baker Oil Tools. Another project under development is a telemetry system for monitoring the alignment of pump components in a geothermal well. This unique system adds only one additional moving part and no electronics to the down-hole assembly. It will operate in very harsh, high-temperature environments while continuously sending data to the surface. Our partner in this project is Johnston Pump Company. We are also assembling a prototype passive-listening system for Tonto Drilling. This system is used on wireline drilling platforms to detect the latching of core-tube assemblies at the drill bit. Tonto estimates that this device will reduce their drilling costs by 5 percent.

We originally conceived this project because of our familiarity with wave propagation in solids with periodic structure. We 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. Our work on an advanced transducer designs continues. We will use these new tools to test signal modulation methods in the field. Future work will build upon our existing system analysis methods, our 1400-foot surface simulation facility and our mobile instrumentation laboratory.

RESEARCH RESULTS

The prototype transmitter for the production monitor has been fabricated and tested at our surface facility. The design has proven to be more robust, easier to assemble, and more energy efficient than the original transducer which we designed for Teleco (now Baker/Hughes INTEQ). We expect system efficiencies of conversion of battery power to acoustic power to exceed 30 percent. Sandia has requested a waiver from DOE on the patent disclosure for this transmitter. The remaining systems components including the magnetic components for the power supply and the microprocessor control circuit have been designed and are being built.

We have completed two field tests at Vale, Oregon and Elko, Nevada. The data from these tests have been used to design a new passive monitoring system for Tonto Drilling. This system uses existing instrumentation and electronic signal-conditioning equipment to provide an ultra-sensitive listening device to detect latching of wireline coil tubes. Tonto intends to field these devices in the spring at their geothermal drilling operations in Indonesia. They are experiencing considerable delays in drilling schedules, and they believe this device will improve this situation.

We have filed a patent disclosure on a new monitor for a line-shaft pump. This novel and simple system measures the alignment of the pump rotor with the pump housing. The measurement is transmitted via the drive shaft to the surface. Typical lengths of these shafts range between 800 and 1800 feet. Johnston Pumps is currently engineering our design. We are preparing a prototype demonstration for fall of 1996.

FUTURE PLANS

The prototype tool for production monitoring is scheduled to be fielded in a test well in late spring of 1996. This test is intended to demonstrate commercial feasibility of the tool. It is our intention to license this technology to Baker Oil Tools. Prototype instrumentation for the passive latch detector is being assembled. We will evaluate this system first at Tonto's drilling operations in Elko, Nevada, and then in Indonesia. We expect this system to evolve into second-generation design before a commercial device is turned over to Tonto Drilling. A prototype of the geothermal line-shaft pump should be available and tested by the end of 1996. We plan to assist Johnston Pumps with commercial development of this instrumentation.

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, fabrication of hardware, field test support, engineering design.
Tonto Drilling	Field test support, engineering design, prototype testing.
Johnston Pumps	Engineering design.

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GEOTHERMAL DRILLING ORGANIZATION

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KEY WORDS

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

PROJECT BACKGROUND AND STATUS

Geothermal drilling technology is based on oil and gas technology. The service industry that provides drilling logging equipment has its 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 Geothermal Drilling Organization (GDO) provides a mechanism for the geothermal industry to pool its 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) adaptation of a retrievable whipstock to geothermal well conditions -- being developed by AZ Grant International; (3) development of rotating head rubbers by AZ Grant International; and (4) 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 instrumentation diagnostics, and additional subcontractor assistance - primarily mud logging; and (5) Novatek is to build an improved mud hammer in order to increase geothermal drilling rates with less weight on the bit. Unocal and California Energy Company will provide test holes for the mud hammer and Mobil will participate in the project in a consultation role.

PROJECT OBJECTIVES

Technical Objectives

- Improve overall geothermal drilling performance while cutting costs.

Expected Outcomes

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

APPROACH

The GDO is composed of geothermal operators and service companies. Potential projects are screened by an executive committee with the criterion that completion should result in a new product or service in the near-term. Project proposals are then presented to the members at periodic (quarterly) meetings or by mail. Projects require at least two industry members participating with the Department of Energy (DOE). Cost sharing by industry is at least 50%, almost invariably in the form of in-kind services or, on occasion, in cash. Most of the development work is accomplished by industry.

RESEARCH RESULTS

(1) Positive Displacement Air Motor for High Temperature

Two prototype 8 inch air motor assemblies for high temperature drilling have been developed by Baker Hughes INTEQ. Prior to the final assembly, sections of the motor assemblies underwent extensive laboratory and bench scale testing at Baker Hughes INTEQ facilities at Houston, TX and Celle, Germany. One unit was tested in the Geysers Field on December 9, 1994. After the test, the tool was shipped to Houston where disassembly and diagnostics were performed.

During the test, the motor had been below the Kelly bushing for 19 hours, tripping about 10.5 hours, reaming about 8 hours, and drilling about 0.5 hours. The motor was incapable of drilling when it reached bottom. The injected air temperature was 58°F, and the temperature returning from the motor assembly was 199°F. The temperature in these strata in this part of the Geysers would not exceed 450°F. However, a heat tab located in a fire stop showed a temperature of 550°F.

The drilling, disassembly, and laboratory reports suggest that the stator elastomer probably overheated. The majority of the elastomer was missing. Air injection probably caused a local burn to spread to the remaining stator elastomer. The fire stop is approximately 10 feet from the bottom of the stator. Thus, the actual stator temperature was probably much higher than 555°F.

It is possible that insufficient mist/water was injected during the test of the air motor assembly. This could cause high friction temperatures. The possibility of rust and scale which cause high friction and temperatures also cannot be ruled out.

A second test with the remaining assembly is being contemplated. Special attention will be given to turning on adequate mist/water at the same time or before the air is turned on. Attention also will be given to assuring that the drill pipe is free of rust and scale, and that corrosion and scale inhibitors are in use.

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

(2) *Retrievable Whipstock for Geothermal Wells*

A prototype 13-3/8 inch diameter retrievable anchor stock (whipstock) assembly has been developed by AZ Grant International (now a part of Smith 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 Smith International 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 primarily used for geothermal drilling. Because there is little domestic geothermal drilling underway, and there is little oilfield drilling at this hole diameter, difficulty has been encountered in securing a test for this unit, but attempts are on-going to accomplish this.

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

(3) *Development of Rotating Head Rubbers*

AZ Grant International, now a part of Smith International, Inc., is optimizing a rubber compound for rotating head and strippers. These compounds have been tested in the Smith laboratory facilities in Houston. The earlier compounds tested proved to be too short lived or they leaked. Additional compounds are under consideration, and the rubber has been redesigned. A butyl elastomer, a candidate for geothermal temperatures, hopefully will be tested in the next fiscal year. A nitrile elastomer of the same modified design, a candidate for use in the somewhat lower temperatures of oil and gas applications, will be tested in the next fiscal year. This work has contributed to new products available commercially in 1990, but the manufacturer is continuously seeking improvements.

Cost: \$30,000 Duration: 7/7/93 0 present

(4) *Evaluation of Cementitious Muds to Stem Lost Circulation*

A project on the field evaluation of Halliburton's new cementitious mud for lost circulation control was initiated in FY95. The mud hardens faster than conventional cement and is chemically compatible with the drilling fluid, thereby potentially reducing loss-zone cementing and mud conditioning costs. In addition to Halliburton, other participants in the project include California Energy Company and Sandia. In the project, California Energy is providing access to their geothermal wells, Halliburton is providing development and laboratory testing of the mud, and Sandia is providing rig instrumentation, downhole logging, and data analysis.

The first phase of the project was completed early in FY95 at the Coso Geothermal Field in California. Sandia instrumented the drill rig with inflow and outflow meters, and also paid for several borehole televiwer logs for examining loss-zone fractures before and after the cementitious mud treatments. Multiple loss zones were encountered throughout the well. In some of these zones, conventional cement was used to treat the zones; in others, the cementitious mud was used. The results of these tests indicated that: (1) the cementitious mud was effective in sealing small-aperture loss zones, but not large-aperture zones; and (2) where it worked, the

cementitious mud was responsible for saving several hours of rig time compared with conventional cement. These results indicated that the viscosity of the cementitious mud needs to be better controlled in order to make it more effective and less temperature dependent.

Based on these results, Halliburton reformulated their cementitious mud, and a second field test was undertaken. In this phase, a California Energy Co. well at the Newberry KGRA was used. Sandia again instrumented the well for inflow and outflow measurements. Unfortunately (from the standpoint of this project), no lost circulation zones were encountered in this well. Consequently, the cementitious mud could not be tested there. As the fiscal year came to an end, plans were being made to continue the project in a Coso well during the first half of FY96.

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

(5) *Development of an Improved Mud Hammer to Enhance Geothermal Drilling Rates*

Novatek will undertake the development of an improved mud hammer for drilling 12-1/4 inch holes in order to improve geothermal drilling rates with less weight on the bit. Discussions of their proposal (Novatek, Unocal and Mobil) began in FY95 with the contract being placed later to initiate this project. Initially, there will be laboratory testing in the first quarter of FY96 on an existing mud hammer. This will be done in order to systematically characterize the existing mud hammers and to optimize the design for the mud hammer that will be built. Later there will be a series of field tests involving California Energy and Unocal. The initial project proposal (by Novatek, Unocal, Mobil and Sandia) included full-scale field tests of the mud hammer only in (Unocal) oil and gas wells. Through interaction with the membership of the GDO, the proposed field test program for the mud hammer was revised to include testing in California Energy geothermal wells. With this revision and the sponsorship of California Energy along with a commitment to utilize their wells for geothermal testing, the proposal was approved by the GDO.

Cost: \$165,000 Duration: March 15, 1995 (first discussions with GDO on this proposal; official contract date with Sandia is November 7, 1995) - 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 proposal for development of an expert system for lost circulation diagnosis and treatment, a proposal for the use of insulated casing, consideration of an ultra slim, high temperature borehole televiewer, 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

Following are the names of specific present collaborators with the DOE and their particular interests. However, it should be emphasized that the entire membership of the Geothermal Drilling Organization 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
Smith International (AZ Grant)	Retrievable whipstock Rotating head, stripper rubbers
Halliburton	Development of new cement formulations Evaluation of cementitious muds
California Energy Co.	Evaluation of cementitious muds and provide test bed for an improved mud hammer
Novatek, Unocal, Mobil	Construction and testing of an improved mud hammer for geothermal use

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Geothermal Drilling Organization - charter

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LONG VALLEY EXPLORATORY WELL

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KEY WORDS

geothermal, exploration, magma, caldera, Long Valley

PROJECT BACKGROUND AND STATUS

This was a phased project. Phase I, drilled in 1989, reached 2568 feet with a 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 was designed 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 intervals between drilling operations.

The initially planned Phase III drilling has been discontinued. However, Sandia is negotiating the transfer of oversight functions with the U.S. Geological Survey.

PROJECT OBJECTIVES

The Long Valley well is located at the point of maximum uplift on the caldera's resurgent dome and above a widespread aseismic zone which is believed to be associated with the brittle-ductile transition for basement rock, indicating a temperature above 350°C. The project's objectives entailed identification of promising thermal sources in young silicic calderas, evaluation of their commercial productivity, and technology development that will permit better access to such resources.

The hole would be a definitive assessment of the local thermal resource, would provide a stringent test of the hypothesis that magma is still present within the central plutonic complex, and could calibrate the geophysical techniques used to identify this location as a thermal target.

The current technical objectives and expected outcomes are listed below. However, these might be different from the USGS' objectives and outcomes once oversight functions are transferred.

Technical Objectives

- Test new drilling technology by drilling Phase III to approximately 14,000 feet,
- Improve definition of the hydrothermal resource in the caldera to expand commercial development in this region of extremely high thermal potential,
- Determine whether crustal magma exists at depths less than 8 km (25,000 feet), and further scientific understanding of the caldera formation and evolution process.

Expected Outcomes

Contingent upon completion of Phase III and partly depending on whether the hole reaches the granite carapace of the hypothesized magma chamber:

- Commercial hydrothermal potential, patterns and conditions of deep fluid circulation, and heat transport characteristics below the caldera floor.
- Unequivocal identification of the geophysical anomalies thought to be magma.
- Amount of collapse and subsequent resurgence of the central portion of Long Valley caldera.
- 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.

APPROACH

DOE's approach has been 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 been supported with \$1.5 million from the California Energy Commission.

RESEARCH RESULTS

Lack of funding for the LVEW limited activity in FY95 to site maintenance and to some scientific measurements. Extensive bailing to extract fluid from the well, with accompanying temperature and water level measurements, were coordinated with an on-going USGS hydrology study. This study was also aided by emplacement of a downhole pressure transducer for long term measurement of water-level fluctuations.

FUTURE PLANS

The Department of Energy plans to transfer control of the well to the USGS, with terms and conditions to be negotiated during FY96.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Both Vulcan Power, who holds the lease for the LVEW location, and California Energy Company, which 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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RESERVOIR TECHNOLOGY

VOLATILITY OF HCl AND THE THERMODYNAMICS OF BRINES DURING BRINE DRYOUT

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KEY WORDS

hydrochloric acid, volatility, corrosion, The Geysers, modeling, thermodynamics, acidity, chloride, brine, steam

PROJECT BACKGROUND AND STATUS

Corrosive solutes in geothermal steam can limit or prevent economic production of steam from relatively high-temperature geothermal resources. Some wells in a high-temperature ($>300^{\circ}\text{C}$), vapor-dominated resource at the Northwest Geysers, California, have produced high levels of chloride at the wellhead, with observed levels greater than 100 ppm in some cases. This 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.

The high volatility of hydrochloric acid and the observed nonstoichiometry of chloride with cations in steam (e.g., Na) lead to the hypothesis that the observed chloride is due to hydrochloric acid. 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 in the Northwest Geysers, and the projected behavior of the 'normal' reservoir with further production. The project began in FY 1990. Early results, including measurements of the partitioning of HCl from liquid to vapor in pure-acid solutions and NaCl(aq) brines, indicated that HCl was unlikely to be the sole source of chloride in steam due to the low brine pH required to give high HCl concentrations in steam. Ammonium chloride volatility, a possible mechanism for transport of chloride from brine to steam in geothermal systems containing ammonia, was shown to give high chloride levels in steam over near-neutral, high-temperature brines containing high concentrations of NaCl(aq). Furthermore, recent measurements have shown that the volatility of NaCl over very concentrated (to halite saturation) NaCl(aq) brines is significantly lower than that predicted from recently-developed equations of state for $\text{NaCl} + \text{H}_2\text{O}$. These new measurements are consistent with very low sodium ion concentrations in wellhead condensate samples having high chloride as a result of $\text{HCl} + \text{NH}_4\text{Cl}$ partitioning at high temperatures. Finally, measurements have been made recently of the partitioning of solutes to steam over NaCl(aq) brines in the presence of finely-ground samples of reservoir rocks from The Geysers. Preliminary analyses of these condensed-steam samples indicate that the chloride concentration in steam is not significantly enhanced by

the presence of the rock samples. Additional cations and anions (other than Na^+ and Cl^-) have been found at relatively high concentrations in these condensed steam samples. Also, although the rock sample was treated with hydrochloric acid prior to beginning the volatility measurements, relatively high concentrations of ammonia have been found in these condensate samples. Efforts to identify and quantify these other volatile species are continuing.

PROJECT OBJECTIVES

The goals of this project are to determine likely sources of highly corrosive steam from high-temperature geothermal wells and to suggest appropriate mitigation procedures based on the thermodynamics of liquid-vapor partitioning of corrosive solutes. This research is of particular importance to the control of 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 precise laboratory measurements of the partitioning of corrosive solutes, including acids and chloride salts, over ranges of temperature and brine composition appropriate to geothermal reservoirs.
- Represent the experimental data quantitatively, using fundamentally sound thermodynamic models, in order to provide the means for reliable calculation of the composition of coexisting brine and steam under both reservoir and surface (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.

Expected Outcomes (continued)

- In collaboration with 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. This research can also contribute to improved efficiency in existing geothermal power plants by providing guidelines for the operation of currently-installed mitigation facilities (*e.g.*, desuperheaters).

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 HCl(aq) and from aqueous mixed brines including {HCl + NaCl}, MgCl_2 , { MgCl_2 + NaCl}, and CaCl_2 . Experiments are currently in progress to measure the partitioning of solutes 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 in the presence of Geysers reservoir rock samples. These experiments provide the data needed to develop quantitative models for the partitioning of solutes to steam from the mixed electrolyte brines encountered in geothermal reservoirs. These models can then be tested under conditions more nearly representing the geothermal reservoir through confirmatory measurements of partitioning in the presence of reservoir rock samples.

This project is part of the program "Physical Chemistry of Geothermal Systems" at Oak Ridge National Laboratory (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, source brine composition, and the presence of added solids. 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. 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. Sample compositions are determined by acidimetric titration, atomic absorption spectroscopy, and/or ion chromatography as appropriate for the solutes in a particular sample. 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.

Under the assumption that solutes 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 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). 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 as a function of the density of steam, which decreases with increasing molality at constant temperature due to the vapor-pressure lowering of NaCl. We have shown that for $t \geq 300^\circ\text{C}$ and $\text{pH} \geq 3$, the volatility of HCl alone is not sufficient to give high (~100 ppm) chloride concentrations in steam, even over highly saline brines. Additional 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 HCl is produced by hydrolysis of cations in these solutions, the total amounts of HCl generated are again 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 relatively high levels of ammonia (to ~1000 ppm). We have combined these field observations with our laboratory measurements on volatilities of HCl and NaCl 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. Our recent measurements on concentrated NaCl(aq) indicate that as the NaCl concentration in brine increases to near-halite saturation, the partitioning of NaCl to the vapor phase decreases below 1 ppm even at temperatures above 300°C. While it is difficult to estimate reliably the activity coefficients of all species in concentrated brines at high temperatures, once estimates are made, the pH within the reservoir of a brine (predominantly NaCl) that is in equilibrium with steam having the observed wellhead concentrations of chloride

and ammonia can be calculated from the partitioning results. The results of these calculations indicate that high concentrations of chloride can partition to steam (as $\text{HCl} + \text{NH}_4\text{Cl}$) from highly concentrated NaCl brines at a near-neutral pH, with minimal sodium concentrations in steam. These results are consistent with observed solute concentrations in condensate samples from some wells in the Northwest Geysers. Establishing a possible mechanism for acid-chloride steam formation and the distribution of species in steam enables calculations to be made of the extent of desuperheating of steam (to partial condensation under equilibrium conditions) required to yield steam with the desired low-chloride concentrations. A knowledge of the partitioning behavior of chlorides (*i.e.*, $\text{NH}_4\text{Cl} + \text{HCl}$) over the wide ranges of temperature encountered at various points in the geothermal steam cycle can lead to performance improvements through guidelines on the operation of desuperheating systems, including indications of chloride concentrations in steam for which plants could be operated reliably without desuperheating.

Recently we have begun measurements of solute volatilities from brines in contact with Geysers reservoir rock samples. Analyses of condensed-steam samples from equilibrations with NaCl(aq) and reservoir rocks indicate the presence of significant concentrations of additional solutes (*i.e.*, other than sodium, hydrogen ion, and chloride). The presence of these solutes also complicates the determination of sodium and chloride concentrations in the samples. Further detailed analyses of these samples are in progress, and additional equilibrations including rock samples from other parts of the reservoir are planned.

FUTURE PLANS

Interactions between brines and reservoir rocks may control important variables (*e.g.*, brine pH) in determining the partitioning of solutes to steam in geothermal reservoirs. Experiments with solids present, including halite and Geysers reservoir rock samples (MLM-3), have begun as described above. Further experiments are anticipated on the partitioning of solutes to steam with other available rock samples from The Geysers reservoir in contact with the equilibrating fluids.

The recent experimental results on the partitioning of chlorides from NaCl(aq) at high concentrations (to halite saturation) have significant implications for both the transport of chloride in geothermal systems and the development of quantitative equations-of-state for the $\text{NaCl} + \text{H}_2\text{O}$ system at high subcritical temperatures. A full quantitative model describing chloride partitioning from NaCl(aq) brines and mixtures is being developed, based on new results from this program. This model will be directly applicable to practical calculations of the composition of coexisting brines and steam throughout geothermal power cycles.

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 California Energy Company sites in California and increasing chloride in steam from two-phase wells at Los Azufres, Mexico), including liquid-dominated as well as vapor-dominated resources.

It is apparent that the application of measured equilibrium constants to the wide range of conditions (temperature, pressure, brine composition) encountered in geothermal systems requires a broad and accurate knowledge of the thermodynamic properties of solutes in brines at high temperatures, including homogeneous reactions (*e.g.*, ion association) and excess properties (*i.e.*, activity coefficients). We expect that further quantitative modeling of the volatility results, and applications to field observations from geothermal systems, will indicate that some closely-targeted experimental measurements of these properties under clearly defined conditions could contribute significantly to an overall understanding of liquid-vapor phase behavior of solutes in geothermal systems. We will propose to perform these experiments in an extension of this program in cases where it is clear that this information is essential to the development of quantitative models of geothermal systems, both in this program and in others supported by the Geothermal Division.

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
California Energy Company	Salton Sea geothermal field process applications
Electric Power Research Institute	Fossil-fired and nuclear steam cycle applications
Pacific Gas and Electric Company	Guidelines for operation of corrosion-mitigation equipment

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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 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, has been widely studied in geothermal systems. This information is used 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 the 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, 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. 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 at temperatures to 500°C. An effort to model the isotopic behavior of geothermal systems has been initiated.

PROJECT OBJECTIVES

The objectives of this research are: (1) to provide precise experimental data on 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, and (2) to investigate the importance of the salt effect on isotope partitioning for isotopic studies of geothermal systems through modeling of the isotopic evolution of fluids (steam and gases) and minerals at various physical and chemical conditions.

Technical Objectives

- Determine precisely the effects of common dissolved salts (NaCl, KCl, CaCl₂, etc.) in geothermal brines on oxygen and hydrogen isotope partitioning in the systems water liquid-vapor and mineral-water at temperatures to 500°C.
- Establish simple, empirical equations based on experimental results for calculating the isotope salt effects in natural, complex geothermal brines over wide ranges of temperature and chemical composition.
- Investigate the importance of the isotope salt effects for the interpretation of isotopic data from geothermal systems through modeling at various physical and chemical conditions.

Expected Outcomes

- A set of internally consistent, precise experimental results on the partitioning of oxygen and hydrogen isotopes among geothermal materials (waters, brines, steam, and minerals) at elevated temperatures, that can be used directly 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.
- Isotopic models of geothermal systems, which can be used to investigate geochemical processes of geothermal fluids and rocks at various conditions.

APPROACH

We measured the salt effect on isotope partitioning by means of salt solution-water vapor equilibration and salt solution-mineral exchange methods at temperatures up to 500°C. Changes in the partitioning of D/H and ¹⁸O/¹⁶O between liquid water, and water vapor and minerals as a function of the concentration of dissolved salts were 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 U.S. Department of Energy (DOE) 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

Experiments for determining the effect of dissolved KCl (1 to 4 molal) on the oxygen and hydrogen isotope partitioning between liquid water and water vapor were conducted at 130°C. The D/H ratios of vapor in equilibrium with KCl solutions were 2.5 to 5.5 ‰ higher than that in equilibrium with pure water; namely the D/H activity ratio in KCl solutions are higher than that of composition ratio. The magnitude of the hydrogen isotope effects are nearly linear with the molality of KCl solutions. These results are very consistent with our results previously obtained from 50 to 100°C. The magnitude of the hydrogen isotope effects decreases gradually from 2.0 ‰/molal at room temperature to 1.1 ‰/molal at 130°C. It was observed that KCl of up to 4 molal has almost no effect within ± 0.2 ‰ on the oxygen isotope fractionation between vapor and liquid water at 130°C. This finding differs notably from that of Truesdell (1974), who reported large negative oxygen isotope effects (as large as -1.32‰ for 4 molal) of KCl solutions at 118°C. It is noteworthy that the measured effect of KCl on the vapor-liquid water isotope fractionation is very similar to that of NaCl in the temperature range from 90 to 130°C, while at near-room temperature, there are clear differences in the oxygen isotope salt effects.

Several hydrothermal experiments of mineral-water isotope exchange were conducted on the system brucite ($\text{Mg}(\text{OH})_2$) - water $\pm$ NaCl or MgCl_2 at three different conditions: (1) 200°C and 21 bars for 180 days, (2) 300°C and 100 bars for 90 days, and (3) 500°C and 800 bars for 28 days. From the brucite-water $\pm$ NaCl experiments at 200°C, we obtained $10^3 \ln \alpha(\text{D/H})_{\text{brucite-water}}$ values of -28.8 ± 3.0 ‰ (87% exchange), -29.5 ± 2.3 ‰ (87% exchange), -26.7 ± 1.5 ‰ (90% exchange), and -24.5 ± 2.9 ‰ (84% exchange) for pure water, and 1, 3, and 5 molal NaCl solutions, respectively. From the experiments at 300°C, we obtained a $10^3 \ln \alpha(\text{D/H})_{\text{brucite-water}}$ value of -22.9 ± 0.9 ‰ (92% exchange) for pure water. For 1, 3, and 5 molal NaCl solutions, values of $10^3 \ln \alpha(\text{D/H})_{\text{brucite-water}}$ were -20.8 ± 1.1 ‰ (87% exchange), -18.3 ± 1.6 ‰ (87% exchange), and -16.0 ± 2.8 ‰ (86% exchange), respectively. For 1 and 3 molal MgCl_2 solutions, values were -20.5 ± 1.4 ‰ (78% exchange) and -11.5 ± 1.0 ‰ (71% exchange), respectively. From the experiments at 500°C, we obtained a $10^3 \ln \alpha(\text{D/H})_{\text{brucite-water}}$ value of -18.8 ± 2.3 ‰ (90% exchange) for pure water. For 1, 3, and 5 molal NaCl solutions, values of $10^3 \ln \alpha(\text{D/H})_{\text{brucite-water}}$ were -15.4 ± 0.8 ‰ (92% exchange), -10.6 ± 0.4 ‰ (91% exchange), and -10.8 ± 1.1 ‰ (91% exchange), respectively. For 1 and 3 molal MgCl_2 solutions, values were -22.5 ± 3.7 ‰ (86% exchange) and -13.5 ± 2.9 ‰ (78% exchange), respectively. Our results for pure water at 200, 300, and 500°C agree well with those of Satake and Matsuo (1984). At each temperature, the measured values of $10^3 \ln \alpha(\text{D/H})_{\text{brucite-water}}$ systematically increase with increasing NaCl or MgCl_2 molality. Hydrogen isotope effects of NaCl solutions, $10^3 \ln \Gamma(\text{D/H}) = 10^3 \ln \alpha(\text{D/H})_{\text{brucite-salt-soln}} - 10^3 \ln \alpha(\text{D/H})_{\text{brucite-pure water}}$ range from -0.7 to +8.0‰, and their magnitudes increase from 1.27 to 2.80‰/molal from 200 to 500°C. At 500°C, there is an indication that the value of $10^3 \ln \Gamma(\text{D/H})$

flattens from 3 to 5 molal NaCl solutions. Hydrogen isotope effects of 1 and 3 molal MgCl_2 are in the range of -3.6 to +11.4‰ at 300 and 500°C. However, temperature and molality dependence of the effects of MgCl_2 on hydrogen isotope partitioning are somewhat ambiguous, due to errors larger than those of the NaCl experiments. The results obtained from the system brucite-water $\pm$ NaCl at 200 and 300°C are very similar to those obtained from our water liquid-vapor equilibration experiments to 350°C reported in the Geothermal Research Program Update last year. However, our results on the system brucite-water $\pm$ NaCl at 200, 300 and 500°C somewhat differ from those of Graham and Sheppard (1980) obtained from the system epidote-water $\pm$ NaCl in the same temperature range, which exhibit more complex temperature dependence.

Hydrothermal experiments of mineral-water oxygen isotope exchange were also carried out on the system strontianite (SrCO_3) - water $\pm$ NaCl at (1) 300°C and 100 bars for 28 days, and (2) 450°C and 1 kbar for 7 days. From the 300°C experiments, we obtained $10^3 \ln \alpha(^{18}\text{O}/^{16}\text{O})_{\text{strontianite-water}}$ values of $+4.57 \pm 0.46\text{‰}$ (61% exchange) and $+4.15 \pm 0.35\text{‰}$ (98% exchange) for pure water and 5 molal NaCl solution, respectively. The 450°C experiment yielded $10^3 \ln \alpha(^{18}\text{O}/^{16}\text{O})_{\text{strontianite-water}}$ values of $+3.91 \pm 0.48\text{‰}$ (69% exchange), $+3.11 \pm 0.42\text{‰}$ (98% exchange), and $+2.15 \pm 0.59\text{‰}$ (94% exchange) for pure water, and 3 and 5 molal NaCl solutions. From the 300°C experiment, we obtained an oxygen isotope effect,

$$10^3 \ln \Gamma(^{18}\text{O}/^{16}\text{O}) = 10^3 \ln \alpha(^{18}\text{O}/^{16}\text{O})_{\text{strontianite-salt soln}} - 10^3 \ln \alpha(^{18}\text{O}/^{16}\text{O})_{\text{strontianite-pure water}}$$

of -0.42‰ for 5 molal NaCl solution. From the 450°C experiment, values of -0.8 and -1.72‰ were calculated for 3 and 5 molal NaCl solutions, respectively. The result of oxygen isotope effects in the system SrCO_3 -water $\pm$ NaCl at 300°C agree within error with those from the systems CaCO_3 -water $\pm$ NaCl and water liquid-vapor at 300°C reported in the previous Geothermal Research Program Update. Our results from the system SrCO_3 -water $\pm$ NaCl at 450°C indicate that the effect of dissolved NaCl on oxygen isotope partitioning keeps increasing (-0.35‰/molal).

The results of the effect of dissolved NaCl or MgCl_2 on isotope partitioning between minerals (calcite, strontianite, and brucite) and water in the temperature range from 200 to 500°C show: (1) the isotope salt effect is a common feature of the isotope fractionation between brines and any other coexisting phases (gases, minerals, and dissolved species), and (2) the isotope effects caused by abundant salts in geothermal brines (NaCl, CaCl_2 , etc.) can be large even at elevated temperatures. High-salinity brines are encountered or considered to be present at depth in many geothermal systems (Salton Sea, The Geysers). The large isotope salt effects observed at elevated temperatures in this study need to be fully incorporated in isotopic studies of such geothermal systems.

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- SO_4 to 350°C, including several mixed salt solutions resembling natural geothermal brines (*i.e.*, Salton

Sea) and acids (HCl, H₂SO₄). Experiments of mineral-water isotope exchange in the presence of salts will continue. Run products of the experiments in the system brucite-water±NaCl or MgCl₂ at 200, 300, 400, and 500°C will be analyzed for their oxygen isotope ratios, in order to determine the oxygen isotope effects. Oxygen isotope exchange experiments in the system SrCO₃-water±NaCl will be carried out at 400, 500, and 600°C. For the effect of dissolved Ca²⁺ on isotope partitioning, the system portlandite (Ca(OH)₂)-water will be investigated at 300-400°C. In order to examine the effects of mixed salt solutions containing Mg²⁺ and Ca²⁺, isotope exchange experiments on quartz (SiO₂)-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.

INDUSTRIAL INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	Using our results to monitor injection
ERSI	Using our results to interpret geochemical data from The Geysers

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GEOCHEMISTRY OF ALUMINUM IN HIGH TEMPERATURE BRINES

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KEY WORDS

aluminum, solubility, complexation, potentiometry, permeability, alteration

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.

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, more 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 that 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.

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 U.S. Department of Energy's (DOE's) 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 "Basic Aqueous Chemistry 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

Boehmite solubility experiments were performed in the 100-250°C range and as a function of ionic strength (NaCl), employing the new large-volume, hydrogen-electrode concentration cell. Experiments at 1 molal (150, 200 and 250°C), 0.1 and 0.3 molal (150°C), and 0.03 m (100, 150, 200°C) are now complete and solubility measurements are in progress at 250°C and $I=0.03$ molal (NaCl).

In most of the experiments, the solutions are allowed to equilibrate with the solid (initial solid:solution ratio is generally 1:40) at a starting pH of 2.5. A platinum dip tube extends into the test compartment allowing withdrawal of samples for chemical analysis of aluminum by ion chromatography. Upon attainment of equilibrium, a small amount of NaCl+NaOH solution is titrated into the cell using a positive displacement pump. The pH generally stabilizes at the new value within *ca.* 24 hours, whereupon another sample is taken for total aluminum analysis. This stepwise process is repeated until the solubility curve between pH 2.5 and 10 (depending on ionic strength) has been mapped out. This process has also been reversed in some experiments including: 1) back titration with acidic titrant (NaCl+HCl) from another pump at the end of a forward titration, or 2) independently starting an experiment at basic pH (around 8 to 9) and titrating with acidic solution (NaCl+HCl) at the same ionic strength. The results show 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 approaching from super- or undersaturation.

Furthermore, forward and back titration spanning periods of up to one month in a continuous experiment give precisely reproducible results with the assurance that the stoichiometric concentration of hydrogen ions in the reference solution remained unaltered. This was also checked by an acidimetric titration of the reference solution removed from the cell at the end of the experiment (0.1 molal ionic strength at 150°C). Also, rapid equilibration (within 8 hours) is obtained after each pH adjustment by addition of an aliquot of titrant. This is a remarkably short period of time, compared to conventional hydrothermal experiments, particularly in acidic solutions.

At 1 molal ionic strength, the base sides of the solubility profiles ($\log [m_{3Al}]$ versus $-\log [H^+]$) have a slope that is not unity above 150°C (*e.g.*, at 200°C the slope is 1.153), as would be predicted from the aluminate anion dominating the speciation at high pH according to the reaction: $AlOOH_{(cr)} + 2H_2O = Al(OH)_4^- + H^+$. These measurements were reproducible with different starting solutions demonstrating that there is no contamination of the test solution or

error in the calculated stoichiometric concentrations in the reference compartment of the cell. Moreover, powder x-ray diffraction established that the only solid phase present before and after these experiments was boehmite.

In the low-temperature solubility experiments, conducted previously in this program using gibbsite as the solid (Wesolowski, 1992; Wesolowski and Palmer, 1994), a strictly linear slope of unity was observed, which was also observed in the present study at 150°C for the same ionic strength, consistent with the formation of tetrahedral aluminate anion. Recently Diakonov *et al.* (1995) observed enhancement of the boehmite solubility in presence of 1M NaCl from 125 to 350°C consistent with the formation of sodium-aluminate ($\text{NaAl}(\text{OH})_4^\ominus$) ion pair. In our case the formation of this ion pair would not explain a greater slope, but would merely lead to monotonically higher total aluminum concentrations at each pH value.

Recently, it has been learned that Professor Peter Tremaine (Memorial University of St Johns, Newfoundland, Canada) has Raman spectroscopic evidence for the existence of an aluminate dimer at elevated temperatures, $\text{Al}_2\text{O}(\text{OH})_6^{2-}$, that could be consistent with the enhanced solubility observed. Including a constant for this dimer ($\log Q_{\text{dimer}} = -20.2$) in the regression of the results obtained at high pH and 200°C, gives a constant for the previous equilibrium of $\log Q_{145} = -10.581$, which is only slightly different from the value obtained from the regression performed without the dimer ($\log Q_{145} = -10.619$), indicating that the dimer may not be significant at the relatively low total aluminum concentrations attained in our experiments, even at high pH. Indeed, according to Moolenaar *et al.* (1970), this dimer is significant only for Al concentrations $> 1.5\text{M}$ at room temperature.

No enhancement in the solubility of boehmite was observed in our experiments in the acidic region that would have been indicative of ion pairing between Al^{3+} or hydrolysed cationic species thereof with Cl^- . This was also demonstrated by the gibbsite solubility experiments where the same value of Q_{s0} corresponding to the equilibrium: $\text{Al}(\text{OH})_{3(\text{cr})} + 3\text{H}^+ = \text{Al}^{3+} + 3\text{H}_2\text{O}$ were obtained both in NaCl/HCl and $\text{NaNO}_3/\text{HNO}_3$ solutions, as well as in NaCl/HTFMS/NaTFMS solutions (where TFMS represents the anion trifluoromethanesulfonate).

The results obtained near the solubility minimum at 1 molal, as well as in the 0.3 and 0.1 molal ionic strength experiments (150°C), showed considerable scatter. The total aluminum concentration is low ($< 3 \cdot 10^{-7} \text{ mol.kg}^{-1}$) at those conditions and samples had to be diluted before analysis by ion chromatography (IC) to minimize the eluting effect of Na^+ ion. Therefore, the minimum solubility was difficult to define. A better analytical technique than IC is required before the entire solubility profiles can be evaluated at each ionic strength. An effort is being initiated to repair and service a graphite furnace atomic absorption spectrometer existing at ORNL. However, as discussed below, the stability field is very narrow with respect to pH for the $\text{Al}(\text{OH})_2^+$ and $\text{Al}(\text{OH})_3$ species, which predominate at and near the solubility minimum. Therefore, a precise knowledge of their thermodynamic stability is not essential to model the geochemical behavior of aluminum with useful accuracy.

The results of boehmite solubility experiments obtained at low ionic strength (0.03 m NaCl) allow a comparison to be made with the two previous batch-type studies of Castet *et al.* (1993) and Bourcier *et al.* (1993). The solubility constants reported in these studies at infinite dilution were adjusted to the ionic strength of 0.03 using the extended Debye-Hückel equation. Excellent agreement between the present results and those authors were obtained on the basic side where the solubility is relatively high and the pH can be determined readily from the free hydroxide ion molality (calculated in the batch studies). On the extreme acidic side of the profile, the stability field of Al^{3+} moves to lower pH with increasing temperature and decreasing ionic strength such that above 100°C, it is necessary to use the solubility constant obtained from the batch method in order to fit the remaining constants to the profiles obtained from the present potentiometric titrations. We have chosen the constants of Castet *et al.* (1993) for the reaction: $\text{AlOOH}_{(\text{cr})} + 3\text{H}^+ \rightleftharpoons \text{Al}^{3+} + 3\text{H}_2\text{O}$ because we found excellent agreement with this previous study, which covered the temperature range 90 to 350°C, with increasing divergence only for the stability of the neutral $\text{Al}(\text{OH})_3(\text{aq})$ species with increasing temperature. Our measurements of the solubility of boehmite at the minimum in the solubility profile, where this species dominates, are lower than those of Castet *et al.*, which in turn are considerably lower than those reported by Bourcier *et al.* (1993). Moreover, this effect disappears at pH above the solubility minimum. The filtered samples are quenched into a small known volume of one molar HCl to avoid precipitation of aluminum and so precipitation could not explain this phenomenon and we will continue to investigate the problem. But this small effect can be ignored in the fitting procedure without significant loss of precision.

All of these results were presented at the recent annual meeting of the Geological Society of America, held in New-Orleans, as an invited paper in the Geochemical Society-sponsored Symposium entitled "Frontiers in Geochemistry." During this talk (Palmer *et al.*, 1995) it was also shown that: 1) at higher ionic strengths only the 3 aqueous species: Al^{3+} , $\text{Al}(\text{OH})_2^{2+}$, and $\text{Al}(\text{OH})_4^-$ are sufficient to account for the bulk of total aluminum in solution over the entire pH range and that the stability fields of the remaining two hydrolyzed species ($\text{Al}(\text{OH})_2^+$ and $\text{Al}(\text{OH})_3^0$) can be estimated from the lower-ionic-strength data, where they are more important, and extrapolated to the high ionic strength by use of the isocoulombic approximations, 2) these new results are entirely consistent with previously-published investigations of the step-wise hydrolysis constants of Al^{3+} , including our earlier work based on gibbsite solubility and potentiometric measurements of the first hydrolysis constant (Palmer and Wesolowski, 1992, 1993); and 3) this new approach to mineral solubility studies, with continuous *in situ* pH monitoring, will permit vastly improved studies of the kinetics of dissolution and precipitation of solid phases.

FUTURE PLANS

Studies of the solubility of boehmite will be completed in 0.03 molal NaCl solutions at 350°C. Improved methods will be developed to analyze the samples from potentiometric solubility studies for total aluminum near the solubility minimum, and we will develop more sensitive tests for the presence of dimeric aluminum species. 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, involving reactions of the type:

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Type and Extent of Interest
California Energy Co.	Corrosion problems in Imperial Valley plants

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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

PROJECT BACKGROUND AND STATUS

In numerous localities worldwide, geothermal resource areas are linked genetically to silicic magmatism. Two important manifestations of this link are heat transfer from magmas to superjacent geothermal systems, and mixing of magmatic fluids with meteoric waters. Concerning the latter event it is known that: (1) the initial chemical compositions of magmatic fluids are strongly influenced by the bulk composition and thermodynamic mixing properties of the magma, (2) incompatible melt components are preferentially partitioned into the aqueous fluids that separate from silicic magmas, and (3) geochemical reactions can potentially produce significant changes in the compositions of magmatic fluids prior to mixing with circulating meteoric waters. These and other magma-hydrothermal processes have been understood semi-quantitatively for many years. To characterize geothermal systems more rigorously, new thermodynamic and kinetic formulations are needed.

A comprehensive thermodynamic model for granitic magmas would facilitate quantitative geochemical investigations of granite-hosted, magma-hydrothermal systems. With such a model, crystallization paths for the melts, which correlate with release of latent heat, could be calculated. Quantitative knowledge of this aspect of the congealing process is critical for estimating rates of heat loss from granitic intrusions. The model would also indicate the P - T - X conditions at which an aqueous fluid begins separating from a granitic magma.

Granitic magmas contain numerous minor and trace components. Consequently, attempts to quantify all of the thermodynamic characteristics of these melts are impractical. Fortunately, a great deal can be learned about granitic melts by investigating "simple" analog systems. The "haplogranite" system—comprising the components $\text{NaAlSi}_3\text{O}_8$ (albite), KAlSi_3O_8 (sanidine), Si_4O_8 (quartz), and H_2O (water)—is widely regarded as an excellent geochemical analog for granites and granitic pegmatites. Thus, we are conducting systematic investigations of the thermodynamics and phase relations of haplogranitic melts. Currently, our attention is focussed on albite-water and albite-quartz-water melts, because equations of state for these liquids are required for accurate thermodynamic modeling of quaternary haplogranitic melts.

PROJECT OBJECTIVES

This project is part of the program "Physical Chemistry of Geothermal Systems" at the ORNL. The immediate goal of the research is to perform laboratory experiments which elucidate the phase relations and thermodynamic mixing properties of haplogranitic 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 silicic magmas. The ultimate aim of the work is to develop thermodynamic models for silicic magmas and high-temperature geothermal fluids.

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.
- Measure the chemical potential of water (μ_{H_2O}) in haplogranitic melts 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 silicic melts, (2) calculating the H₂O-undersaturated hypersolidus phase relations of silicic igneous systems, and (3) estimating the quantities and compositions of magmatic fluids in geothermal systems associated with silicic intrusions.

APPROACH

The integral thermodynamic mixing properties of hydrous haplogranitic melts can be determined if sufficient amounts of accurate experimental data are obtained on: (1) the hypersolidus phase relations of haplogranitic systems, (2) the chemical potential of water in haplogranitic melts, and (3) the free energies of fusion of stoichiometric silicate components (NaAlSi₃O₈, KAlSi₃O₈, Si₄O₈). To obtain these data, experiments are being performed in an internally-heated pressure vessel and in a 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.

Laboratory experiments and computer calculations are being performed concurrently to ensure that resulting equations of state are tightly constrained over a wide range of pressure, temperature, and/or composition.

RESEARCH RESULTS

A. 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. The equation is also qualitatively consistent with the H₂O dissolution model for silicate melts advanced by Stolper and coworkers (Silver and Stolper, 1985, 1989; Silver *et al.*, 1990), the key elements of which are that: (1) hydroxyl groups are the dominant hydrous species at very low total water contents; (2) molecular water predominates at high total water contents; and (3) once total dissolved water exceeds a few weight percent, essentially all additional water dissolves in molecular form.

B. A Provisional Thermodynamic Model for Albite-Quartz-Water Melts at 2.5 Kilobars

The modeling methods outlined by Blencoe (1992) are most directly extensible to melting relations of the albite-quartz-water (*ab-qz-w*) system. This has been demonstrated by calculating phase relations for *ab-qz-w* melts at 2.5 kbar. It was assumed for these calculations that the thermodynamic mixing properties of the melts can be represented accurately by a six-parameter excess free energy equation of the Margules type (Wohl, 1953; Saxena, 1973). The six parameters in this equation are binary interaction parameters: two parameters for each binary subsystem. Melting relations were calculated for 2.5 kbar, 750, 800, 900 and 1000°C, and the results are completely rational. To determine the accuracy of the calculated melting relations, we performed numerous phase equilibrium experiments at 2.5 kbar, 720-1000°C. Results of these experiments suggest that—at 740, 800, and 900°C—the one-phase melt fields are significantly larger than those predicted by our provisional thermodynamic model. The discrepancies imply that NaAlSi₃O₈ and Si₂O₈ mix with negative deviations from Raoultian behavior in *ab-qz-w* melts. Additional experimental data that we will collect for *ab-qz-w* and other haplogranitic melts will be used to verify this result, and to develop a polythermal excess free energy equation for *ab-qz-w* melts at 2.5 kbar.

C. Water-Solubility Experiments

The solubility of water in haplogranitic melts is being determined by reversing the bivariant reaction "melt $\leftrightarrow$ melt + vapor." Reaction reversal is demonstrated by obtaining "water-increasing half-reversals" and "water-decreasing half-reversals." A water-increasing half-reversal is obtained by reacting water-undersaturated haplogranitic melt with an amount of

water that is more than sufficient to saturate the melt. During experimentation, some of the "free" water dissolves in the melt. After experimentation, a vacuum extraction/manometry technique is used to measure the water content of the hydrous glass obtained from the reacted sample. This measurement yields a minimum solubility of water in the melt. A water-decreasing half-reversal is obtained by reacting water-oversaturated haplogranitic melt at experimental P - T conditions. During experimentation some of the water dissolved in the melt exsolves to form a separate aqueous fluid. Measuring the water content of the hydrous glass obtained from the reacted sample yields a maximum solubility of water in the melt.

We have measured the solubility of water in albite-water and albite-quartz-water melts. 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.

D. Experiments to Measure the Chemical Potential of Water in Haplogranitic Melts

Two different experimental methods are being used to measure μ_{H_2O} - X_{H_2O} relations for hydrous haplogranitic melts: a "mixed-volatile" method and a "controlled- f_{H_2O} " method (Blencoe and Anovitz, 1995). Each technique permits quantification of μ_{H_2O} — the chemical potential of water in an aqueous fluid coexisting with melt (mixed-volatile method) or dissolved in the melt (controlled- f_{H_2O} method).

In mixed-volatile experiments, an aqueous fluid containing an "inert" diluent gas— CO_2 , N_2 or Xe—reacts with hydrous melt, causing the water content of the melt to either decrease or increase. After experimentation, the masses of water and gas in the fluid are determined manometrically, and the mass of water in the quenched melt is measured using a vacuum extraction/manometry method similar to that described by Ihinger *et al.* (1994). The resulting data yield values for μ_{H_2O} .

In controlled- f_{H_2O} experiments, oxygen fugacity (f_{O_2}) in each experimental sample is set by an internal oxygen buffer (Ni-NiO), and hydrogen fugacity (f_{H_2}) is fixed by controlling the concentration of H_2 in the Ar- H_2 gas that surrounds the samples. During experimentation there is mass transfer of H_2 across the wall of each Pt or Ag-Pd capsule. Depending on the f_{O_2} - f_{H_2} conditions in the capsule, and the initial water content of the melt, water is either generated or consumed by the reaction $H_2 + NiO \leftrightarrow Ni + H_2O$. In the first case the water content of the melt increases; in the second case the water content of the melt decreases. An experimentally based value for f_{H_2} is obtained by measuring the pressure of hydrogen (P_{H_2}) on the low-pressure side of the membrane (Shaw, 1963; Shaw and Wones, 1964). After experimentation, the mass of water in the quenched melt is measured using the same vacuum extraction/manometry method applied to determine the water contents of hydrous haplogranitic glasses formed in mixed-volatile experiments.

In both mixed-volatile and controlled- f_{H_2O} experiments, data are collected at closely-spaced intervals of X_{H_2O} , and anhydrous bulk compositions are selected to ensure that the thermodynamic mixing properties of the melts are determined accurately for a wide range of silicate compositions. These experimental strategies are essential because, in our thermodynamic modeling, we use measured thermodynamic mixing properties of water in haplogranitic melts to calculate the thermodynamic mixing properties of the silicate components.

E. Fluid-Composition Experiments

A number of factors have limited the ability of previous researchers to determine the composition of aqueous fluid coexisting with haplogranitic melt. The most serious difficulty is that the high P - T composition of a melt-saturated aqueous fluid is not retained on quenching. Silicate materials precipitate out of the fluid as films and "quench roe" (amorphous silica-rich spheres). This prevents direct analysis of the fluid that is stable at high P - T conditions. The tendency of the silicate to precipitate on the glass further complicates the analysis.

We have developed a method that overcomes many of these difficulties, and we are currently determining the compositions of aqueous fluids equilibrated with haplogranitic melts. These experiments will establish the Na, K, Si, and Al composition, as well as δD and $\delta^{18}O$, of an aqueous fluid coexisting with haplogranitic melt. Hydrous haplogranitic glasses of known chemical and isotopic composition are synthesized to serve as starting materials for the experiments. Nine such compositions have been prepared, five in the haplogranite system, three

on the bounding binaries (2.5 kbar minimum melt compositions), and albite. In each case, water-oversaturated and undersaturated glasses are prepared to allow reversal of the equilibrium water content of the melt. To date, experiments have been performed at 2.5 kbar, 950°C, for periods ranging from 1 to 11 days, to investigate reaction kinetics, and to determine the time required to achieve equilibrium. Future experiments will reverse the equilibrium water contents of the melts.

FUTURE PLANS

In the future we plan to conduct additional experimental/thermodynamic investigations of haplogranitic melts and associated igneous fluids. Currently, we are performing experiments and computer calculations to determine the thermodynamic mixing properties of albite-water and albite-quartz-water melts. As this work progresses, we will gradually start performing experiments and calculations to determine the thermodynamic mixing properties of K-bearing haplogranitic melts. Finally, to the present time our research on the composition of aqueous fluid coexisting with haplogranitic melt has emphasized analysis of experimental data obtained at 2.5 kbar, 950-1000°C. Future work in this research area will emphasize analysis of data obtained from melt-fluid experiments performed at 2.5 kbar, $T < 950^{\circ}\text{C}$, and at $P < 2.5$ kbar, $800 \leq T(^{\circ}\text{C}) \leq 1000$.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

To perform our research, we have developed laboratory techniques for acquiring highly precise and accurate data on the volatile contents and bulk chemical compositions of very small masses of aluminosilicate material. These methods have numerous potential practical applications in geothermal R&D. We have started reporting the results of our work at technical meetings (Anovitz *et al.*, 1995). After further refinement, the methods will be described in detail in articles written for leading geochemical journals. Researchers and technologists interested in the progress of our research are encouraged to contact us for further information.

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LIQUID-PHASE TRACER DEVELOPMENT

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KEY WORDS

tracers, tracer tests, geothermal, fluorescein, amino G, rhodamine WT, pyranine, reservoir simulation

PROJECT BACKGROUND AND STATUS

Chemical tracers play a fundamental role in the production of geothermal resources. Since almost all geothermal-reservoir management strategies require the reinjection of cooled, produced fluids, a knowledge of the injection/production flow patterns is essential to the correct placement of injection and production wells. The purpose of reinjection is to avoid surface and ground water pollution and to maintain reservoir pressures. The proper location of the injection wells within the three-dimensional network of fractures that form the reservoir is critical to the successful exploitation of the field. Properly located wells lead to increased power production due to enhanced pressures, less reservoir scaling from boiling around the production wells, and reduced 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., fluid-chemistry data, and such data is not available in the early stages of production when reservoir-management strategies are being formulated. Introduction of a tracer into the injection-production loop is the fastest and most effective 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. In addition, an insufficient knowledge of the thermal stability of these known tracers produced a lack of confidence in the results of tracer field tests. Surveys of the geothermal industry by the DOE indicated a strong belief that tracer 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 of tracers have subsequently been developed and field-tested (Adams *et al.*, 1992; Adams and Davis, 1991; Adams *et al.*, 1990; Adams *et al.*, 1989; Rose *et al.*, 1995; Rose and Adams, 1994), the need persists for new tracers, especially for easily analyzed, liquid-phase fluorescent compounds that are relatively inexpensive and that are mutually compatible.

PROJECT OBJECTIVE

The most efficient and accurate means of mapping the injection/production flow paths in geothermal reservoirs is through the use of chemical tracers. Therefore, the overall objective of this research project is to identify and test candidate compounds for use as geothermal tracers in liquid-dominated reservoirs. An ideal tracer is nontoxic, environmentally benign, thermally stable (or possessing an easily determined rate of decay under geothermal conditions), detectable at very low concentrations, fairly nonreactive with the reservoir rock and relatively inexpensive. As many of these compounds as possible should be identified because of the need for identifying individual injector/producer flow paths in reservoirs containing multiple injection and production wells.

Technical Objectives

- Prove the stability of several candidate compounds for use as geothermal tracers. Use both laboratory and field tests to provide the evidence of stability.
- Develop numerical simulation techniques for evaluating the information that tracers can provide, such as fracture-surface area, fracture density and spacing, steam fraction, and reservoir volume. This will serve to provide more information about reservoir performance than is currently being extracted from tracer tests. Likewise, it will allow for the evaluation of tracers and tracer-injection strategies using powerful numerical simulation methods.

Expected Outcomes

- We expect to provide a minimum of ten affordable, easily identifiable tracers that are stable at temperatures up to 300°C.
- Numerical modeling will be used more extensively as a means of evaluating candidate tracers and improving tracer-test designs.

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 is 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 using high-pressure autoclaves to create an environment of temperature, pressure, and solution matrix that simulates the reservoir environment. Upon completion of the laboratory phase, the candidate tracers are field-tested in

geothermal reservoirs. The results of the full-scale field tests are then compared to the results of the laboratory tests in order to refine the laboratory-derived parameters. Finally, the results of the laboratory experiments and field tests are published in the open literature. These methods provide for rapid evaluations of candidate compounds and immediate and up-to-date access to our results for the geothermal community.

RESEARCH RESULTS

Among the new fluorescent compounds evaluated this year for use as tracers in geothermal reservoirs was lissamine FF, which in laboratory tests simulating reservoir conditions was found to possess sufficient thermal stability for use in geothermal systems having temperatures less than about 180°C. Its reported low toxicity and low adsorptivity are additional qualities that recommend its use as a geothermal tracer.

Another promising fluorescent compound that was tested in the laboratory this year was pyranine. In addition to possessing low toxicity and low adsorptivity at reservoir conditions, early results suggest that it has sufficient thermal stability to allow its use in reservoirs with temperatures approaching 250°C. The only other fluorescent dye that we have identified that possesses comparable thermal stability is fluorescein.

A third promising fluorescent compound that was found to possess very good thermal stability was amino G. In addition to being very affordable, the literature suggests that it is nontoxic and nonadsorptive at reservoir conditions. Its thermal stability in the presence of the companion dyes fluorescein and rhodamine WT was studied in our laboratory under conditions of temperature and pressure that simulate reservoir conditions. In this manner, the potential of amino G for use in combination with fluorescein and rhodamine WT was evaluated. (Fluorescein and rhodamine WT have previously been qualified for use as geothermal tracers.) Since the excitation and emission wavelengths of amino G, fluorescein, and rhodamine WT are sufficiently separated, the three tracers can potentially be used for the simultaneous tracing of 3 independent injection/production pathways. Although the need for simultaneously tagging multiple injection wells has existed for some time in the geothermal industry, such a test has never been conducted due to the lack of a sufficient number of mutually compatible liquid-phase tracers.

FUTURE PLANS

Our plans for the forthcoming year include a tracer test at the Bradys geothermal field in western Nevada using the three mutually compatible tracers amino G, fluorescein, and rhodamine WT, which were described in the results section above. To our knowledge, this is the first instance of the use of three liquid-phase tracers in a geothermal setting to simultaneously tag three separate injectors. This test will also constitute the first use of amino G in a field test and provide important data that will serve to verify the laboratory studies.

In addition to the test at Bradys, a field test will be conducted at Dixie Valley, Nevada, for the purpose of evaluating the performance of the fluorescent compound pyranine. Since the temperature of the fluids in this reservoir average about 250°C, this test will provide an

opportunity to evaluate a fluorescent compound in an intermediate temperature range--significantly hotter than the temperatures ($<180^{\circ}\text{C}$) for which rhodamine WT and lissamine FF are appropriate.

Numerical-simulation computer models have emerged as powerful tools for investigating the natural and induced flow patterns and energetics of geothermal reservoirs. While tracer data from field studies have long been available for calibrating and tuning reservoir simulators, very little R&D effort has been directed towards simulating tracer tests with the objective of predicting the performance of proposed tracers. Using PC-based versions of Tetrad (Vinsome, 1995) and/or TOUGH2 (Pruess, 1991) that have been obtained by our laboratory, we will conduct numerical studies to model the performance of tracers in geothermal settings. Starting with simple, idealized systems, the models will be made progressively more complicated until it is possible to simulate an actual field test. Once a match is obtained, it will be possible to vary such parameters as tracer-input mass, adsorption equilibrium constants, and decay-rate constants in order to determine the effect of such parameters on tracer return curves. In this manner, it will be possible to predict the performance of proposed tracers and to evaluate the tracer-test plan before performing the field studies.

The cost of conducting geothermal-reservoir tracer tests can approach tens of thousands of dollars when one considers the combined costs of the tracer compounds, the well sampling, and the tracer analyses. Typically, hundreds of pounds of tracers are used for each injection well tagged. One means of significantly reducing the overall cost would be by significantly reducing the amount of the tracer, without simultaneously increasing the cost of either the sampling or the analysis. An added benefit would be in significantly increasing the list of potential tracer compounds, since only a small fraction of the commercially available tracer compounds are manufactured in the bulk quantities that are currently required for a tracer test. Through the use of the laser-fluorescence-detection technology that has recently emerged from the Department of Chemistry at the University of Utah, it is possible to reduce the detection limits of aqueous solutions of fluorescent-tracer compounds by several orders of magnitude over what is currently available commercially. Such reductions in detection limits will allow for equally dramatic reductions in the amount of tracer material used. A program has recently been initiated that will continue throughout the forthcoming year with the objective of significantly reducing the detection limits, and, as a result, the quantity of tracer required for a tracer test.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

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. The following table lists the name of the company as well as the type and extent of interest that it has demonstrated:

Organization(s)	Type and Extent of Interest
Far West Capitol Inc.	Cost-shared tracer test at Steamboat Hills geothermal reservoir
Oxbow Power Services Inc.	Cost-shared tracer test at Dixie Valley geothermal reservoir
Oxbow Power Services Inc.	Cost-shared tracer test at Beowawe geothermal reservoir
Beowawe Geothermal Power Company	Cost-shared tracer test at Beowawe geothermal reservoir

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GASEOUS TRACERS

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KEY WORDS

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

PROJECT BACKGROUND AND STATUS

Gaseous tracers are high-volatility compounds that possess all of the desired qualities of a tracer, i.e., thermal stability, low toxicity, and high detectability. Some of these compounds, such as SF_6 , are highly stable because the central atom is surrounded by a sphere of tightly-bonded fluorine atoms. These fluorine atoms also make the molecule highly detectable; detection limits below 10^{-9} grams per kilogram can be achieved using a gas chromatograph equipped with an electron-capture detector. Gaseous tracers were originally sought for use in vapor-dominated systems. However, they are equally useful in liquid-dominated systems. SF_6 has been successfully tested as a liquid-phase tracer at the hot dry rock project at Rosemanowes quarry, England (Upstill-Goddard and Wilkins, 1995) and the Wairakei, New Zealand geothermal system (Bixley et al., 1995). A highly-detectable gaseous tracer should also be very useful in high salinity systems such as the Salton Sea, where it can be sampled from the steam line. Low-volatility tracers, which are sampled from the liquid line, are difficult to use in high-salinity systems because the high ion concentrations make quantification of the thermal stability difficult and because they interfere with analysis of the tracer. The main drawback to the use of gaseous tracers in liquid-dominated systems is that there must be no contact with steam in the subsurface. If this occurs the tracer will quantitatively fractionate to the steam phase.

The Geysers, the largest geothermal field producing electricity in the World, is a vapor-dominated geothermal system. 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 a beneficial effect on production.

Prior to our research, successful tracer tests at The Geysers used either deuterated 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. Deuterated water 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 deuterated water as a tracer in several units. Recently, a method for using ammonia was developed by J. Beall to replace deuterated water as a natural tracer. However, 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 has been 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. Alcohols appear to possess these qualities, and our laboratory tests have shown them to be stable at the temperatures found in the majority of reservoir at The Geysers. However, the detection limits of alcohols are too low for use as a tracer at The Geysers. To lower the detection limit we will explore the possibility of using fluorinated alcohols, which are highly detectable.

Gaseous tracers have had mixed reviews at The Geysers. In moderately depleted regions of The Geysers reservoir R-13 (chlorodifluoromethane) has been used successfully to trace the flow of injected water. In contrast, difficulties have been encountered with the use of SF_6 as a Geysers tracer. The major difficulty seems to lie in the early release of SF_6 from the boiling injectate due to its lower solubility in water. This early release can lead to false negatives because the tracer has already gone through the system before sampling takes place. In seriously depleted regions of The Geysers early release can also lead to the tracer taking a pathway different from the bulk of the injected water. Our work this year is oriented on demonstrating the stability of SF_6 through laboratory experiments. Once this is accomplished we will return to the field tests and try to work out a more successful methodology for using SF_6 in a vapor-dominated system.

At the present time the gaseous tracers project is approximately 50% complete.

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 gaseous compounds for use as geothermal tracers that are nontoxic, 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.

Technical Objectives

- Prove the stability of several gaseous compounds with a range of volatilities that can be used as tracers in geothermal systems. Use both laboratory and field tests to provide the evidence of stability.
- Evaluate the effects of solubility on the transport of gaseous tracers.
- Develop methods and criteria for the use of gaseous tracers in liquid-dominated geothermal systems.

Expected Outcomes

- A variety of tracers (minimum of 6) suitable for use in moderate- to high-temperature geothermal systems.
- Theory and methodology for planning and interpreting a tracer test using a gaseous tracer.

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 preexisting 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 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.

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 Energy Resources, Calpine Corp., and the 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, SF_6 , 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 low liquid saturation, to significantly less depleted, with higher reservoir pressure and higher 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 (Voge et al., 1994; Adams, 1995).

During the past year our research has focused on SF_6 because of recent environmental restrictions on the use of chlorofluorocarbons. Field tests in liquid-dominated systems and qualitative considerations indicate that SF_6 should be stable at high temperatures. However, tests using SF_6 at The Geysers have been problematic. Three tracer tests using SF_6 have been performed at The Geysers. The first test, performed by Calpine Corporation in a relatively undepleted area, was only sampled for a few days and abandoned when only a trace of SF_6 was detected (Joe Beall, personal communication). A later test in the same area using R-13 was characterized by long return times, much longer than a few days. So it appears that the false negative may have been produced by expectations of travel time. The second test was the DV-11 joint DOE/industry test. As discussed above, SF_6 was detected but it came out early and traveled in a different direction than the bulk of the injectate due to the extreme under saturation (depletion) in this portion of the reservoir. The third test was performed by Thermochem Inc. in conjunction with a tritium tracer test being conducted by Calpine Corporation. No SF_6 samples were taken until the third day, when tritium began to appear, and no SF_6 was detected. It appears that the SF_6 may again have been missed again due to uncertainty about how fast SF_6 is released from the injection plume.

Because many questions about the stability of SF_6 have arisen from the SF_6 tests at The Geysers, we have set up our laboratory to examine the stability of SF_6 under geothermal conditions. The one test that we have completed indicates that SF_6 is stable in pure water at 280°C for one week.

More tests need to be conducted at longer times, higher temperatures, and with rocks. These will be performed during the next year.

FUTURE PLANS

Our plans for the coming year are to continue our laboratory tests of SF_6 . We hope to incorporate the effects of mineral catalysis and reactive gases such as CO_2 , H_2S , and NH_3 into our experiments. If SF_6 proves stable, we will re-evaluate the tests that have been performed at The Geysers and work up some methods by which SF_6 can be used successfully in vapor- and liquid-dominated systems. We also hope to extend our research to fluorinated alcohols, which would fractionate into both the liquid and vapor phases.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Type and Extent of Interest
Calpine Corporation Northern California Power Agency Unocal Energy Resources Pacific Gas & Electric	Cost-shared tracer test, The Geysers
California Energy Corporation	Inquiries re Salton Sea and Coso tracers

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Figure 1. Concentration-time curves from a production well in four tracer tests. The DV-12, SMUD, and Bear Canyon tests were conducted at The Geysers, a vapor-dominated geothermal system. R-13 was used as a tracer in these tests. The Dixie Valley test was conducted in a liquid-dominated geothermal system using fluorescein. In the tests conducted in the vapor-dominated systems the return time is related to the degree of depletion of the reservoir. Note that the least depleted area, Bear Canyon, has a return curve similar to that of the liquid-dominated Dixie Valley curve.

CHEMICAL MODELS FOR OPTIMIZING GEOTHERMAL ENERGY PRODUCTION

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KEY WORDS

chemistry, brines, gases, computer models, reservoir, scaling, rock/water interactions, simulation, solubility, thermodynamic data, pH, breakout, phase transitions, geothermal, energy

PROJECT BACKGROUND AND STATUS

Many of the most significant problems encountered in the economic production of geothermal energy result from various chemical behaviors of the natural brines from which the energy is extracted. Because of the complexity of the physical chemical interactions within the fluids, this behavior is difficult to predict from tables or past experience. For many important applications this problem is made more tractable because the fluids remain near *local chemical equilibrium*. For such systems the behavior may be calculated from equilibrium thermodynamics, via the free energy of the system. The free energy is a function of the pressure, temperature and composition of the phases included in the system: fluids, solids and liquids. For a sufficiently general model of a geothermal system the variation of the free energy with all these parameters must be taken into account.

We have developed highly accurate models (see Table 1) incorporating phenomenological equations for the free energy of gas, liquid and solid mixtures (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 could be used to accurately predict complex solubility relations in multi-component brines to high concentration. These equations are soundly based on theoretical results, but contain parameters that must be evaluated from experimental data in binary and ternary systems. The evaluation of these parameters is a difficult task, but once completed the model may be applied to systems of arbitrary complexity.

The original work of Harvie and Weare (1980) was supported primarily by grants from the National Science Foundation (NSF) and from the American Chemical Society (ACS). With funding from the Department of Energy (DOE), NSF, and ACS the modeling package was expanded to include carbonate, silica, and borate additional species as well as acid-base reactions, pH and variable temperatures ($T < 250^{\circ}\text{C}$). (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 develop these models it was necessary to develop extremely reliable methods of handling the massive data evaluation program required by model parameterization and validation and of solving the

complicated chemical equilibrium problem associated with simulating complex geothermal brine/gas systems (Harvie et al. (1987)).

Table 1. Capabilities of Present Models

- Predict behavior of calcium carbonate scale formation in NaCl and CaCl₂ brines for T = 0° to 250°C
- Predict solubility of CO₂ and CH₄ in NaCl brines for T = 0° to 250°C
- Predict pH and complete carbonate equilibria in seawater brines (Na-K-H-Ca-Cl-SO₄-H₂O system) as a function of CO₂ at 25°C
- Predict solubility of amorphous silicascale in seawater-type brines for T = 0° to 250°C
- Predict solubilities of marine scaling minerals (e.g., NaCl, CaSO₄) to 250°C
- Predict onset of two-phase behavior in NaCl brines
- Predict solubility of hydrogen sulfide (H₂O-H₂S-HS⁻) systems (0° to 200°C; 0 to 100 atm)
- Predict liquid-gas- phase equilibria in the NH₃-H₂O system to 350°C and 200 bar
- Predict partial fugacity in mixed gas systems (CO₂-CH₄-H₂O) T = 0° to 1000°C and P = 0 to 1000 bar
- Predict enthalpies of brines (0° to 250°C) and gases (0° to 1000°C)
- Predict gas-liquid equilibrium in the CO₂-CH₄-H₂O system to 1000°C and 3000 bar
- Predict gas-liquid equilibrium in the NaCl-H₂O-CO₂ system to 1000°C and 5000 bar

With support from the DOE Geothermal program and the ACS, significant breakthroughs were also made in developing new phenomenology for predicting the behavior of gases and liquid/vapor coexistence for complex mixtures. Using this phenomenology we produced a gas model of the CH₄-CO₂-H₂O system which accurately predicts phase equilibria and PVT properties from 0 to 1200 bars and from 0 to 1000°C (Duan *et al.* (1992 a,b). This was the first model that could accurately predict both single and two phase behavior of gas mixtures. This new phenomenology is incorporated in our model of gas breakout in highly pressured systems in the GEOFLUIDS program.

In June of 1993, our chemical modeling group received funding under a five-year (1993-1997) DOE grant (DE-FG07-93ID132747: Renewable Energy Research and Development) to continue our research in the development of models of geothermal brine chemistry. The research projects proposed in the program (see Table 2) are designed to add new species, as well as to expand the parameterization of the major species in the models to higher temperatures. The proposed 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 efforts in order to design the best models and best user interfaces.

PROJECT OBJECTIVES

To improve the productivity and efficiency of geothermal operations and exploration by providing user friendly computer models of the thermochemical and thermophysical properties of geothermal brines and their associated noncondensable phases and reservoirs. These easy to use models supply a reliable means to predict the chemical consequences of plant operations and the chemical properties of the reservoir. They, thereby, provide plant operators, engineers and consultants with the ability to enhance operation by adjusting process variables or to rapidly analyze potential problems and to develop strategies for their amelioration. Our project also includes much communication with the geothermal community to improve technology transfer and to increase the relevance of the models to the problems of the industry.

Technical Objectives

- Construct thermodynamic models for predicting chemical behaviors such as breakout, scaling, and reservoir degradation created by the extraction of energy from geothermal brines. These models must accurately predict the thermodynamic properties, e.g. the solubilities, liquid/vapor coexistence, enthalpies, etc., of complex natural fluids for a wide range of pressures, temperatures and compositions. The models must be able to treat the special problems associated with calculating multiple phase equilibria.
- Develop new phenomenologies to use in the models which more efficiently represent the thermodynamic behavior of natural fluids.
- Develop user-friendly application software for PC's and Macintosh computers to facilitate the transfer of the modeling technology to industrial operators.

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 densities. 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.
- ***GEOFLUID Application Package*** -- This series of computer programs will include models for calculation of the PVT properties and vapor/liquid equilibrium from subcritical to supercritical temperatures and pressures. Application of these programs include: gas breakout, fluid inclusion studies of reservoir evolution, and the solubility of gases.
- ***GEOHEAT Application Package*** -- This series of computer programs will include specific heat and enthalpy calculations for complex liquid/gas mixtures. It will allow the rapid calculation of gas breakout, liquid/vapor ratios, available heat etc.
- ***GEOPHASE Application Package*** -- This package (under development) will provide visualization capabilities to aid in the interpretation of complex gas/liquid/solid phase relations.
- ***Reliable Summary of Data Sets for Brine/Solid/Gas Species*** -- The chemical modeling process includes the correlation and evaluation of many data sets.

APPROACH

To have the predictability required for geothermal applications, highly accurate models of the chemical behavior and physical properties of the resource formation and working fluid and their interaction 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 measured chemical behavior of brines, solubility and liquid/vapor coexistence, and heat content of both liquids and gases. The models have been applied to well-determined production situations with remarkable success. Our gas modeling approach utilizes our recently developed phenomenologies which can reproduce PVT properties in both the liquid and gas phases as well as liquid/vapor coexistence.

Our research program also includes a continuing effort to develop new phenomenological expressions which will more succinctly summarize the thermodynamic behavior of solids, liquids and vapors. As new models are developed, they are included in user friendly software packages, TEQUIL, GEOFLUID and GEOHEAT (not yet distributed). These can be loaded from diskettes to PC's or Mackintosh computers. Periodically, workshops are given on the use of these programs to treat problems of interest to the geothermal community. A manual is in preparation

explaining the operation of the software and loading procedures. A continuing effort is made to determine the needs of the geothermal community and build appropriate software.

Our modeling technology has wide application in other industries. For example they have been used in the development of chemical processing, solar pond engineering and in waste isolation applications. As a result, in addition to the support from the DOE Geothermal program, we have received support from other government agencies such as NSF, ACS, and the DOE nuclear waste program, as well as from industrial sources such as UNOCAL, Potash Corporation of Saskatchewan, Canada.

RESEARCH RESULTS

Parameterization of the Na-H-Ca-Cl-HCO₃-SO₄-CO₂-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 sulphate, and amorphous silica scale forming minerals as well as CO₂ solubility. Our equations of state for the CH₄-CO₂-H₂O, the NH₃-H₂O and the NaCl-CO₂-H₂O systems can predict behavior from the two phase region to the homogenous region. A solid NaCl phase has recently been included in the NaCl-CO₂-H₂O model, allowing the precipitation of solids. Model parameterization of complex systems requires very large sets of thermodynamic data. In addition model validation requires comparison with data in more complex systems and direct comparison with field data. Results of this validation show that the models reproduce experimental data nearly within the accuracy of the measurements.

Recently we added H₂S-NaCl-H₂O and NH₃-H₂O models to the GEOFLUIDS program. The error in the H₂S model is about 10% which is about that of the data. The error in the NH₃ model is 1-2% in the density again similar to the intrinsic error of the data. A silica geothermometer has also been implemented in this software package.

We have completed much of the proposed research for the five year program. However, because of reduced funding we have not been able to begin modeling of the important aluminum silicate system. Funds may be available to begin that project this fiscal year. Variances in the planned activities also include changes in the time line for a few projects. For example our molecular dynamics program has been so successful in developing new equations of state (EOS) that we have increased effort in this area. Also the development of models of available heat was not in the original research program, but appears to be a very popular addition. We have also focused additional effort on the development of user interfaces. This emphasis has paid off already by making our software more directly available to various users. With these improved interfaces it is possible to become familiar with the operation of the program without attending a workshop. The workshops, however, still provide a easy way to become familiar with the application of the models to geothermal problems and serve as a mechanism for keeping us aware of the special problems of the geothermal industry.

*Highlights of the Most Recent Results***Reliable Simulation of Phase Equilibria in Complex Systems**

In many operations the efficient production of geothermal power is intimately affected by the phase equilibria of the working fluid, e. g. gas breakout, scale formation etc. Traditionally phase equilibria are studied by experiments. However, to obtain phase equilibrium data for the range of intensive variables that are common to geothermal problems would require a very large experimental effort. Recently using the Monte Carlo Gibbs ensemble method we have been able to simulate phase equilibria in the system $\text{CO}_2\text{-CH}_4\text{-N}_2$. This method is direct and intuitive. Both the equilibrium composition and mole volume (or density) can be obtained simultaneously. Recently we found that latent heat can also be reliably simulated by this method. Compared to other simulation methods (such as grand canonical ensemble method), the Gibbs ensemble method is more direct. A priori knowledge of phase relations is helpful but not necessary. Comparison of the simulated results with experimental data indicates that the equilibrium compositions and mole volumes are predicted with accuracy close to that of experiments. An example of one such calculation is given in Figure 1. The simulation has advantages over both experiments and EOS such as the popular Peng-Robinson EOS (1976) and Lee-Kesler EOS (1975). In comparison with EOS, our simulations with fewer adjustable parameters are more accurate for a larger temperature and pressure range. We believe this method has great potential in the study of geothermal fluid chemistry.

Modeling of the Enthalpy of Geothermal Fluids for a Large T-P-X Range -- Quantitative estimation of heat transfer in geothermal energy extraction requires the knowledge of fluid and gas enthalpy as a function of temperature, pressure and composition. Unfortunately, little enthalpy data is available for mixed systems. Only pure water has a relatively complete data base. For this reason geologists and geothermal engineers use the pure water steam table when enthalpy or other related properties are required. However, in most settings the fluids contain substantial amount of gases, such as CO_2 , CH_4 , H_2S , H_2O , O_2 and N_2 (Lyon, 1974, Ellis, 1977). Mahon and Finlayson (1972) reported CO_2 concentrations of several percent in the total discharge from a number of drill holes in the Broadlands Geothermal fields, New Zealand. Submarine hydrothermal systems contains appreciable amount of CH_4 , CO_2 and other gases (Kim, 1983). The presence of gases can substantially alter the manner in which convective fluids transfer heat.

We have developed a model calculating enthalpy of geological fluids composed of H_2O , CO_2 , CH_4 , N_2 , H_2S , O_2 , H_2 , CO , HCl , Ar and possible additional gases from the subcritical two phase region up to 2000°C and 30 kbar (possibly up to 3000°C and 300 kbar), with accuracy close to that of the experiments. This model uses canonical partition functions to calculate enthalpy of ideal gases as a function of temperature, and uses EOS to calculate the departure of real systems from the ideal gas state. The largest deviation from experimental data is about 0.4 kJ/mole for temperatures below 1000°C . For temperatures above 1000°C the error may be less than 1 kJ/mole. An example of a calculated enthalpy pressure diagram is given in Figure 2. As far as we know, this is the first model able to calculate mixed system enthalpies. This model can be used in the study of various thermal processes associated with power production. For example, it can be used to estimate steam ratios in gas breakout, density of fluids, and available heat.

Modeling of the Thermodynamic Properties of Supercritical Fluid Mixtures -- The pressure-volume-temperature-composition (PVTX) properties of natural fluids composed of pure members or mixtures of the system $\text{H}_2\text{O}-\text{CO}_2-\text{CH}_4-\text{N}_2-\text{H}_2\text{S}-\text{CO}-\text{Ar}-\text{He}-\text{H}_2$ and O_2 are very important in the study of various geochemical systems, since almost all thermodynamic properties can be derived from these PVTX relations. Although many experimental PVTX data sets have been published, these cover only a small TPX range. In order to bridge between the various TPX ranges of experiments, many EOS have been proposed. However, any given EOS can cover only a small part of PVTX space with accuracy close to that of the experimental data.

Based on molecular simulation, we have developed a molecular dynamics representation of the system which is much more accurate, and covers a much larger part of TPX space than any previous EOS for supercritical fluids. This EOS contains only two parameters for each pure component and two additional parameters for each binary mixture. No higher order parameters are needed for more complicated mixture systems. The two mixing parameters can be eliminated for non-aqueous mixtures with a slight loss of accuracy in both total mole volume and in the excess volume. Comparison with a large amount of experimental PVTX data in pure systems (including H_2O) and for mixtures in the systems $\text{H}_2\text{O}-\text{CO}_2-\text{N}_2-\text{CH}_4$ and $\text{N}_2-\text{CO}_2-\text{CH}_4$ results in an average error of 1.6 % in density. Comparisons with commonly used EOS for supercritical fluids shows that the simulation results of this study covers far larger T-P-X space with the required accuracy. We believe that it is accurate from supercritical temperature to 2000°K and from 0 to 25,000 bar or higher with an average error in density of less than 2 % for both pure members and mixtures in the system $\text{H}_2\text{O}-\text{CO}_2-\text{CH}_4-\text{N}_2-\text{CO}-\text{H}_2-\text{O}_2-\text{H}_2\text{S}-\text{Ar}$ and possibly with additional gases. Comparison with published data suggests that this EOS is approximately correct up to 300,000 bar and 2800°K .

Liquid Density Brines

Testing of the solubility predictions for the variable temperature model for the seawater ($\text{Na}-\text{K}-\text{Ca}-\text{Mg}-\text{Cl}-\text{SO}_4-\text{H}_2\text{O}$) system was continued this year. Most of the 39 salts included in the model are single (e. g. Bischofite: $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) or double (e.g., carnallite: $\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) salts and therefore can be parameterized from correlation with binary or ternary salt solution data. However, two triple salts, polyhalite ($\text{K}_2\text{SO}_4 \cdot \text{MgSO}_4 \cdot 2\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and Kainite ($4\text{KCl} \cdot 4\text{MgSO}_4 \cdot 11\text{H}_2\text{O}$) are also included in the system. Parameterization of the chemical potential of kainite requires data in quaternary or higher systems. In good agreement with the majority of the data, the resulting model predicts that for the $\text{K}-\text{Mg}-\text{Cl}-\text{SO}_4-\text{H}_2\text{O}$ system the stable assemblage, sylvite-carnallite-kieserite, transforms into sylvite-carnallite-kainite at 13.7°C and that kainite is stable until 84.1°C when the kainite-sylvite-langbeinite assemblage transforms into kieserite-sylvite langbeinite. At 25°C the model solution compositions are in excellent agreement (within 6%) with the data for the kainite-epsomite-leonite, the kainite-epsomite-hexahydrite and the kainite-carnallite-sylvite invariant points. The model is also in excellent agreement with the available data at 55°C .

Recently Ziegenbalg et al (1991) investigated solid-liquid phase equilibria in the quinary $\text{Na}-\text{K}-\text{Mg}-\text{Cl}-\text{SO}_4-\text{H}_2\text{O}$ system over the 90 to 149°C temperature range. The kiserite solubilities in the $\text{MgCl}_2-\text{MgSO}_4-\text{H}_2\text{O}$ ternary were used to extend the parameterization to high temperature.

Quinary data were used to test the predictions of the model. Remarkable agreement for the four salt coexistences as a function of temperature was found. Model predictions of the solution compositions also compare well with the quinary data. Phase diagrams comparing model calculations with data in the quinary have been prepared for publication.

The polythermal representation of the saturated phases in the seawater system have proven useful in many applications. These diagrams delineate the stability fields of the phases in a brine system as a function of temperature and ion concentration. Polythermal diagrams from 0 to 250°C of the solid phases in the ternary systems containing magnesium have been constructed. For the most part these diagrams show remarkable consistency with the experimental data. Fine tuning of the temperature functions for the chemical potentials of the various phases improved the predictions. The polythermal representation also clearly illustrate transition points in selected brines. The models prediction of these points are in excellent agreement with the data.

User Interfaces

Our efforts to make the programs more user friendly by improving the graphical user interfaces on the Macintosh's and PC's are continuing. The following new features have been added in response to feedback from researchers who have been using our programs.

- 1) Options for scaling brine mixtures: A user may now select scaling parameters by changing values listed in fields in a user interface window. Thus, they may, for example, choose the proportion with which to mix two brines or select an evaporation rate.
- 2) Centigrade and Fahrenheit temperature units may be chosen from a pull down menu.
- 3) Concentration units may be chosen from a pull down menu. Currently, molality and PPM (parts per million) are supported. The calculations are still done internally in moles.
- 4) Input file storage and retrieval options have been included. In our prior interface user starting the TEQUIL interface, had to re-enter all the composition data and the calculation options. The SAVE field on the user interface may now be selected. That saves the user's composition data and all other options (temperature, step direction etc) to a file of the user's choice. Data is retrieved by choosing the RESTORE field and entering the file name.
- 5) New options giving the model flexibility have been added. Previously, TEQUIL only read the file "tequil.dat" which contained the Pitzer parameters, and "input.dat" which contained pure phase data. Now, the TEQUIL user interface program reads a file that contains a list of files that define the model: the name of the Fortran executable, the names of the parameter files and the name of a description file that tells the user what components make-up the model, what temperature range it covers, and who to contact regarding the model's use. This information also appears in a banner when the program is started. An "initialization" option has also been added that allows a user to change the mode, the Fortran executable, and the description banner without exiting the program.

FUTURE PLANS

We plan to continue the model developments listed in the five-year plan, as well as improving the program by including research projects identified as important by the geothermal community.

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, 0 - 250°C) $T_{\max}$ depending on data availability
Sulfide scale solubilities	Initiate and continue (T, 0 - 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-temperature 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	

INDUSTRY AND ACADEMIC INTEREST AND TECHNOLOGY TRANSFER***A. Contacts, FY95***

The following is a list of contacts made with potential users of our modeling technology over the last year.

Institute fur Tieflagerung, Deutschland: Requested TEQUIL model and provided new data for model validation. Excellent agreement was found. This work will be summarized in the thesis of Dr. H. J. Herbert.

Virginia Polytechnical Institute: Requested GEOFLUIDS and NHC* program for testing against their new data. The model agrees well with these data.

USGS: I. Ming Chou: requested GEOFLUIDS program for testing

Sinica China Geological Institution, Taiwan: Requested GEOFLUID and NHC

Instituto de Investigaciones Electricas, Cuernavaca, Morelos, Mexico: Requested TEQUIL

Pacific Northwest Laboratories: Technology transfer of our simulation methods and requested that we help them evaluate their graphical chemistry environment.

Geothermex: Requested updates and help with interpreting the predictions of TEQUIL

Technische Universitat Bergakademie: Freiberg, Germany: Provided data for the validation of TEQUIL

Canadian Potash, Saskatchewan, Canada: Requested copies of TEQUIL

INEL: Requested copy of GEOFLUID to analyze field pressure data

Los Alamos National Lab: Requested copies of TEQUIL and GEOFLUID to use in the analysis of data from the Hot Dry Rock Project

US Army Cold Regions Research and Engineering Laboratory: Requested and utilized cold temperature model and TEQUIL

Lawrence Livermore Laboratory: Requested and tested TEQUIL

Yankee/Caithness: Requested copies of TEQUIL and GEOFLUIDS for testing against field data

Korea Institute of Science and Technology: Visited and reviewed our program as a potential program for Korea

Korean Science and Policy Institute: Visited and reviewed our program for possible implementation of a similar program in Korea

*NHL NaCl-CO₂-H₂O model

B. Presentations at Technical Meetings, FY95

March 13-16, 1995: DOE Geothermal Program Review XIII, San Francisco, California
"Advanced Technology for Prediction Geothermal Brine/Gas Chemistry."

July 20-21, 1995 Geothermal R&D Workshop, Geothermal Energy Association, San Francisco

July 22, 1995 User Interface Workshop on Parallel Programming Software (AAPSS), Santa Barbara, CA

C. Technical Papers

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2. Molecular Dynamics Equation of State for Nonpolar Geochemical Fluids, Z. Duan, N. Møller and J. H. Weare, *Geochim. et Cosmochim. Acta*, **59**, No. 8, 1533-1588 (1995).
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Figure 1. Fluid compositions in the N₂-CH₄-CO₂ system.

Figure 2. Enthalpy Pressure Temperature Steam Ratio diagram and for the CO_2 - H_2O system.

CALIBRATION AND TESTING OF THE BRINE CHEMISTRY MODELS GEOFLUID AND TEQUIL AT NEVADA GEOTHERMAL RESOURCES

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KEY WORDS

scale prediction, geothermal fluids, rock/water interaction, aqueous geochemical models

PROJECT BACKGROUND AND STATUS

Scale buildup of carbonates, sulfates, silicates, or metal sulfides have the potential to occur during energy extraction at all Great Basin geothermal resources. These problems range from calcium carbonate scale formation in non-pumped production wells to stibnite deposition in binary heat exchangers. Although various chemical additive strategies such as inhibitors and crystallizers are available to help control scaling problems, these methods generally require substantial cost in chemicals, additional equipment, and maintenance. Because of this expense, it is important to fully assess both the nature and the magnitude of the scaling potential anticipated during geothermal energy production and the effectiveness of various strategies to mitigate the problems.

The DOE Geothermal Division has supported the development of the computer models GEOFLUID and TEQUIL, which have demonstrated the ability to accurately reproduce the measured laboratory behavior of simple brines, the solubility and liquid/vapor coexistence of gases, and other thermodynamic properties of aqueous systems (Weare, 1987; Moller, 1988; Duan et al., 1992b). In addition to modeling mineral-brine behavior, these programs (developed by the University of California San Diego Chemical Modeling Group (UCSD CMG)), also have the capability to predict the behavior of gas phases of most compositions associated with geothermal formations (Duan et al., 1992a; Duan et al., 1992c).

These calibrated and field tested models would provide the geothermal industry with: (a) a cost effective method of predicting problems related to brine chemistry during resource site assessment; (b) a method of identifying causes of chemical scaling problems in systems already in operation; (c) an inexpensive means for testing strategies to abate these problems; and (d) a tool for simulating brine behavior for optimal plant performance. Work on the current project began in April, 1995, and the anticipated completion date is November 30, 1997.

In their current state of development, the GEOFLUID and TEQUIL models should have the capability to describe the chemical behavior of Ca, Na, Cl, CO₂, HS, H₂S, and H₂O present in Great Basin geothermal brines. Based on the models' excellent predictive capability of experimental brines it is anticipated that the models will be able to simulate scaling problems in real systems.

PROJECT OBJECTIVES***Technical Objectives***

- Enhance the cost-effective utilization and development of Great Basin geothermal resources through the calibration and refinement of the GEOFLUID and TEQUIL geochemical models.
- Field calibrate the models using data collected from several geothermal power plants in Nevada in order to improve their ability to provide reliable predictions of chemical behavior in geothermal fields.

Expected Outcomes

- Successfully predict existing mineral scale deposition at geothermal power production facilities using the GEOFLUID and TEQUIL models.
- Use of the GEOFLUID and TEQUIL models to effectively analyze existing scale deposition, and as a tool to explore alternate production and injection strategies.

APPROACH

The brine (solution, solid, and gas phase) chemistry models GEOFLUID and TEQUIL will be applied to data collected from nine geothermal power plants across Nevada (Figure 1), and analyzed at Los Alamos National Lab. Brine, condensed steam, and separated water samples were obtained from production wells and mineral scale samples will be gathered from wellbores in non-pumped fields and from the heat exchangers in binary plants.

To date, brine samples have been collected for chemical analysis from production wells throughout Nevada from the following geothermal fields: Beowawe, Brady, Desert Peak, Dixie Valley, Empire, Soda Lake, Steamboat Terrace, Steamboat Hills, and Stillwater (Figure 1). Production fluids were sampled using a mini-steam separator and a condenser coil. Power plants utilizing flashed-steam technology were sampled adjacent to one production well. Binary power plants were sampled at both the entrance and exit of the heat exchanger. Brine, separated water, and condensed steam and gas samples were sent to Los Alamos National Lab. Brine and separated water samples were analyzed for the following constituents: Ag, Al, Ar, B, Ba, Br, Ca, Cd, Cl, Co, CO₃, Cr, Cs, Cu, Fe, Fl, H⁺, HCO₃, Hg, I, K, Li, Mg, Mn, Mo, Na, NH₄, Ni, NO₃, OH⁻, pH, PO₄, Rb, Sb, Se, Si, SO₄, S₂O₃, Sr, TDS, Ur, Zn. Preliminary evaluation of the results of these analyses began in December, 1995. Deuterium and Oxygen-18 isotope analyses are also being conducted on brine and separated water samples. Condensed steam and non-condensable gas samples have been analyzed for NH₄, Ar, CO₂, He, H, H₂S, CH₄, N, and O.

These data will be used to field calibrate the models and improve their ability to provide reliable predictions of the chemical behavior of the resource (potential for scaling and gas breakout) under a variety of conditions. The calibrated models will provide operators and engineers with the ability to rapidly analyze potential scaling and to test strategies for problem abatement and resource enhancement.

Wellbore scale samples were obtained during well clean-out/milling operations or scraped-off of downhole chemical injection tubing. Samples were selected from the beginning and ending depths of scale formation and at the depth of maximum scale accumulation, for a total of three samples per well. Binary plants utilize pumped production wells and scale does not deposit in the wells. At these sites, scale samples from the heat exchanger were collected during a maintenance cleaning period in which the scale is mechanically removed from the exchanger tubing.

RESEARCH RESULTS

Model calibration has not yet begun.

FUTURE PLANS

Mineral scales will be chemically analyzed at the Nevada Bureau of Mines and Geology, University of Nevada, Reno, using whole-rock analysis and petrogenic trace element analysis using atomic adsorption spectroscopy / inductively coupled plasma/x-ray fluorescence. The scale samples will also be mineralogically analyzed using x-ray diffraction.

Computer simulations of scale formation will be run for each site using GEOFLUID and TEQUIL. Model results will be compared to known conditions, and the performance of GEOFLUID and TEQUIL will be evaluated. Further simulations will be conducted covering a range of brine temperatures and pressures. A detailed discussion of the chemical behavior of the geothermal brine will be conducted for all production fields. Selected sites will be compared for optimal operational conditions and predicted mineral solubility problems in a discussion of the hydrogeochemistry of Nevada's moderate-temperature geothermal fluids.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

After project completion, the results of this research will be communicated to the geothermal industry. The augmented and calibrated computer model should provide geothermal developers and operators with a tool capable to predict gypsum-anhydrite, carbonate, silica, and metal-sulfide scaling in geothermal brines, and assist in the design of optimum production strategies which would minimize production costs. The final results will be useful to all geothermal plant operators exploiting moderate-temperature resources.

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Figure 1. Producing Geothermal Fields Selected for Study

NOBLE GAS ISOTOPE GEOCHEMISTRY OF GEOTHERMAL RESERVOIR FLUIDS

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KEY WORDS

high-temperature reservoir, magmatic gas, noble gases, isotopes, The Geysers, Dixie Valley, Cerro Prieto

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 (HTR, $T > 350^{\circ}\text{C}$) in the NW Geysers was thought to be related to metamorphic or magmatic brines. High gas and HCl, and the uncertainties as to the location, origin, and persistence of the high-gas component in the HTR have made exploitation difficult because the high-gas (and HCl) steam cannot be used in some power plants without expensive modifications. Preliminary study of noble gas isotopes in fluids from the HTR of the Coldwater Creek field have revealed a magmatic origin which probably applies also to the associated high total gas and HCl. Noble gas studies of the other two fields will be made in FY 1996.

PROJECT OBJECTIVES

Many wells in the northwest Geysers produce corrosive gas-rich steam from a high-temperature reservoir (HTR) hampering future development. The objectives of this study at The Geysers are to: 1) identify the origin of gases in the HTR and their potential for persistence, 2) examine the influence these gases may have on the overlying normal-temperature reservoir (NTR), and 3) determine if the HTR extends under the normal Geysers reservoir further south.

The Dixie Valley geothermal field has the highest recorded reservoir temperatures in the Basin and Range province and is located above very thin crust. Our objective at Dixie Valley is to determine through isotopic studies if the origin of the heat is entirely due to deep fluid circulation or is in part magmatic.

Cerro Prieto has been highly stressed by intensive exploitation since 1973 with large changes in reservoir thermodynamic and chemical characteristics. Our objective is to study Cerro Prieto as

an example system for anticipated exploitation-induced changes in reservoir properties expected in U.S. fields in the nearby Imperial Valley (Salton Sea, Heber, and East Mesa) when they are similarly stressed.

Technical Objectives

- The Geysers: (1) Identify the origin of the gases associated with corrosive steam produced in the NW Geysers HTR. (2) Identify a characteristic or unique chemical-isotopic signature of these gases to evaluate the occurrence and distribution of the HTR throughout The Geysers geothermal field. (3) Evaluate the implications of the origin, distribution, and influence of the HTR gases to genetic models of The Geysers.
- Dixie Valley: Indicate the origin of heat from noble gas isotope signatures to enable more complete modeling of the size and resources of this and other Basin and Range systems.
- Cerro Prieto: (1) Determine the fraction and homogeneity of magmatic fluid input to this field. (2) Identify possible deep as well as shallow recharge that occurs in response to drawdown of reservoir pressures. (3) Establish how deep the transfer of heat and volatiles from magma to shallow fluids occurs in order to improve genetic models of the system.

Expected Outcomes

- The Geysers: (1) Minimize or alleviate the uncertainty as to the location, origin, and persistence of the high-gas component in the HTR which has made exploitation difficult. (2) Identify areas throughout The Geysers where the HTR may contribute gas-rich corrosive steam to production as pressures are depleted. (3) Provide a new natural and conservative tracer for early detection of HTR steam intrusion.
- Dixie Valley: Improve knowledge about the origin of the heat supplied to the geothermal system (of great interest to the developers of Basin and Range geothermal fields). Magmatic fluids might indicate larger resources.
- Cerro Prieto: Establish the deep fluid recharge regime in the field. That would improve estimates of resources in Imperial/Mexicali Valley geothermal field.

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 (e.g. ^{36}Ar) origin can be readily identified (e.g. Lupton, 1983; Kennedy *et al.*, 1985; Hiyagon and Kennedy, 1992). We plan to also analyze $\delta^{13}\text{C}$ in CH_4 and CO_2 as a relatively durable indicator of deep temperatures.

RESEARCH RESULTS

Noncondensable gas (NCG) samples from eleven Geysers production wells and one sample of injection liquid were collected for noble gas studies from the Coldwater Creek steam field (CCPA#1) and analyzed in the noble gas laboratory, Center for Isotope Geochemistry, Lawrence Berkeley National Laboratory.

All production wells sampled in this study are enriched in ^3He with helium isotopic compositions ranging from 6.6 to 8.3 Ra. We also found that, (1) the highest $^3\text{He}/^4\text{He}$ ratios occur in fluids produced from the HTR, (2) helium isotopic compositions are correlated with the radiogenic $^{40}\text{Ar}/^4\text{He}$ ratio, total helium to noncondensable gas ratios, ^{36}Ar concentrations, and the ratio of total helium to atmospheric noble gases, and (3) He-Ar abundance correlations require three distinct fluid components influencing gas composition in the NW Geysers (Kennedy and Truesdell, 1994).

Steam with the highest $^3\text{He}/^4\text{He}$ ratio is from well Pratti 37. This steam also has the lowest ^{36}Ar showing that there is almost no atmospheric influence. Steam samples from Pratti 37 have also had the highest total NCG and highest HCl of the production field (data from CCPA). Steam from this well apparently has almost exclusively magmatic noble gases and possibly other magmatic gases as well. In addition, the Pratti 37 steam has a $^3\text{He}/\text{CO}_2$ ratio ($\sim 4 \times 10^{-10}$) comparable to the best estimate for the source of mid-ocean ridge basalts (Marty and Jambon, 1987).

These analyses have consequences for the evolution of The Geysers reservoir. The sharp boundary between strongly magmatic steam from Pratti 37 and more ordinary steam confirms the hypothesis of Truesdell *et al.* (1993) that the NW Geysers reservoir is distinguished from those in the Central and SE Geysers by the lack (in the NW) of saturated liquid layer at the bottom, and that without such a layer, lateral steam flow and large-scale convection could not occur. In addition, the persistence of the near-magmatic gas and its similarity in composition with mid-ocean ridge basalts in the HTR supports genetic models which invoke heating by recent emplacement of magma (Truesdell, 1991; Truesdell *et al.*, 1993; Williams *et al.*, 1993) and indicates that the degassing of the magma is a continuing process.

This study also suggests that wells containing the high-temperature reservoir gas component can be distinguished from gases derived from the normal-temperature reservoir (like those of the SE Geysers) on the basis of total helium to noncondensable gas ratios. Our preliminary results indicate that wells with an HTR component have He/NCG ~ 2.5 times greater than that in NTR

steam. This may assist the detection of HTR steam migrating into the southern reservoirs from below.

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 produced 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.

Methods used at The Geysers will be applied in much more limited studies of Dixie Valley and Cerro Prieto. Because more is known of reservoir processes in these fields, the noble gas isotope studies can be more focused.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Calpine Corporation Unocal Geothermal	Origin of production gas in NW Geysers and potential for production of corrosive steam in SE Geysers.
Central California Power Agency	Origin of production gas in NW Geysers.
Northern California Power Agency	Potential for production of corrosive steam in SE Geysers.
Oxbow Energy Co.	Indication of the origin of heat and the size of the resource.

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ADVANCES IN GEOTHERMAL RESERVOIR SIMULATION

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KEY WORDS

numerical modeling, automatic history matching, coupled processes.

PROJECT BACKGROUND AND STATUS

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

PROJECT OBJECTIVES

The objective of this research is to improve the power and utility of geothermal reservoir simulation as a robust and accurate engineering tool, by developing enhancements and novel applications of our general-purpose reservoir simulator TOUGH2 (Pruess, 1991).

Technical Objectives

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

Expected Outcomes

- More powerful numerical simulation capabilities.
- Improved evaluation and development of geothermal resources.
- Enhanced energy production and reservoir life.

APPROACH

In close interaction with the large TOUGH/MULKOM user community, we continue to enhance code capabilities and provide support for cutting-edge applications.

RESEARCH RESULTS

A version of our general-purpose reservoir simulator TOUGH2 specially adapted for PCs was released to the public through DOE's Energy Science and Technology Software Center (ESTSC; Antunez *et al.*, 1995). A module of preconditioned conjugate gradient solvers for TOUGH2 was released through ESTSC, making possible the solution of large problems ($\geq 10,000$ grid blocks) on PCs (Moridis and Pruess, 1995). A powerful inverse version of TOUGH2, developed primarily under nuclear waste funding and dubbed "ITOUGH2," was adapted and applied to geothermal reservoir modeling. Automatic history matching of geothermal field performance was demonstrated (see Fig. 1; Finsterle and Pruess, 1995a, b). The application of enhanced versions of TOUGH2 including dissolved solids and non-condensable gases was demonstrated (Battistelli *et al.*, 1995a, b; Oldenburg *et al.*, 1995). The description of multiphase flows in heterogeneous media was enhanced with a novel "phase-dispersive" flux term (Pruess, 1995b).

FUTURE PLANS

We plan continued development efforts for TOUGH2, and release of additional modules, to maintain the code in the forefront of general-purpose reservoir simulators. Applications of geothermal reservoir simulation benefit from the fact that much of the continuing development of TOUGH2 capabilities is now supported by DOE programs in the nuclear waste and environmental areas.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The TOUGH workshop at LBNL attracted 100 participants from 10 countries (Pruess, 1995a). The TOUGH and TOUGH2 reservoir simulation programs are currently in use by approximately 150 organizations in 22 countries. Our research results are being presented at conferences and in technical journals.

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"Inverse" Modeling

Figure 1. The inverse modeling process uses the mismatch between predictions from a numerical reservoir model and field data to automatically re-adjust model parameters, until model calibration (history match) is optimized.

LINEAR OPTIMIZATION OF NATURAL STATE GEOTHERMAL RESERVOIRS

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KEY WORDS

simulation, linear optimization, natural state, native state

PROJECT BACKGROUND AND STATUS

In simulating a geothermal reservoir, petrophysical properties and production areas are estimated and a numerical model built. A natural state history match of a reservoir must be conducted prior to production forecasts. The natural state is the thermodynamic state of the geothermal reservoir at discovery, where heat and fluid fluxes are at assumed pseudo-steady state conditions. Geothermal reservoir engineers spend countless hours of simulation time to model the native state. It has been reported that up to 60% of actual project time is related to achieving natural state history match.

History matching has been optimized by the use of merit functions and optimization schemes in petroleum engineering and hydrology simulations. These schemes have not been used in geothermal simulations. The application of this technology and a working knowledge of geothermal reservoirs would give the geothermal industry a time and money saving tool. We proposed to apply a linear optimization routine to geothermal reservoir natural state history matching.

The scheme has been applied to a simple geothermal reservoir model to test the principle. The functionality of the reservoir description coupled with implicit reservoir property relationships has proved to be difficult to establish with one set of rules in linear optimization. We believe this is due to the large change in volume during the boiling of water in the reservoir. Testing and modification of algorithms and matrix solvers has expanded the scope of this problem from the initial problem statement.

PROJECT OBJECTIVES

Technical Objectives

- Develop linear optimization techniques for geothermal natural state reservoir simulation.
- Demonstrate application of techniques to actual geothermal reservoirs.

Expected Outcomes

- User friendly code easily adapted to commercial simulators.
- Significant reduction in time required for natural state history matches.

APPROACH

We started out with a linear assumption, without knowing whether a geothermal native state numerical model is linear or nonlinear. To incorporate this idea, reservoir parameters in the matching process are related to a merit function which is in turn a function of the errors from the observed to the calculated data. The reservoir parameters to be matched strictly included the rock properties, regional saturations, and regional temperature distributions. The data is compiled with a least squares technique and solutions are determined with linear programming techniques.

The initial data set used for this study includes a "Wairakei" type reservoir, the Stanford #6 problem. The problem specifications are assumed to be observed data. The permeability, water saturation, and temperature are varied in the optimization to achieve a history match. Regions are selected from this model and properties in these regions are modified by a random number generator for a select 'bracketed' set of variables (P, T, K). The data set is run 10 - 30 times with a new set of random variables generated each time. This simulated set is compared to the observed data, and an optimization routine performed to minimize the residual error. The optimized set is then compared with the observed data.

The data set of regional variables, calculated results, and observed results (from the pre-modified data set, used as a 'truth') is used for the linear optimization. In order to establish a linear set, the errors are used. These errors are $(y_i^{obs} - y_i^{calc})$. The model form for functional dependence in a linear form would be

$$e_i = \sum_{j=0}^J a_{ij} x_j \quad (1)$$

These are in turn used with a merit function. The merit function is of the form

$$D_i^I \equiv E \frac{I}{i} - \sum_{j=0}^J a_{ij} x_j^I \quad (2)$$

The least squares technique would minimize

$$\sum_{i=1}^N (D_i^x)^2 \quad (3)$$

A set of simultaneous linear equations is generated with the data set providing the coefficients a_{ij} . A set of regional parameters, x_j , that will satisfy a history match is determined by linear optimization techniques. The simplex method is employed for linear optimization. The simplex method uses the set of linear equations established with the least squares technique, including the boundry set for the regional parameters, and determines a set of parameters for the history match.

A linear optimization approach was chosen as opposed to a non-linear approach due to the simpler and more systematic solutions. The establishment of a linear set of equations based on observation versus a set of calculated results would reduce the iterative process required for natural state history matching. This methodology has been established in other applications regarding fluid flow in a porous medium and should apply to geothermal reservoirs.

RESEARCH RESULTS

The first pass at this technique involved the match of three permeability variables, which were well defined in separate regions of the reservoir. The data set proved to generate a history match with a 2-5% deviation from observed data. This technique was then applied, with the same data set, in a spreadsheet format. Again, the results were very favorable. Once the data set was manipulated to more complicated history matches, the technique proved to not be very robust. As stated earlier, this inconsistency is believed to be related to the large change in volume during boiling of water.

At the present time, non-linear techniques are being applied to investigate this problem. The testing of modifications to the linear equations has also provided some favorable results. The problem with reservoir specific modifications to the linear optimization techniques is that this may be leading to neural network type programming.

FUTURE PLANS

Future plans are to establish suitable methods in order to do natural state history matching of geothermal reservoirs. These methods will then be tested with a real geothermal reservoir. The linear optimization work is D.E. Simpson's thesis work at Colorado School of mines and will be completed in May 1996.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

There is some interest of this work by S-Cubed, a geothermal consulting company. Industry contacts and technology transfer will be initiated in the spring of 1996. This work is also planned to be submitted for publication and presentation at the fall Geothermal Resources Council (GRC) conference.

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DEVELOPMENT OF AUTOMATIC HISTORY MATCHING TECHNIQUES FOR GEOTHERMAL APPLICATIONS

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KEY WORDS

numerical modeling, inverse modeling, calibration, parameter estimation, sensitivity analysis

PROJECT BACKGROUND AND STATUS

The project is developing automatic history matching techniques for the multiphase flow simulator TOUGH2 (Pruess, 1991). Using inverse modeling techniques, the numerical model of a geothermal field is automatically calibrated against data obtained during testing or exploitation. The advantage of inverse modeling procedures is that they overcome the time and labor intensive tedium of trial-and-error model calibration. Furthermore, effective, model-related parameters are determined on the scale of interest. This ensures that the reliability of subsequent simulations for predicting the future reservoir performance can be greatly improved.

Inverse modeling capabilities for the TOUGH2 simulator have been previously developed for applications in nuclear waste isolation and environmental sciences. The ITOUGH2 code ("Inverse TOUGH2") (Finsterle, 1993) allows one to estimate TOUGH2 input parameters based on any type of observation for which a corresponding TOUGH2 output can be calculated. Furthermore, a detailed residual and error analysis is performed, and the uncertainty of model predictions can be evaluated. Successful application of the code to a variety of multiphase flow problems on different scales has been demonstrated (Finsterle and Pruess, 1994, 1995a,b). The ITOUGH2 code is continuously revised and updated to account for newly incorporated physical processes and to improve the robustness and effectiveness of the optimization algorithm.

PROJECT OBJECTIVES

The general objective of the project is to adapt the ITOUGH2 code to the specific needs of geothermal applications and to demonstrate its usefulness for the calibration of large geothermal reservoir models.

Technical Objectives

- Develop a robust and efficient inverse modeling code, able to handle the strong nonlinearities pertinent to the simulation of geothermal fields. Information relevant to the simulation of geothermal field performance (parameter sensitivity, estimation error, and prediction uncertainty) will be provided. An application of the code aims at demonstrating an integrated approach to history matching, reservoir characterization, as well as prediction and optimization of future field performance.
- Enhance ITOUGH2 to allow for the calibration of data typically observed during geothermal field exploitation (e.g. temperature, flowing enthalpy, liquid/vapor ratio, etc.)
- Enhance ITOUGH2 to allow for the automatic estimation of parameters relevant to the performance of geothermal fields (e.g. heat conductivity, specific heat, etc.)
- Improve the efficiency of ITOUGH2 by parallelization of TOUGH2 simulations in order to enable the calibration of large, three-dimensional models.
- Demonstrate automatic history matching and improved model prediction using data from a geothermal field.

Expected Outcomes

- Fully documented code for automatic model calibration of geothermal reservoir models. The inverse code will be based on the widely used numerical simulator TOUGH2, and made available through standard distribution channels. The application of the program to data from geothermal fields will be demonstrated.
- Automatic history matching of past reservoir performance replaces the previous tedium of trial-and-error model calibration. Parallelization of ITOUGH2 improves the efficiency of the code by a factor as high as the number of parameters being estimated.
- A report and/or user's guide will be written describing the inverse method and applications to synthetic data and field data.
- The source code will be made available to industry and research institutes through DOE's Energy Science and Technology Software Center (ESTSC).

APPROACH

The inverse problem is solved based on a maximum likelihood approach. The Levenberg-Marquardt algorithm is used to minimize the strongly non-linear objective function. The sensitivity matrix is calculated numerically to assure flexibility in the adjustment of ITOUGH2 to updates of the TOUGH2 simulator. While this approach is computationally not very efficient, it is straight-forward to implement a parallel version of ITOUGH2 for fast calculation of the sensitivity matrix. Parallelization will be done in collaboration with the School of Engineering, University of Auckland, New Zealand.

RESEARCH RESULTS

A preliminary version of ITOUGH2 for geothermal applications has been developed. The code has been applied to synthetic data of a geothermal field, and is currently undergoing beta-testing in collaboration with New Zealand researchers. Results have been presented at the 17th New Zealand Geothermal Workshop (Finsterle and Pruess, 1995c, see attached figure). Collaboration with the School of Engineering, University of Auckland, New Zealand, has been initiated regarding parallelization of ITOUGH2.

FUTURE PLANS

After parallelization of the code, ITOUGH2 will be applied to the calibration of a large three-dimensional model of a geothermal field. The code will be further tested and forwarded to the Energy Science and Technology Software Center (ESTSC) for distribution.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal	Automated history matching techniques
Researchers at the University of Auckland in collaboration with industry	Participating in beta testing of ITOUGH2 code and development of field applications

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Figure 1. Calibration and prediction of pressures, temperatures, water and vapor flow rates. Squares are synthetic data points used for calibration. Triangles represent the true system response. Simulation results based on the estimated parameter set are shown as solid lines. Error bands (dash-dotted lines) are calculated using linear error propagation analysis.

STEAM-WATER RELATIVE PERMEABILITY IN GEOTHERMAL ROCKS

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KEY WORDS

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

PROJECT BACKGROUND AND STATUS

Reliable measurement of relative permeability functions for steam-water flows in porous media is of great importance for geothermal reservoir simulators in order to forecast production performance of geothermal reservoirs. Despite their importance, these functions are poorly known due to the lack of understanding of steam-water flows, and the difficulty of making measurements. Traditionally, these functions are borrowed directly from isothermal, immiscible gas-liquid displacement processes. However, use of such functions may not be appropriate because these processes do not involve the two important phenomena pertinent to steam-water flows: heat transfer and phase change.

The first phase of this project involved numerical simulations to estimate the optimal experimental parameters, such as fluid injection rates, length of the core and locations of pressure taps and thermocouples. Experimental conditions were simulated using a commercial thermal simulator and the optimum operating conditions and requirements of a typical laboratory experiment (nitrogen-water and steam-water) were obtained. This stage is finished.

Using simulation results, the second phase was to design and to construct an apparatus with a core holder for experiments at elevated temperatures (140°C). The second phase also included several preliminary experiments to better understand and to verify our numerical results. The core holder is made of high temperature epoxy and plastic materials (a restriction imposed by the X-ray CT scanner). Several preliminary experiments with nitrogen and water have been conducted. In the new core holder design, several pressure taps, thermocouples and heat flux sensors were placed at various locations along the core to measure pressure, temperature and heat losses, respectively. Also, implementation of an extensive data acquisition system for data collection and computer-automation of experiments is in progress. Preliminary experiments will soon be conducted for steam and water at 115°C. With the third and final stage that includes experiments with nitrogen-water and steam-water, our objective to measure relative permeabilities will be accomplished.

PROJECT OBJECTIVES

Technical Objectives

- Determine the correct relative permeability functions for steam-water flows in porous media.

Expected Outcomes

- Improved predictions of geothermal reservoir behavior.

APPROACH

A review of the previous experimental and theoretical studies (see Satik et al., 1995) suggests the use of the steady-state experimental method to determine these functions. In this method, a known ratio of steam and water at a given temperature is injected into a core at a constant rate. A steady-state condition is achieved when injection and production rates become equal for each fluid and also when fluid pressures and temperatures have stabilized. At the onset of a steady state, pressures and temperatures are measured using pressure taps and thermocouples placed at several locations along the core. From these readings, the relative permeability at a given ratio of steam and water is calculated using Darcy's equation modified for multi phase flow. The analysis requires knowledge of the saturation corresponding to the calculated relative permeability value and relies on the existence of a *flat saturation* profile along the portion of the core where the measurements are taken. Next, the injection rate is changed and the previous procedure is repeated until the relative permeability values corresponding to the whole saturation range (from 0 to 1) are obtained.

Effects of heat transfer and phase change will be explored by comparing results obtained from the experiments with steam and water to those with nitrogen and water at various temperatures. Numerical simulations have been used in the design of the experimental apparatus. As an important advantage over previous experimental attempts, our high resolution X-ray CT (Computer Tomography) scanner will be used to obtain accurate saturation profiles as experiments are being conducted.

RESEARCH RESULTS

Our research over the past year has yielded the following very important preliminary results. The numerical simulation results revealed that, owing to the *end-effects* (see Satik et al., 1995 for a detailed discussion), the pressure gradient of the wetting phase (water) would be much less than that of non wetting phase (nitrogen or steam). Thus pressure measurements taken at the inlet and outlet ends of the core may lead to significant errors in the permeability calculations.

1. The maximum core length over which the *end-effects* would dominate for typical laboratory conditions was determined from numerical simulations.
2. Preliminary nitrogen-water relative permeability experiments were conducted for Berea sandstone core samples. The experimental results showed that the *end-effects* would dominate over a core length of 10 inches at a total flow rate of 12 cc/min (Satik et al., 1995). With an increase in the total flow rate, the *end-effects* have been observed to diminish.
3. Preliminary experiments have demonstrated that the X-ray CT scanner is a very useful tool in obtaining accurate saturation profiles. In Figure 1, we show three-dimensional gas (nitrogen) saturation distribution constructed by using X-ray CT data obtained during one of the experiments.
4. Preliminary experiments suggested the need for computer automation of the experiment to collect the data, to control the operation of the apparatus and to analyze the X-ray CT data during or after the experiments.

FUTURE PLANS

This research project is under direction of Research Assistant Willis Ambusso, Dr. Cengiz Satik and Prof. Roland N. Horne. We have also engaged the services of two undergraduate students to assist in the experimental work. In addition we are collaborating with scientists from the other research groups within Stanford University. Experimental results and discussion are posted regularly to the Stanford Geothermal Program web page <http://ekofisk.stanford.edu/geotherm.html>.

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Figure 1. 3-D Gas saturation distribution obtained by using X-ray CT scanner.

BOILING AND CONDENSATION IN GEOTHERMAL RESERVOIRS

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KEY WORDS

injection, vaporization, condensation

PROJECT BACKGROUND AND STATUS

A numerical pore-network model has been developed to investigate phase change in porous media. The model includes effects of heat conduction from grains to the fluid and is being used to establish how the region of phase change develops with time.

In addition we have developed similarity solutions that describe the growth of liquid-saturated zones around well bores as liquid is injected. These similarity solutions are particularly useful as they help expose the fundamental controls governing the fraction of injected liquid that can vaporize and be produced from nearby production wells. However, these solutions are highly idealized and only apply to certain injection scenarios such as constant rate injection in a radial geometry. In order that other rates and geometries of injection may be examined, we are also developing a generalized numerical model.

The research is being conducted using a number of innovative techniques including laboratory and theoretical methods. Experimental work has commenced on the injection of water into a fracture. The laboratory apparatus has been constructed and initial experiments have been performed. We are currently focusing our attention on the case in which no boiling occurs in order to isolate the effects of fluid dispersion resulting from the fracture roughness. This will enable us to analyze the effects of phase change on the morphology of a propagating liquid-vapor interface in subsequent experiments.

PROJECT OBJECTIVES

Technical Objectives

- Gain a fundamental understanding of the controls upon the vaporization (or condensation) of water (or steam) as fluid is introduced into a vapor- (or liquid-) dominated geothermal reservoir.

Expected Outcomes

- A numerical model that will help reservoir engineers to forecast field performance and to estimate likely thermal breakthrough times of injected water.

APPROACH

The study of phase change in geothermal reservoirs is pertinent to both vapor-dominated and pressure-depleted regions of liquid-dominated reservoirs. Most reservoirs are extensively fractured and as fluid is injected into a vapor-dominated rock, some of the liquid boils. Furthermore, some of the liquid and newly formed vapor migrates into the porous rock bounding the fractures.

At present there is insufficient knowledge of the fundamental behavior of fluid flow between porous media and fractures to develop a model of the coupled problem. Hence, in this research project, we are initially focusing on the end-member problems of fluid migration and phase change within (i) a porous medium and (ii) a fracture.

- (i) In the study of phase change within porous media, a number of novel theoretical approaches are being pursued. A pore-network modeling technique is being used to analyze the complex flows resulting from steam migration into a liquid-filled lattice. Using this technique we are able to study how the morphology of the vapor-liquid transition zone depends upon the degree of heterogeneity in the porous medium, the latent heat and the rate of supply of fluid. In addition to this theoretical method, one-dimensional similarity solutions are being developed in order to determine how the rate of boiling (or condensation) depends upon injection rate, reservoir superheat and geometry.

Development of laboratory methods are also planned. In particular, experiments in both glass micromodels and real geothermal rock samples will be conducted in order to improve our understanding and to verify the results obtained from the theoretical studies.

- (ii) The study of liquid injection into a fracture is following both theoretical and experimental approaches. We are initially investigating the fluid flow within a single fracture and have constructed a transparent Hele-Shaw cell in order to visualize the flow. The series of experiments will include liquid injection into (i) a cold, dry fracture, (ii) a cold, liquid-filled fracture, (iii) a hot, liquid-filled fracture and (iv) a hot, vapor-filled fracture. These results will reveal the fundamental flows in rough-walled fractures within liquid- and vapor-dominated geothermal reservoirs.

A number of previous theoretical studies have been conducted for the case without phase change and our experimental results will initially be used to verify these findings. The situation in which boiling occurs is much more complex and numerical simulations will be required.

RESEARCH RESULTS

A number of important results have been obtained during the last year.

1. The propagation of the transition zone was found to be highly unstable and form fingers if steam migrates into a liquid-dominated zone. However, the growth rate of the steam fingers depends upon the latent heat of condensation. Hence, the liquid-vapor interface is more stable when the transition zone is at lower pressures and temperatures.
2. The fraction of liquid that vaporizes varies non-monotonically with injection rate. At low rates of injection, thermal diffusion can become important and reduce the vaporizing fraction; that is, more of the heat from the hot rock is used to heat the water surrounding the injection well. At high rates of injection the pressure, and hence temperature, at the liquid-vapor interface can increase significantly so that vaporizing fraction decreases. It therefore appears that an optimal injection rate exists for injection from a radial source.
3. The morphology of a liquid-vapor transition zone within a fracture is very different from that within a porous medium. Fingers of liquid tend to spread rapidly away from the injection site. The rapid movement of liquid along preferential pathways within a uniform fracture indicate that the danger of premature thermal breakthrough from an injection well is greater than had previously been envisaged.

FUTURE PLANS

We will extend the research projects along the lines discussed in the previous sections. This research is being conducted by Acting Assistant Professor Shaun Fitzgerald and Research Associate Dr. Cengiz Satik. We have recently engaged the services of three undergraduate students to assist in experimental work. In addition we are collaborating with scientists from USC, LBL and the University of Cambridge.

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DEVELOPMENT OF AN IMPROVED MATRIX-FRACTURE INTERACTION TERM FOR SIMULATING NATURALLY FRACTURED RESERVOIRS

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KEY WORDS

dual porosity, fractured media, numerical simulation, dual continua, Warren and Root

PROJECT BACKGROUND AND STATUS

Simulation of fluid flow in fractured media is among the most challenging problems faced in geothermal reservoir engineering. Due in large part to complex fracture geometries, irregular fracture spacing, and lack of detailed information regarding contact areas between rock matrix and fracture, a dual continua approach is most frequently taken to describe storage and flow in fractured reservoirs. In dual continua formulations, specific details of the reservoir (detailed geometry, for example) are not required; rather, averaged properties are used. Furthermore, the numerical grid blocks are typically much larger than the rock matrix blocks, so effective properties (such as an effective surface area for fluid exchange between fractures and matrix) are used. While these assumptions facilitate the simulation of fluid flow in fractured reservoirs, the use of multiple continua remains numerically intensive. For example, it has been shown that 7 nested shells are required in the Multiple Interacting Continua (MINC; Pruess and Narasimhan, 1982) formulation in order to adequately resolve pressure and saturation gradients between the fracture and matrix domains (Zimmerman et al., 1992).

Many of the numerical models used to simulate flow in fractured media invoke variations on the Warren and Root (1963) model of fractured reservoirs. The Warren and Root model is a dual continua model in which one continuum contains the fracture domain and the other contains the matrix domain. Interaction between the two is assumed to be linearly dependent on the pressure difference between the (numerical) grid block fracture pressure and average matrix pressure. This linear dependence has been referred to as the "pseudo steady state assumption."

The assumption of pseudo steady state interaction between the two continua is valid only at long time and for slightly compressible fluids. There is a need for an improved matrix-fracture term for use in dual continua models that correctly resolves the matrix pressure gradient over all time scales. Work began in FY 95 to identify an improved matrix-fracture interaction term for this purpose.

PROJECT OBJECTIVES

The goal of this project is to identify a simple functional form that correctly describes the pressure transient in the rock matrix arising from variations in pressure in the fractures. Similar functional forms describing saturation and thermal transients will be developed as well.

No specific form of function is required. One characteristic of interest would be that the function be readily differentiable (it is the pressure gradient within the rock matrix that describes flow between fracture and matrix). It would also be beneficial to identify a functional form that utilizes variables already calculated in Warren and Root-style dual continua models, in order to minimize the amount of code modifications required.

Technical Objectives

- Develop a function that accurately describes pressure transients in the rock matrix for a single phase, slightly compressible, isothermal fluid.
- Develop a function that accurately describes saturation gradients in fractured media.
- Develop a similar expression for thermal gradients in fractured media.

Expected Outcomes

- Improvement in the treatment of pressure, saturation, and thermal gradients in fractured reservoir simulators will improve our ability to estimate long-term behavior of geothermal resources and predict reservoir response to injection. Furthermore, if these modifications can be implemented in Warren and Root type simulators, extensive numerical computational savings can be realized over other means of simulating fractured domains (e.g., MINC, or fine grid simulation).

APPROACH

The approach taken in this study was to identify analytical solutions to various test cases in the literature, and to construct functions that mimic those analytical solutions. In doing so, we anticipate identifying a function that a) mimics the analytical solution, b) utilizes variables already available in "conventional" dual porosity simulators, and c) is readily implemented in existing numerical models. We have restricted this work to single phase, slightly compressible, isothermal fluids thus far.

RESEARCH RESULTS

Several possible functions have been considered during the first portion of study. The most promising functional form identified thus far that describes the pressure in the matrix as a function of position is

$$P(\eta) = P + (P_f - P) e^{-\frac{\eta - a}{D}}$$

Only parallelepiped rock matrix blocks have been considered thus far; therefore, η is the distance from the centroid of the rock matrix (effectively a radial distance) and a is the effective radius of the matrix. P_f and P are the fracture and average matrix pressures, respectively. D is a characteristic distance associated with a change in pressure, and is related to the diffusivity of the medium and time by

$$D = \left[\frac{k\tau}{\phi\mu c} \right]^{1/2}$$

This function has been tested against several analytical solutions. One such comparison is given in Figure 1. This problem represents a step function change in pressure in the fracture, and the corresponding pressure transient in the rock matrix. The entire system is initially at a constant pressure of 1000 kPa. At $t=0$, the fracture pressure is reduced to 100 kPa. Other data for the rock matrix are: $k = 10^{-16} \text{ m}^2$, $\phi = 0.1$, $\mu = 10^{-3} \text{ Pa-s}$, $c = 10^{-6} \text{ Pa}^{-1}$. The diffusivity is then calculated as $10^{-6} \text{ m}^2/\text{s}$.

The solutions shown in Figure 1 are truncated at $\eta/a = 0.9$, since we are only concerned with the pressure profile at the fracture-matrix interface (i.e., where the pressure gradient must be accurately resolved). This figure shows that excellent agreement is obtained with the test function on this particular problem. The largest errors near the interface occur at small times. Calculated pressure gradients at the fracture-matrix interface agree within about 25% at $t=10^4 \text{ sec}$ (the agreement improves at larger time); in contrast, the pressure gradient calculated from the pseudo steady state assumption is low by a factor of 40.

FUTURE PLANS

This function was implemented in an existing dual continua simulator, and is being tested and compared against fine-grid simulation. Additional testing is planned for single phase, slightly compressible, isothermal fluids before attempting to incorporate multi-phase simulations. For example, the functional form given above is known to be inaccurate for non-monotonic behavior at the fracture-matrix interface, and a correction term will be required. This project will continue through FY-96 as outlined above.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Several discussions have been held with geothermal operators and researchers. We anticipate making a modified version of TETRAD available for distribution in FY-96.

Organization(s)	Type and Extent of Interest
UNOCAL, PG&E, Calpine, Comisión Federal de Electricidad CFE, Stanford	Interested in new formulation and new version of TETRAD

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Figure 1. Comparisons between analytical solutions and a test function for step change in fracture pressure at $t=0$. Differences are largest at small time. Solid lines are the analytical solutions.

WATER INJECTION INTO FRACTURED VAPOR-DOMINATED RESERVOIRS

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KEY WORDS

reinjection, The Geysers, reservoir heterogeneity, numerical modeling.

PROJECT BACKGROUND AND STATUS

Water injection is an extremely important tool for reservoir management and condensate disposal at The Geysers. It gives rise to complicated fluid flow and heat transfer process, with two-phase flow of boiling water-steam mixtures, primarily along fractures, and strong latent heat effects. The design and optimization of injection operations require reliable and robust numerical modeling techniques, which must be based on a sound understanding of the underlying physical processes. Past research, summarized by Pruess (1995a), has clarified water injection behavior for depleted vapor zones in porous media. However, large-scale permeability at The Geysers is fracture-dominated. Further work is needed to understand water injection into hot fractures containing steam at relatively low pressures, of order 10 bars.

PROJECT OBJECTIVES

The objective of this research is to develop a better understanding of fluid flow and heat transfer processes during water injection into fractures, and to provide robust and accurate engineering tools for the design of injection systems.

Technical Objectives

- Understand and quantify the role of fracture heterogeneity in injection.
- Improve description of physical processes during injection.
- Develop efficient numerical capabilities for simulating injection.

Expected Outcomes

- Improved description and design of injection at The Geysers.
- More powerful numerical simulation capabilities.
- Enhanced energy production and reservoir life.

APPROACH

Our general-purpose multiphase simulator TOUGH2 (Pruess, 1991), enhanced with a set of preconditioned conjugate gradient solvers for large problems (Moridis and Pruess, 1995), is being applied to investigate effects of water injection into hot fractures containing superheated steam. Improvements to the code continue to be made to (i) describe the important physical processes during injection more accurately, and (ii) more realistically treat fracture heterogeneity. We are also collaborating with Stanford University researchers on a study of basic issues of fluid and heat flow during water injection into fractures.

RESEARCH RESULTS

A review of numerical simulation of water injection into vapor-dominated systems was presented at the World Geothermal Congress (Pruess, 1995a). Water injection into horizontal fractures gives rise to the development of very extensive boiling zones with non-monotonic temperature profiles (see Figure 1). The fraction of injected water vaporized decreases with increasing injection rate (see Figure 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 (see Figure 3). Geostatistical techniques can be used to generate spatially correlated fields for representing aperture distributions of natural heterogeneous fractures (Figure 4). Initial simulations of water injection into "cold" fractures (ignoring vaporization effects) demonstrated phenomena observed in unsaturated fractured zones, such as preferential flow paths, localized ponding, and bypassing (Figure 5).

FUTURE PLANS

We plan to investigate the behavior of vaporizing injection plumes in realistic representations of natural heterogeneous fractures (Pruess, 1996). Laboratory experiments are being planned to examine gravity-driven water flow in sub-vertical fractures (Su et al., 1995). Effective parameter and process descriptions for scale-up from laboratory to field scale are being developed (Pruess, 1995b).

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Our research results are being presented at conferences and in technical journals. The TOUGH and TOUGH2 reservoir simulation programs are currently in use by approximately 150 organizations in 22 countries.

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Figure 1. Simulated results for cold water injection at a rate of 10 kg/s into a hot horizontal fracture ($T = 240^\circ\text{C}$, $P = 0$ bars). Fracture permeability is 10 darcy. (a) shows flow rate and saturation profiles after 10^4 seconds, while (b) gives temperature profiles at 3 different times.

Figure 2. Fraction of injected water vaporized as a function of time.

Figure 3. Vapor pressure lowering (VPL) effects for water injection into a depleted matrix block.

Figure 4. Stochastic permeability field for representing a heterogeneous fracture. Correlation lengths are 0.2 m (horizontal), 0.1 m (vertical).

Figure 5. Water saturations in the medium of Fig. 4, shown 4.6 days after releasing a square plume of $8 \times 8 \text{ m}^2$ size from the top, center of the domain.

FLUID FLOW CHARACTERISTICS OF FAULT ZONES: THE FAULT ATLAS

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KEY WORDS

fault, core, damaged zone, protolith, permeability, fluid flow simulation

PROJECT BACKGROUND AND STATUS

Exploration for geothermal resources concentrates on locating zones of enhanced permeability in hot rock. Because drilling and exploration activities typically target faults and fault-related fractures, improved understanding of fault architecture, geometry, and fluid flow properties can help guide the geothermal exploration or development geologist.

Faults and associated fractures can both create zones of enhanced permeability and serve as impermeable barriers that create reservoir compartments. For example, faults often produce intense fracturing that, depending upon the geologic history and mechanical character of the fractured rock, could cause a single fault to act as a barrier, a conduit to flow or as a combined barrier-conduit system (Smith et al., 1990; Forster et al., 1993; Scholz, 1993).

Our own field work and observations of others (Forster and Evans, 1991; Scholz, 1993) indicate that faults typically comprise three distinct, and mappable, structural components: a core or gouge zone, a heavily fractured damage zone, and less fractured protolith (Fig. 1). Each component of the fault architecture is mechanically significant and can form a distinct fluid flow unit (Sibson, 1981; Chester and Logan, 1987; Smith et al., 1990; Forster and Evans, 1991; Caine et al., 1993; Hippler, 1993; Scholz, 1993). The sealing characteristics of the core control reservoir compartmentalization while the fracture "haloes" of the damage zone yield regions of enhanced permeability that may be exploited for improved reservoir production or lead to premature injection breakthroughs. The less intense, but more pervasive, fracture networks found in the surrounding protolith may lead to enhanced reservoir storage but only minor geothermal fluid production.

PROJECT OBJECTIVES

The objective of this project is to map fault and fracture geometry and determine the porosity and permeability of components of exhumed faults. This work will lead to the compilation of a "Fault Atlas" that will describe the geometry and porosity/permeability relationships of faults from different tectonic environments.

Technical Objectives

- Determine the geometry and fluid flow properties of faults from different tectonic environments.
- Simulate geothermal fluid flow along permeable zones defined by mapping.
- Publish results as a fault atlas

Expected Outcomes

- Provide 'ground truth' for modeling geophysical and reservoir engineering responses of fault zones.
- Enhance reservoir models to improve the efficiency of exploration and development.

APPROACH

Well-exposed examples of fault zones will be studied to develop a Fault Atlas. A typical entry in the Atlas will include outcrop photographs, thin-section photos, the results of detailed geological and architectural mapping, permeability and porosity test results, mineralogical studies, and fracture characteristics. These data form the basis for developing a representative model of the fault exposure. Once a fault model is developed, a series of numerical simulations will be used to illustrate how the specific, internal characteristics of the fault might influence fluid flow within and near the fault.

Our first data set has already been developed at the Stillwater Fault in Dixie Valley, Nevada (near the Dixie Valley geothermal field) during work on a project funded by the U.S. Geological Survey. One new site will be chosen for detailed study this year.

RESEARCH RESULTS

The Stillwater fault zone has major mappable components that correspond with the generalized model shown in Fig. 1. These components not only reflect different deformational processes, they have experienced different fluid flow histories. The protolith for this fault is a granodiorite. Silicification has principally affected the fault core where most of the deformation has been concentrated. The damage zone is highly fractured and veined and was produced by multiple deformation events.

FUTURE PLANS

The field work on the Stillwater fault zone has been completed and will be presented to the geothermal community, probably at the Geothermal Resources Council meeting in 1996. We are

searching for another well-exposed fault zone, associated with an active geothermal system, that can be used to continue this work.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Major Oil Company	Funding similar fault studies in Greenland

We will be establishing a web site, accessible through the ESRI Home Page, (<http://www.esri.utah/index.htm>), for updates on the progress of the research.

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Figure 1. A) A conceptual model of a fault zone with protolith removed to reveal the anastomosing, interleaved character of the core and damaged zone (after Smith et al., 1990). B) Permeability as a function of position in a fault zone at an effective confining pressure of 4 Mpa (Forster and Evans, 1991). Core diameters are indicated by filled circles (5.08 cm) and open circles (2.54 cm).

FRACTURE PERMEABILITY OF THE MATALIBONG-25 COREHOLE, TIWI GEOTHERMAL SYSTEM, PHILIPPINES

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KEY WORDS

fractures, fluid entry, fluid inclusions

PROJECT BACKGROUND AND STATUS

The Tiwi geothermal field (Gambill and Beraquit, 1993; Alcoraz et al., 1989) is located on the Bicol peninsula of Luzon. It occupies the NE flank of Mt. Malinao and extinct Quaternary stratovolcano. The field has been in production since 1979 and presently has an installed capacity of 330 Mwe. In 1992, Unocal completed the Matalibong-25 (Mat-25) corehole as a monitoring well in the Tiwi geothermal system. Continuous core was collected from a depth of 2563 feet to total depth of 8000 feet. Unocal has made the core available to us for investigation of fracture permeability and fluid inclusion systematics. Early in 1995, the core was logged with particular attention being paid to the orientation and permeability of fractures. At that time, samples were also collected for thin-section and fluid inclusion investigations. The fluid inclusion analysis has not been completed; however, information from the investigation is being presented at the 1996 Stanford Geothermal Reservoir Engineering Workshop (Nielson et al., in press). The project should be completed in the first quarter of 1996.

PROJECT OBJECTIVES

Continuous core into a geothermal reservoir associated with andesitic volcanism in an island arc setting provided a unique opportunity to investigate the character and distribution of permeability controls.

Technical Objectives

- Document the character and distribution of permeability.
- Analyze fluid inclusions to determine the temperature and chemistry of fluid circulating through the geothermal reservoir.

Expected Outcomes

- Increased efficiency of exploration and development drilling at Tiwi and geothermal fields in similar geological environments.

APPROACH

The cost of this work was shared between Unocal Corporation (Philippine Geothermal Inc.) and the U.S. Department of Energy. The lithology and hydrothermal alteration of the core from Mat-25 had been described by Unocal geologists. The core was logged in the field concentrating on the frequency and dip angles of both sealed veins and permeable features (fluid entries). At that time, samples of the core were collected for petrographic and fluid inclusion investigations.

RESEARCH RESULTS

Throughout the 5,413 feet of core, the fractures were classified as sealed versus those that were permeable and, we assume, are geothermal fluid entries. Since the core was not oriented, only fracture frequency and dip as a function of depth was determined. The fractures are principally steeply dipping and have a measured density of up to 0.79 per foot in the vertical well (Fig. 1). Below 6500 feet depth, the fracture intensity decreases dramatically and measured and fluid inclusion temperatures also decrease. The highest recorded temperatures are found at a depth of 6500 ft.

Common vein minerals include quartz, calcite, and anhydride from depths of 3768 to 7778 ft. Homogenization temperatures within this interval ranged from 195° to 325°C, while the salinities ranged from 0.0 to 3.7 equivalent weight percent NaCl. Examination of the data demonstrates a close relationship between the composition and temperature of the inclusion fluids and depth within the well. Above about 6100 feet (1860 m), where volcanic rocks dominate, the maximum homogenization temperatures range from 280 to 300°C. Salinities in this interval are less than about 1.7 weight percent NaCl equivalent. In contrast, maximum temperatures in samples from the lower part of the well where sandstones dominate typically exceed 300°C while salinities are greater than 2.5 equivalent weight percent NaCl. Evaluation of the salinity-temperature relationships suggest that the observed variations reflect complex mixing of condensate, seawater, and meteoric fluids. An $^{39}\text{Ar}/^{40}\text{Ar}$ age indicates that the hydrothermal system has been active for at least 320,000 years.

FUTURE PLANS

This project should be completed in the first quarter of 1996. A summary paper is being presented at the Stanford Reservoir Engineering Workshop.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Unocal Corporation	Cost-share Sponsor

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Figure 1. Frequency of veins/entries, MAT-25

CHARACTERIZATION OF SUBSURFACE FRACTURES BY ANALYZING MICROEARTHQUAKES

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KEY WORDS

Coso geothermal reservoir, crack orientation, crack density, shear-wave splitting, microearthquake data

PROJECT BACKGROUND AND STATUS

Beginning January 1993, Department of Energy and two members of Geothermal Technology Organization (GTO) (California Energy Company, Inc. (CECI) and the US Navy) co-sponsored a three-year project *Characterization of subsurface fracture patterns in the Coso geothermal reservoir by analyzing shear-wave splitting from microearthquake*. The main goal of the project is to develop a new and cost-effective geophysical technology for exploration, identification of fracture orientation, fracture density in the Coso, California, geothermal reservoir. The project was carried out in Wave Propagation Laboratory, Department of Geology, University of North Carolina at Chapel Hill.

Shear-wave splitting due to stress-aligned cracks in the crust has been widely observed in a variety of earthquake recordings or controlled-source seismic data. It has also been recognized that the polarization of the leading split shear wave is usually parallel to the local strike of cracks (or normal to the direction of the minimum horizontal stress), and the time delay between fast and slow shear waves is directly related to the intensity of crack-induced anisotropy in the medium (see also Crampin 1987, Crampin and Lovell 1991, Crampin 1993). Therefore, the interpretation of shear-wave splitting is an important diagnostic tool to determine the direction and evaluate the bulk density of subsurface fractures in hydrocarbon or geothermal reservoirs (Sachpazi and Hirn 1991, Sato et. al. 1991).

The Coso geothermal area is a very active seismic zone, averaging 20 microearthquakes per day, nearly half of them associated with the geothermal field activity (Malin 1994). Since 1990 Duke University has operated a three-component seismographic network with the support from CECI and China Lake Naval Air Weapons Station, US Navy (Alvarez 1992). During the past two years, we have clearly identified the shear-wave splitting from the numerous seismic data recorded by this seismic network. A shear-wave splitting catalog has been accumulated to extract information of fracture strike and fracture density of the Coso geothermal reservoir.

By December 1995, we determined the fracture orientation around most seismological stations in the Coso geothermal field, and have obtained the three-dimensional fracture density distribution

of the field by tomographic methods. The research results have aided the planning of production/injection drilling in the Coso geothermal field.

PROJECT OBJECTIVES

To determine fracture orientation and fracture density distribution in the Coso geothermal area through the interpretation of shear-wave splitting of microearthquake data from the geothermal field.

Technical Objectives

- Develop procedures to detect split shear waves from microearthquake data.
- Determine fracture orientation from the polarization direction of leading split shear waves.
- Determine the three-dimensional fracture density distribution of the geothermal field from the time delays between two split shear waves.

Expected Outcomes

- Shear-wave splitting induced by the alignment of the cracks in the reservoir has been widely observed.
- The strikes of fractures around most seismological stations in the field have been estimated. The result shows excellent agreement with the near-surface fracture trend, providing useful reference to geothermal drilling in the Coso field.
- A three-dimensional fracture density distribution has been determined from the tomographic inversion of time delays of split shear waves for the Coso geothermal field. The initial examination of the result shows that the blocks having a relatively large crack density coincide with the most productive geothermal areas.

APPROACH

Shear-wave splitting can be often identified by direct examination of polarization diagrams of the two horizontal orthogonal components of shear-wave arrivals. In anisotropic media, almost all shear-wave first arrivals are observed to have linear polarization. After a time delay (usually hundredths of a second in a microearthquake survey), the first motions are followed by abrupt changes in direction that evolve into elliptical motion, or further linear motion along different polarization directions, provided the time delay is long enough to separate the late signal from the initial arrival.

To quantitatively determine the polarization and time delay of split shear waves, the following processing method is used (Lou and Rial 1994). First, the two horizontal components of the shear wave seismograms are numerically rotated to search for the orientation along which the ratio of the projections of the particle displacement reaches a maximum. In a time window that contains only the fast shear-wave arrival, the azimuth at which this maximum ratio occurs is taken as the polarization direction of fast shear wave. Second, after the appropriate rotation of the seismogram components to the azimuth angle previously determined has been performed, the time delay between the split shear waves is measured by cross-correlation.

Although straightforward, the analysis of shear-wave splitting for the purpose of seismic imaging must be based on a large set of shear-wave seismogram data. The behavior of shear-wave splitting above small earthquakes is usually very complicated, because of the complexity of the source signal, subsurface geology structure, and surface topography. One major restriction to the analysis of shear-wave splitting is that in order to obtain correct interpretation of split shear-waves, the recording site needs to be within a shear-wave window (Booth and Crampin 1985, Lou and Rial 1994).

To determine the local strikes of cracks in the Coso area, we plotted rose diagrams of the leading split shear wave polarization directions vs. their relative frequency for each working Coso seismographic station. The local strike of fracturing then can be inferred from the dominant polarization directions of the rose diagrams (Lou and Rial 1994). From the time delays between two split shear waves, we can estimate the crack density (ϵ) ($\epsilon = Na^3/V$, where N is the number of cracks of average radius a in volume V) along each raypath. In order to determine the three-dimensional crack density distribution, we have employed a non-linear tomographic method to invert seismic shear-wave anisotropy in the Coso geothermal field. The work is done through co-operation between the UNC and Dr. Peter Malin's group at Duke University. The UNC provides input data points of the time delays in the assembled shear-wave splitting catalog, as well as the formalization of fracture density inversion from shear-wave splitting. Duke University adapted their existing P-wave tomographic code to perform the fracture density inversion.

RESEARCH RESULTS

A shear-wave splitting catalog from over 600 microearthquake events has been assembled. The catalog contains the polarization directions and time delays of split shear-waves, as well as microearthquake location. We have obtained the following information from the interpretation of the shear-wave splitting catalog:

(1) Crack Orientations

The rose diagram of polarization of the leading shear waves shows a dominant direction for most Coso network stations, which is here interpreted as the local strike of fracturing or direction of the maximum horizontal stress around each station. Basically, there are three predominant strike groups observed in the Coso geothermal field (Figure 1): N 40°-60° E (for stations S2, S7, N5), N 0°-25° E (for stations S1, S4, S8, N1), and N 25°-35° W (for station N4). Field blind tests gave excellent agreement with our interpretation. We estimate that for a distance of at most 5

wavelengths (~1000m) around the borehole seismometers these crack orientation determinations are accurate.

(2) Three-Dimensional Crack Density Distribution

The main research result during 1995 is that we have determined the three-dimensional crack density distribution in the Coso geothermal field by employing a seismic anisotropic tomographic inversion scheme. Figure 2 displays the two selected horizontal sections of crack density distribution at depth 2.5km and 3.5km. The blocks having a relatively large crack density (0.04) are in fact the most active geothermal production areas. It suggests that our technique provides a powerful and cost-effective tool for three-dimensional crack density imaging of geothermal reservoirs.

FUTURE PLANS

In order to expand the usage of shear-wave splitting in characterization of fracture patterns in other similar geothermal reservoirs, we need to incorporate our existing shear-wave splitting processing and interpretative technique to a user-friendly, graphics-oriented computer program.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
China Lake Naval Air Weapons Station California Energy Company, Inc. U.S. Department of Energy	Cost-share participants
Geothermal Program of U.S. Navy California Energy Company, Inc.	Monitor the progress of the project, and have attempted to apply the research results to their drilling plan and interpretation of Coso geothermal development.

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Figure 1. Map view of the crack strikes inferred from the polarizations of the leading split shear waves for the Coso geothermal field.

Figure 2. Tomographic inversion results for the crack density determined from time delays of split shear waves for the Coso geothermal field. The two selected horizontal sections of crack density distribution at 2.5 km and 3.5 km are displayed.

HYDROTHERMAL SYSTEMS IN GRANITIC ROCK: A SYNOPTIC SURVEY OF GEOCHEMICAL CONDITIONS DURING EARLY STAGES OF DEVELOPMENT

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KEY WORDS

fluid geochemistry, Steamboat Springs, stable isotopes, gas composition, water composition, fractured granite reservoir

PROJECT BACKGROUND AND STATUS

The geothermal system in the Steamboat Hills near Reno, Nevada, has been present for at least 3 million years, although activity seems to have been intermittent. The surface expression of the geothermal system consists of three prominent silica terraces. The Main Terrace and Low Terrace have discharged thermal fluid in historic times but no springs were active when we began sampling in 1991. Some leakage from well GS-5, a shallow research hole drilled on the Main Terrace in the 1950's (White and others, 1964), was present through 1993 but had ceased to discharge fluid onto the terrace by the summer of 1994. These terraces consist of siliceous sinter deposited from the spring water and are as much as 80 feet thick. Natural discharge from the system was about 1130 gpm in the 1950's. Wells drilled by Nevada Thermal Power Company in 1962 one mile west of the Main Terrace attained a maximum temperature of 186°C at 726 feet. Phillips Petroleum drilled a deep well (228°C at 3050 feet) in 1979 near the crest of the Steamboat Hills about 2 miles southwest of the Main Terrace. A geochemical study of the Steamboat geothermal system under way at that time indicated a possible maximum system temperature of about 230°C (Nehring, 1980).

Subsequent drilling has led to the development of two geothermal fields in the Steamboat Hills. A high-temperature geothermal field (Caithness Power) is located on the top and south side of the Steamboat Hills at elevations of 5300 to 5800 feet. Production wells in the high-temperature field are 2500 to 3000 feet deep and are drilled near a contact between Cretaceous granite and Triassic (?) metamorphic rock. Production is from hydrothermally altered granite and metamorphic rock at depths of 2200 to 2700 feet. Spent fluids from the high-temperature plant are reinjected about 3/4 mile NE of the plant on a direct line with the moderate-temperature field. The moderate-temperature field (Far West) extends from the High Terrace to the north end of the Main Terrace at an elevation of about 4700 feet. Wells in the moderate-temperature field are about 1500 feet deep and produce fluid from hydrothermally altered Pliocene and Pleistocene basaltic andesite. Spent fluids from the two Far West power plants are reinjected at the north end of the High Terrace (old plant) and north end of the Main Terrace (new plant).

PROJECT OBJECTIVES

The goal is to measure the geochemical characteristics of reservoir fluids in fractured granitic rock and the changes in chemical and isotopic compositions of these moderate- and high-temperature fluids associated with geothermal development. High-temperature geothermal systems in granitic rock have been drilled and produced for power generation at Steamboat Springs, Nevada; Coso Hot Springs, California; and Roosevelt Hot Springs, Utah. We chose to study the Steamboat Springs system because it is partially developed and is the most accessible. The study in cooperation with operating companies at Steamboat Springs will enhance the understanding of the granitic-hosted geothermal system and will benefit the development and management of the resource.

Technical Objectives

- Use chemical and isotopic data to show how the moderate and high temperature systems are related.
- Use chemical and isotopic data to show how various physical processes produce the range in chemical and isotopic characteristics observed in the fluids collected from the wells in the field.

Expected Outcomes

- A geochemical model of the system based on the chemical constituent, gas composition, and isotopic data.
- Provide proof of the relations between the moderate-temperature, high temperature, and hot spring systems.
- Provide a base line against which future changes in chemical and isotopic constituents can be compared.

APPROACH

Obtain high quality chemical and isotopic data on the thermal waters and gases discharged from both deep geothermal wells and shallow groundwater wells. Periodic sample collection from a representative array of wells will be used to document changes in fluid characteristics with time and stress. Field operators will provide the physical data necessary for interpretation of reservoir conditions. Chemical and isotopic compositions of the thermal fluids will be used to determine origins of constituents, reservoir properties, fluid flow paths, and fluid-rock interaction. We will develop a geochemical model for the system, and use the model to detect changes in the system brought about by production and injection.

RESEARCH RESULTS

Production wells in high-temperature and moderate-temperature fields and a selection of domestic wells associated with the low-temperature part of the field were sampled in November of 1991, January and August of 1993, and July of 1994 (Fig. 1). Basic chemical, isotopic, and gas composition results are complete and were published with our preliminary interpretations (Mariner and Janik, 1995). Our results show that all chemical and isotopic data are compatible with the presence of a single geothermal system (Fig. 2). High-temperature (240°C) fluid for the system rises up beneath the Steamboat Hills near the Caithness Power plant and is modified principally by boiling and minor water-rock reaction to produce all of the thermal fluids recovered from the high-temperature and moderate-temperature wells. All wells in the field discharge fluid which has boiled prior to entering the bore although chemical equilibrium with silica (equilibrium with quartz in the high-temperature field and with chalcedony in the moderate-temperature field) has been reestablished after boiling.

The hottest well in the field (Caithness 23-5) is an excess enthalpy well with an unusual gas composition. Measured temperatures and quartz geothermometer temperatures for this well indicate about 220°C but gas geothermometer data for constituents which reset fairly quickly indicate equilibrium at about 180°C. This unusual juxtaposition can be explained if the well draws in 180°C steam with the hotter (220°C) fluid when it flows. Quartz geothermometer temperatures and enthalpy-chloride relations show that this well is cooling with time. Enthalpy-chloride relations (Fig. 3) show that all moderate and high-temperature waters are produced by boiling of a single parent water. Historic chemical and isotopic data from springs on the silica terraces (Nehring, 1980) show that they were produced by boiling of either the high-temperature or moderate temperature fluids. Domestic wells in the adjacent valley have various proportions of thermal and freshwater components and many have lost some heat by conductive cooling. One domestic well located north of the high-temperature field has water which has been heated principally by steam although it also contains a small amount of chloride-rich thermal water.

Gas geothermometers (Table 1) for constituents which reset very slowly are very consistent for all wells in the field and indicate a possible maximum system temperature of 240° to 245°C. Chalcedony and potassium-magnesium (K-Mg) geothermometry for the moderate-temperature field show that these geothermometers have reset to the measured temperatures of the field. The chalcedony geothermometer lags a little bit relative to K-Mg geothermometer values. The K-Mg geothermometer and dissolved calcium concentrations show a low temperature zone which extends NE-SW across the moderate-temperature field. Consideration of sodium(Na)-potassium(K)-magnesium(Mg) relations show that the moderate-temperature fluids are only partially reequilibrated (Fig. 4). Very little adjustment of the Na/K values has occurred in the moderate-temperature waters relative to the high-temperature waters; most of the change is due to Mg increase.

FUTURE PLANS

Preliminary results and interpretations along with basic chemical and isotopic data collected for the Steamboat Hills Geothermal System were presented at the 1995 Annual Meeting of the

Geothermal Resources Council (GRC) and published in the Proceedings (Mariner and Janik, 1995). We are working on manuscripts for formal publication in which we discuss the data in more detail, and add some data for strontium, boron, lithium, lead, and iodine isotopes which were not available at the time the manuscript for GRC was written. The chemical and isotopic changes which are occurring in the Steamboat Hills Geothermal System provide an opportunity to see how the field responds to the stress of development. We would like to resample selected wells in the fields at intervals of every 1½ to 2 years in order to document the chemical and isotopic changes which occur as a result of development. However, sudden changes in the discharge characteristics of the production wells might require sample collection at any time. Our original intent was to look at the geochemical characteristics of the various granitic-hosted high-temperature geothermal systems in the Great Basin, therefore, we now need to collect comparable chemical and isotopic data sets from the geothermal fields at Coso Hot Springs, California and Roosevelt Hot Springs, Utah

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Yankee Caithness Power Company	System model and data which show that the high-temperature and moderate-temperature systems are related by simple boiling. Chemical, isotopic, or gas data which indicate where the major upflow upflow zone is located.
SB GEO, Inc.	System model and movement and source of isobutane in the geothermal fluids.

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Table 1. Gas geothermometers for samples from the Steamboat Hills area

Site	Date	Coll. T °C	T-DP ¹ °C	T-HA ² °C	T-CO ₂ ³ °C
23-5	11/05/91	167	174	180	243
	01/27/93	168.5	173	173	243
	08/02/83	172	175	184	243
	07/25/94	170	175	185	243
83A-6	11/06/91	156	187	193	242
	08/02/93	156.5	184	188	242
	07/25/94	151	200	183	241
21-5	11/05/91	154	190	201	243
	01/27/93	153.5	192	198	242
	08/03/93	155	183	157	241
	07/25/94	152	221	188	239
13-5	08/07/93	130.5	186	147	240
PW1	11/07/91	128.6	201	210	242
Fumarole at PW3-4	07/28/94	98	241	194	239

¹ - D'Amore and Panichi (1980);² - Giggenbach and Goguel (1989);³ - Arnorsson and Gunnlaugsson (1985)

Figure 1. Location of selected springs and wells in and near the Steamboat Hills.

Figure 2. Conceptual model for the Steamboat Hills geothermal system.

Figure 3. Enthalpy-chloride diagram for thermal waters associated with the Steamboat Hills.

Figure 4. Na-K-Mg diagram for selected water from the Steamboat Hills. Points along the upper curve are fully equilibrated. Points between the two curves are partially equilibrated.

LEAD AND STRONTIUM ISOTOPES INDICATE DEEP THERMAL-AQUIFER IN TWIN FALLS, IDAHO, AREA

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KEY WORDS

stable isotopes, thermal water, $^{208}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, rhyolite, limestone, Twin Falls, Idaho

PROJECT BACKGROUND AND STATUS

Thermal fluids occur at many locations along the entire length of the Snake River Plain in southern Idaho. Near Twin Falls in south-central Idaho, thermal waters occur between the Snake River and the mountains of northern Nevada. Topographically the area is a plain that slopes gently upward from the Snake River toward northern Nevada. Numerous thermal wells scattered over the plain and near the Snake River draw on thermal water in a regional geothermal system. Quaternary and Tertiary volcanics and Paleozoic marine sediments underlie the plain.

The Tertiary Idavada Volcanics are at least 2,000 feet thick in part of the area and have been considered to be the major aquifer for the thermal water. They consist of Miocene to Pliocene silicic welded tuffs and occasional basalt flows. The thickness and extent of the Paleozoic rocks (principally limestone) are unknown, but up to 5,000 feet of Paleozoic sediments have been described in the mountains of northern Nevada. Most geothermal development is near the Snake River and uses 25° to 70°C water for space heating, greenhouses, aquaculture, and irrigation. Pressure heads have decreased as much as 25 lbs/in², and some previously artesian wells must now be pumped. The conceptual model for the system, proposed by Lewis and Young (1989), consists of a single 2,000 foot thick aquifer in the Idavada Volcanics with surface recharge to the system near the Idaho-Nevada boundary.

PROJECT OBJECTIVES

The objective of our study was to determine if the thermal fluid recovered from the Tertiary rhyolite had ever circulated in a deeper aquifer in the Paleozoic limestone. Previous studies left some confusion in the relationship between thermal fluids recovered from wells in Paleozoic limestone located along the Idaho-Nevada boundary and the thermal fluids recovered from wells completed in Tertiary rhyolite at Twin Falls and along the Snake River both east and west of Twin Falls. Geologic considerations indicated that the Paleozoic and Tertiary rocks slope gently to the north, but the northern extent of the Paleozoic limestone is unknown. All producing wells along the Snake River and in Twin Falls are completed in Tertiary rhyolite and have chemical constituents typical of thermal waters in young rhyolite.

Technical Objectives

- Use isotopes of lead dissolved in the thermal waters to determine if fluids recovered from wells in rhyolite have a component of fluid from the deeper limestone.

Expected Outcomes

- Determine if thermal fluids in the Paleozoic limestone are providing pressure support and appreciable fluid volumes to the shallow geothermal system in the rhyolite. If the aquifers in the Tertiary rhyolite and Paleozoic limestone are connected, then the volume of fluid available will be greatly increased and the useful life of the system would be greatly extended.

APPROACH

Lead isotope values of Paleozoic limestone and Tertiary rhyolite are very different. Water samples for isotopic and chemical analysis were collected from selected wells for which some previous chemical data were available. Wells were selected which had limestone-related waters (low silica and fluoride but high calcium), rhyolite-related waters (high silica and fluoride but low calcium), and waters of intermediate character. The waters of intermediate composition tended to be very similar to the clearly rhyolite-related waters, but they were not as high in pH, silica, and fluoride and had more calcium than clearly "end-member" rhyolite-related waters.

Previously existing water chemistry data were used to determine which wells to sample, but new samples were collected for basic dissolved constituent analysis to see if any significant changes in the major element chemistry and/or stable isotope compositions had occurred. A separate set of samples were collected for Pb-isotope analysis. Pb-isotopes were considered the best candidate for preserving evidence of fluid circulation through limestone because their values will change slowly as new lead is dissolved from the rhyolite. Pb-isotopes should preserve evidence of circulation in limestone much better than normal chemical constituents such as silica, sodium, calcium, bicarbonate.

RESEARCH RESULTS

Thermal wells in the Twin Falls area (Mariner and others, 1991) produce water which ranges in temperature from 26° to 70°C and is moderately to slightly alkaline in pH (7.3 to 9.6). Wells in limestone provide water that is low in silica (20 to 30 mg/L), sodium (10 to 24 mg/L), and fluoride (generally less than 2 mg/L). Wells in rhyolite yield waters that are variable in composition, but the most typical "rhyolite" waters are rich in silica (>70 mg/L), sodium (>100 mg/L), and fluoride (>15 mg/L). The different concentrations of silica, calcium, and fluoride could be due to chemical changes occurring in the fluids as they move from limestone to rhyolite. Silica should increase along with fluoride, although fluoride could not begin to increase until

calcium concentrations have decreased. Increases in pH due to feldspar dissolution could lead to calcite deposition and loss of calcium from solution.

A plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ (Figure 1) shows that waters from limestone are higher in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ than water from most rhyolites and that there is a strong linear trend among most of the samples. Isotopic ratios for waters from rhyolites are much more variable than those for waters from limestones; some waters from rhyolites have ratios that completely overlap the ratios for water from the limestones. This overlap could indicate that waters with compositions typical of a rhyolite source have circulated for a long time in Paleozoic limestone. Samples 1, 3, 7, and 30 do not plot on the same trend as most of the data, indicating that these waters have derived at least part of their lead from some other rock type. Sample 1, 3, and 7 are all along the Snake River at the western edge of the study area. Sample 30 is from a cold spring in the mountains of northern Nevada.

A plot of silica versus $^{206}\text{Pb}/^{204}\text{Pb}$ (Figure 2) produces a distribution of data points extending from low silica-high $^{206}\text{Pb}/^{204}\text{Pb}$ (limestone-type water) to high silica-low $^{206}\text{Pb}/^{204}\text{Pb}$ (rhyolite-type water). Most data points plot between these extremes and probably represent limestone-type waters which have picked up silica from the rhyolite. The lead isotopes have partially shifted toward the value for the rhyolite. Samples 17, 20, 23, 27, and 28 represent waters from limestone. Samples 7, 9, and 22 represent waters which have extensively reacted with rhyolite. Samples 2, 3, 18, and 24 represent limestone-type waters which have reacted with rhyolite to increase dissolved silica but have not reacted with enough rhyolite to assume the lead isotope composition of rhyolite.

Sample 8 is clearly anomalous; chemically it is a rhyolite-type water, but it has higher ratios of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ than any limestone-type waters sampled in the region. The most likely explanation is that it is a limestone water which has moved up and into the rhyolite where it chemically reequilibrated. Drillers logs for a 2,000 foot well near Buhl (about 8 miles WSW from town) record the presence of limestone at a depth of 1,600 feet. Unfortunately this well no longer exists, but fluid from this or a similar Paleozoic limestone could be the source of the waters in sample 8.

$^{87}\text{Sr}/^{86}\text{Sr}$ values for all sampled waters were within the range expected for Paleozoic limestone. None of the waters were as enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ values as the rhyolite, and no shift in $^{87}\text{Sr}/^{86}\text{Sr}$ was observed as dissolved silica concentrations increased. Strontium concentrations are appreciably higher in limestone than in rhyolite; therefore much more water-rock reaction must occur in the rhyolite before sufficient strontium dissolves from the rhyolite to change the dissolved $^{87}\text{Sr}/^{86}\text{Sr}$ values. It appears that dissolved $^{87}\text{Sr}/^{86}\text{Sr}$ values are preserving evidence of circulation through a limestone for at least a significant part of all thermal waters in the area.

Lead and strontium isotope data indicate that fluid from Paleozoic limestone is leaking upward into the Tertiary rhyolites where wells intersect it. The fluids react with the volcanic rock to produce silica rich, calcium poor compositions typical of thermal fluids in rhyolite, but the lead isotope compositions are not as easily changed, preserving evidence of the limestone aquifer at depth. Most thermal fluids in the area appear to be a limestone water which has reacted with

rhyolite. Limestone waters which have not reacted with rhyolite occur only near the upper and middle parts of the system. Rhyolite dominated waters occur in the lower and eastern parts of the system. The lead and strontium isotope data coupled with dissolved silica concentrations require that a limestone aquifer exist beneath most if not all of the study area and that fluids from this deep aquifer leak upward into the Tertiary rhyolite. Isotopic evidence indicates that the thermal fluids in the rhyolite and limestone are hydrologically connected even though they have differences in major element chemical constituents, and that the volume of fluid in the geothermal system may be appreciably larger than if the fluids were restricted to the rhyolite.

FUTURE PLANS

Do additional sampling of Tertiary rhyolite and Paleozoic limestone are required to better define the range of Pb-isotope values possible in the study area. Take additional water samples from wells along the Snake River to better define changes in water characteristics as influenced by thermal fluid from the east which enters the study area beneath the Snake River and to see if sulfate-water isotope geothermometer values might be preserving evidence of temperatures in the deeper limestone aquifer. Obtain enough samples to demonstrate that either numerous upflow sites exist which permit thermal water from the deeper limestone to flow upward into the rhyolite where they spread laterally, or to demonstrate that the thermal fluids are deflected upward into the rhyolite along a single structure.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Idaho Water Resources Research Institute	Interested in the technology and data which require the presence of a deep aquifer beneath the aquifer presently being utilized. They need the data for the development of conceptual and computer models of the geothermal system.
Idaho Department of Water Resources	Interested because this is a ground-water management area and better understanding of the system will lead to better management.
Private companies	Aquaculture and space heating (greenhouse) users than depend on the heat and fluid to sustain their operations.
Public entities (City of Twin Falls, College of Southern Idaho, and the Twin Falls School District)	These entities use the resource extensively for heating public buildings.

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Figure 1. $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for waters in the study area.

Figure 2. Dissolved silica versus $^{206}\text{Pb}/^{204}\text{Pb}$ for waters from the study area,
 Limestone $^{206}\text{Pb}/^{204}\text{Pb} > 19$
 Rhyolite $^{206}\text{Pb}/^{204}\text{Pb} < 18$.

NUMERICAL STUDIES OF THE FORMATION AND LONG-TERM BEHAVIOR OF A 'HIGH TEMPERATURE RESERVOIR'

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KEY WORDS

vapor-dominated, high-temperature reservoir, The Geysers, corrosive steam, NCGs

PROJECT BACKGROUND AND STATUS

It is well established that a high-temperature anomaly underlies portions of The Geysers geothermal field in Northern California. This feature has come to be known as the "High-Temperature Reservoir" (HTR) in the literature, although no barrier separating the HTR from the "normal" vapor-dominated reservoir above 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, its initial liquid saturation (and therefore its probable behavior under exploitation), and the relationship between the HTR and the high chloride content of the steam remain unclear.

Previous years' efforts have focused on the formation and native-state behavior of the HTR through 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). A sensitivity study on HTR formation was recently published (Shook, 1995), and comments regarding that work are being received. Several additional projects on HTR formation and behavior are underway. These include examinations of the partitioning of chloride to the steam phase at high temperature and new isotopic analyses.

PROJECT OBJECTIVES

The goal of this continuing project is to develop a numerical model of a high-temperature reservoir (HTR) similar to that observed in Northwest Geysers, in order to better predict reservoir response to exploitation. Ultimately, this model is useful in evaluating the long-term behavior and potential for injection into and extraction from the HTR, for predicting non-condensable gas concentrations in the HTR, and for understanding how gas concentrations might change under injection conditions.

Technical Objectives

- Integrate reservoir observations and analyses into a consistent reservoir description to evaluate possible evolutionary pathways for HTR formation.
- Develop a conceptual model description of an HTR using observed data in Northwest Geysers. Numerically simulate a venting episode, and 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.
- Evaluate possible relationships between the presence of the HTR and the incidence of corrosive steam in Northwest Geysers.
- Using previously unavailable isotopic data, perform sensitivity studies to determine the relative amount of water throughput in the HTR, and compare that throughput to estimates for the "normal" reservoir. Correlate water throughput to parameters such as distance to a vent, flow barriers, etc.

Expected Outcomes

- Favorable comparisons between observed properties in Northwest Geysers with simulated HTR properties will 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, and how injection might effect gas concentrations in the steam.

APPROACH

The approach taken in this project was to accumulate what observations are available for the HTR (and adjacent "normal" reservoir) in the 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 pressure gradient throughout the reservoir). Finally, sensitivity studies were conducted that evaluated possible effects of variations in the conceptual model parameters.

On the basis of the numerical studies noted above, a model for HTR formation was developed. This numerical model will be modified to determine if partitioning of chloride between the liquid and vapor phases can be responsible for the high chloride concentrations in HTR steam. The

model will also be expanded to examine the relationship between high gas concentrations, degree of "flushing" associated with a venting episode, the distance from a hypothesized vent site, and the response of gas concentrations in the steam to various injection scenarios.

RESEARCH RESULTS

The conceptual model that was developed was based on several field observations. These are discussed in detail by Shook (1995), but include pressure continuity between the normal reservoir and the HTR, a facies change at depth in Northwest Geysers, and the use of a saline solution as the reservoir fluid.

A numerical model was developed on the basis of available field observations to study HTR formation. A schematic of the domain is given in Figure 1. Two distinct lithologies were used, with Lithology 1 representing "normal" Geysers rock and Lithology 2 the argillite noted by Sternfeld (1989). 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 regarding initialization and equilibration of the model are given by Shook (1995).

Thermodynamic conditions in the fracture domain 10,000 years after the venting are shown in Figure 2. This figure clearly shows several features similar to those observed in 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 left-hand portion of the field, however, relatively large temperature gradients are observed, and temperatures in excess of 350°C are seen at depth. This "High-Temperature Reservoir" has a surface depth that varies significantly, also as observed in Northwest Geysers.

Liquid saturation profiles are given in Figure 2c. The low liquid saturations 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 shown in Figure 2d 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 water in the HTR.

Sensitivity studies indicate that the formation of such an HTR is not limited to the specific conditions used in this conceptual model. However, 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, and each is supported by field observations. This study has been recently published (Shook, 1995).

FUTURE PLANS

Additional studies are planned to develop a better understanding of certain aspects of Northwest Geysers. While the study described above offers a possible genesis of the HTR, several issues were specifically not addressed. We are in the process of studying the possible relationship between the presence of the HTR and the high incidence of corrosive steam in Northwest Geysers. In order to perform this study, modifications to the numerical model TETRAD must first be made. Until recently, partitioning of chloride into the steam phase was considered to be negligibly low until the rock dried out. This has been shown to be incorrect (Simonson et al., 1994) at sufficiently high temperatures, such as those found in the HTR. A study is therefore planned to determine if equilibrium partitioning of salts from the brine in the HTR can be responsible for the high incidence of NCGs found in Northwest Geysers steam. Effects of injection into the HTR, and how NCG concentrations respond will also be studied in this project.

A second study is planned in collaboration with ESRI and a consulting geologist. On the basis of recent isotopic analyses of Northwest Geysers core, it appears that a correlation exists between NCG concentrations in the steam, presence of an HTR, the degree of water flushing through a system, the presence of flow barriers (e.g., partially sealing faults), and the distance from a vent site. We will be using the numerical model of HTR formation to study these relationships.

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 have been received from the *Geothermics* paper from independent geothermal geologists, researchers at Victoria University of Wellington (New Zealand), Earth Sciences & Research Institute (ESRI), and will be used to direct additional aspects of the study, including reinjection considerations. Several collaborative studies are in the process of being developed, including one project with ESRI and a second project with Montana Tech.

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Figure 1. Schematic showing the reservoir model developed from field observations. Lithology 1 represents graywacke; Lithology 2, argillitic turbidites.

a) Fracture pressure (kPa)

b) Fracture temperature (°C)

c) Fracture liquid saturation

d) Fracture distribution of salt

Figure 2. Fracture properties at 10,000 years after venting.

GEOLOGIC RESEARCH AT THE GEYSERS

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KEY WORDS

The Geysers, graywacke, pluton, felsite, alteration, mineralization, borosilicates, porosity, permeability, fracturing, brecciation, oxygen-isotope ratios

PROJECT BACKGROUND AND STATUS

Geologic research at The Geysers relies heavily upon detailed investigation of cores and cuttings from individual geothermal wells in the field and vicinity, as well as broad-scale characterization of The Geysers pluton. Our detailed study of these rock samples has revealed or refined knowledge of numerous critical features of The Geysers hydrothermal system, in particular the evolution of The Geysers magmatic-hydrothermal system (e.g. Moore and Gunderson, 1995), major textural and mineralogic differences between the steam reservoir and its caprock (e.g. Hulen et al., 1991; Hulen and Nielson, 1995a); the nature of secondary porosity and permeability (e.g. Nielson et al., 1993, 1995; Hulen et al., 1992; Hulen and Nielson, 1995b) in the steamfield; and the complexity and composite nature of The Geysers pluton (e.g. Hulen and Nielson, 1993), a batholith-sized intrusive body intimately related to the development and configuration of The Geysers hydrothermal system.

A major goal of ESRI's geologic research at The Geysers is helping steamfield operating companies refine their knowledge of the complex, vapor-dominated geothermal system they exploit. The geology of The Geysers is fundamental to this understanding: the field's rocks and porosity networks are its first-order controls. Accordingly, this research seeks to determine how and to what extent various geologic parameters (e.g. metamorphic- and hydrothermal-vein distributions; subsurface plutonic-rock compositions and configurations), individually and in combination, control the flow and storage of geothermal fluids. Results of these geologic studies are being integrated with the geochemical and fluid-inclusion investigations of J.N. Moore (e.g. Moore and Gunderson, 1995). As part of this project, ESRI is also charged with the characterization and curation of an extensive collection of Geysers cuttings and cores, donated by the steamfield operators. Carefully documented samples from this collection, where practical accompanied by detailed mineralogic and petrographic descriptions, are routinely supplied to collaborating investigators from various institutions across the USA.

Our work this year has involved: (1) Petrographic, mineralogic, and stable-isotopic analysis of cuttings from hot but non-productive geothermal wells drilled just outside The Geysers' presently defined boundaries; (2) Cataloguing and detailed geologic logging of recently-received drill cores from numerous geothermal wells throughout the field -- these studies are being carried out in part

to support the efforts of other (non-ESRI) Geysers researchers; (3) Refining a major manuscript summarizing results of our investigation of The Geysers pluton. Efforts to finalize this work have been hampered by the unavailability of drift surveys for some critically located study wells (all the data have been collected for these wells, but without the surveys, complete and accurate maps and cross sections of the intrusive body and its alteration and mineralization cannot be prepared -- see, for example, Figure 4). Nonetheless, we optimistically anticipate that the missing information will be obtained, and the manuscript submitted (to *Geothermics*) during the next few months.

PROJECT OBJECTIVES

Technical Objectives

- Improve understanding of The Geysers' porosity and permeability controls through detailed characterization of its reservoir- and caprocks; structural disruption (faults, fractures and breccias as well as their mineralized counterparts; hydrothermal alteration and vein mineralization; and metamorphism (pluton-contact and regional). Where possible, correlate these parameters with steam-entry frequency and quality and caprock characteristics in both individual geothermal wells and broader sectors of the entire geothermal field.
- Map the subsurface configuration, composition, hydrothermal alteration, vein mineralization, and metamorphic effects of The Geysers pluton ('the felsite'). Determine the influence of each of these features on steam-reservoir quality within this intrusive body and in overlying metaclastic rocks. Help identify regions of the pluton and its host rocks potentially permissible for the discovery of additional, deeper, steam reserves.
- Since The Geysers occupies but a small portion of the much broader Geysers-Clear Lake heat-flow anomaly, identify and characterize the special geologic parameters which permitted the creation of a vapor-dominated geothermal system in rocks which would otherwise be hot but dry. Use this information to help target other portions of the heat-flow anomaly that might harbor additional resources.
- Help constrain hypotheses on the origin and evolution of The Geysers hydrothermal system.

Expected Outcomes

- More efficient and cost-effective exploitation of remaining steam reserves at The Geysers, both in The Geysers pluton and in overlying metaclastic rocks.
- Development of information useful for optimization of water-injection strategies, particularly for deeper portions of the reservoir.
- Targeting of deeper new reserves at The Geysers, both beneath currently drilled depths in the felsite and laterally beyond the field's presently defined limits.

APPROACH

The foundation of The Geysers geologic research effort is an array of basic geological and geochemical techniques of proven value in characterizing the rocks of high-temperature geothermal systems. Critical cuttings and cores are first geologically logged in detail, noting lithology, structural disruption (faults, fractures, and breccias of tectonic or hydrothermal origin), metamorphism, hydrothermal alteration, vein mineralization and paragenesis, and (especially) various types of porosity controls. This work is supported as necessary by petrographic examination, X-ray diffraction analysis, whole-rock geochemistry, radiometric age-dating, and light-stable-isotope analysis. The results are plotted as individual composite geologic logs for each well or drill core, and on a series of field-wide maps and cross sections designed to reveal key reservoir controls. The individual well logs, maps and sections can be used for correlation with various reservoir parameters such as steam-entry frequency and quality, injection characteristics, and reservoir-fluid geochemistry. The collected data are integrated with results of allied research projects (e.g. fluid-inclusion studies; Moore and Gunderson, 1995) to clarify the origin and evolution of The Geysers hydrothermal system.

RESEARCH RESULTS

Deep geothermal exploration wells drilled beyond the currently defined margins of The Geysers geothermal system to date have been hot ($>235^{\circ}\text{C}$) but nonproductive, yet many penetrate the same metaclastic rocks that host the bulk of the productive steam reservoir. To begin investigating this discrepancy, we have completed a detailed petrographic, mineralogic, and oxygen-isotopic investigation of drill cuttings from two such "dry holes" -- Sunoco's Bud Taylor No. 3, just northwest of the field; and MCR's Tellyer 1-24, about two km to the east (Figure 1; Hulen and Moore, 1995). Both hot wells were drilled to depths in excess of 3000 m (Figs. 2 and 3) in similar rock sequences, but neither was commercially productive. The reasons for this discrepancy are different for the two wells. The rocks penetrated by Tellyer 1-24 are nearly identical to those which host the steam reservoir to the west -- they have been extensively altered and mineralized by the hot-water system which preceded formation of the modern steam field. Whole-rock oxygen-isotopic ratios reflect this fluid-rock interaction -- $\delta^{18}\text{O}$ values systematically decrease downhole with approach to the felsic intrusive rocks penetrated below 12,000 ft (Figure 3). The difference between the rocks of this well and those of similar but non-

productive wells in the field is that otherwise open veins in this well contain abundant, late-state calcite. We believe that this calcite "chokes off" what would otherwise be productive steam channels, and may be an important element of The Geysers' essential lateral permeability barriers. By contrast, the rocks of Bud Taylor No. 3 are nearly unaltered and unmineralized, a condition reflected in $\delta^{18}\text{O}$ values minimally disturbed from the regional norm (Figure 2). This well was apparently nonproductive in part because it was only minimally invaded by the circulating hot waters that created porosity within what is now productive steam-reservoir rock.

The felsic intrusives discovered deep in Tellyer 1-24 were initially logged as graywacke, but in fact are dacite and granodiorite similar to those documented for the greater Geysers pluton. As in the steam reservoir, alteration, vein mineralization, and metamorphism are vertically zoned with respect to these intrusive rocks. Recognition of the intrusives in wells where they were not suspected suggests that deep plutonic rocks will be (or have been) intersected elsewhere within the greater Geysers heat-flow anomaly defined by Walters and Combs (1988). It is conceivable that some of these deep intrusives have altered otherwise tight Franciscan host rocks into porous and permeable geothermal reservoir rocks -- in other words, other areas of the heat-flow anomaly might harbor additional, pluton-centered geothermal resources.

The model for such a resource is The Geysers itself, where the spatial relationship between the deep felsic pluton and enveloping steam reservoir is beyond doubt: this relationship is apparent on Figure 4, showing the close match in the configurations of pluton and reservoir. The pluton is fundamentally a three-phase igneous body, with high-level granites (>1.3 Ma; Dalrymple, 1992; Hulen and Nielson, 1993) intruded at depth by 1.0 Ma granodiorite (Pulka, 1991; Hulen and Nielson, 1993). These rocks are intensely mineralized with borosilicates (tourmaline and ferroaxinite), and concentrations of these secondary minerals are commonly associated with productive steam entries. The pattern of borosilicate mineralization, however, transgresses intrusive contacts (Figure 4), suggesting that the patterns are related to a deeper, still younger pluton.

Another noteworthy feature of the cross section of Figure 4 is the apparent major vertical discontinuity in the pluton between the two northernmost wells depicted (drift surveys for the wells not shown remain proprietary). Since the pattern of intrusive rock types is duplicated in the two wells across this discontinuity, it is intriguing to speculate that the discontinuity is a major fault zone at the northwestern edge of the pluton. Such a discontinuity might in part explain the separation of the northwestern part of the field, which has a deep, "high-temperature" component, from the rest of the field, which apparently does not.

FUTURE PLANS

- Finalize and distribute maps and cross sections of The Geysers pluton. This will require securing still unavailable drift-survey information for several critically located pluton-study wells which are not in the public domain. Once this information has been obtained, a detailed manuscript can be submitted to *Geothermics* within three months.

- Complete detailed petrographic, mineralogic, and oxygen-isotopic analyses of selected, additional exploration wells completed within The Geysers heat-flow anomaly, paying particular attention to the nature and extent of hydrothermal alteration and vein mineralization encountered, and to the possible presence of previously unidentified plutonic rocks. Combine results of these investigations with those obtained earlier in this study to evaluate the possibility of other, prospective geothermal target areas in the region.
- Continue detailed petrographic characterization of recently obtained Geysers drill cores. Evaluate results in the light of allied fluid-inclusion data (e.g. Moore and Gunderson, 1995) to help characterize porosity and permeability controls within the steam reservoir and its caprock. Distribute results of these investigations to collaborating investigators in a timely fashion. Continue to fulfill such researchers' requests for carefully documented samples of these cores from The Geysers study collection at ESRI. Accompany these samples with all available pertinent petrographic information.

INDUSTRY RESEARCH AND TECHNOLOGY TRANSFER

Results of this project ideally will be useful not only for more efficient and cost-effective exploitation of The Geysers resource, but in the search for and exploitation of high-temperature geothermal systems worldwide. The study should directly benefit Unocal Corporation, Calpine Corporation, NCPA, and CCPA at The Geysers, and, indirectly, all companies engaged in global geothermal exploration and development.

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Figure 1. Location Map.

Figure 2. Log of lithology, secondary mineralization, and whole rock $\delta^{18}\text{O}$ values for well Bud Taylor No. 3.

Figure 3. Log of lithology, secondary mineralization, and whole rock $\delta^{18}\text{O}$ values for Geysers well Tellyer 1-24.

Figure 4. Northwest-southeast cross sections through The Geysers pluton. A - Intrusive rock types. B - Borosilicate mineralization (tourmaline plus ferroaxinite).

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 BACKGROUND AND STATUS

Over the last two years, a suite of laboratory measurements have been conducted on Geysers rocks recovered from reservoir depths in well NEGU-17. The measurements have enabled us to refine interpretations of observed field seismic anomalies and have uncovered correlations between mechanical, transport, and water storage properties that may prove useful for reservoir assessment and management. Here we continue this suite of measurements and focus the additional work on core recently recovered from SB-15-D.

One of the main discoveries of our previous work has been the observation that the presence of water causes a reduction in the dynamic shear modulus. This frame-weakening is important in that it is one of the primary effects of saturation on mechanical properties. It is thus directly linked (and may be the dominant cause) of V_p/V_s anomalies observed in the field and interpreted to reflect undersaturation in the reservoir.

The underlying physical processes involved in producing this shear weakening remain uncertain. The degree to which a sample exhibits frame weakening appears to be correlated with other important physical/transport properties. Among metagraywacke samples from NEGU-17, frame weakening correlates with elevated high-frequency dielectric permittivity, high saturated electrical conductivity, and low permeability to liquid water. These observations provide a link between the fundamental physical and transport properties that may be exploited for purposes of reservoir assessment. The observations suggest that a subtle petrographic feature, possibly smectite content, may be a controlling factor for both seismic and transport properties of the matrix. An understanding of the physical processes that cause these effects is central to interpretations of saturation effects and their possible detection using field seismic and other geophysical measurements.

PROJECT OBJECTIVES

The observations summarized above are limited in that they are based only on measurements on core recovered from a restricted depth range in NEGU-17. Recently, The Geysers Coring Project in SB-15-D has added significantly to the amount of reservoir core available for testing. This

material provides us with an excellent opportunity to further our understanding of the properties of the reservoir matrix with the goal of improving our capabilities in the assessment and prediction of reservoir performance at The Geysers.

The SB-15-D material allows us to determine if the patterns observed from experiments on the NEGU-17 core are representative of the reservoir as a whole. Additionally, since the core spans the transition from cap-rock to reservoir, the SB-15-D core is well suited for exploring the nature of the cap-rock/reservoir boundary. Recently, Hulen and Nielson [1995] have suggested that the presence of illite/smectite and chlorite/smectite phases in the veins of the cap-rock are responsible for plugging the flow conduits and thus creating the cap-rock. It is important to know if this difference in vein-mineral assemblage is also reflected in the matrix, and/or if there are any systematic differences between cap-rock and reservoir matrix. With a sufficient understanding of the mechanical, transport, and electrical properties, we will be able to assess the use of geophysical methods for predicting and monitoring reservoir performance as well as delineating the cap-rock/reservoir boundary.

Technical Objectives

- Measurement of ultrasonic velocities, permeability, porosity, and complex electrical impedance of reservoir matrix material.
- Characterization of the effect of partial water saturation on the mechanical (ultrasonic velocities) and electrical properties of the cores.
- Development and constraint of physical models relating measured transport and mechanical properties to the underlying pore structure of the matrix material.
- Integration of measured core-scale properties with field scale observations to assess possible properties that may be used for reservoir characterization and modeling. Test to see if there is a change in matrix properties associated with the proposed caprock/reservoir boundary penetrated by SB-15-D.
- Exploration of differences between core material from NEGU-17 and SB-15-D and understand implications to reservoir characterization and management.

Expected Outcomes

- Development of 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.

Expected Outcomes (continued)

- Assessment of interrelationships between seismic, electrical, and fluid transport properties needed to help interpret borehole geophysical properties.
- Critical examination of field-seismic observations and interpretations of reservoir properties in the context of the laboratory measurements.

APPROACH

The main focus of the project is to make integrated measurements of ultrasonic velocities, permeability, and complex electrical impedance on cores from SB-15-D. Bulk properties, such as grain density and porosity are also being measured, along with documentation of petrographic characteristics through the use of thin sections. The results, in conjunction with the results of the NEGU-17 experiments, will be analyzed in the context of developing physical models of The Geysers matrix and used to aid in interpretation of field observations.

The results of the work will be shared with others who are currently working on research concerning The Geysers. These include, Brian Bonner (LLNL - water storage, heterogeneity, and physical properties of SB-15-D core), Al Duba (LLNL - electrical properties of SB-15-D core at reservoir conditions), Jeff Hulen (ESRI - the petrography and petrology of The Geysers core material), and Ernie Major (LBNL - field-seismic studies in the Southeast Geysers).

RESEARCH RESULTS***Overview***

During the last year, new experiments have been performed on samples from NEGU-17 and SB-15-D. Combined with tests previously performed on NEGU-17 samples [see Boitnott and Bonner, 1994; Boitnott, 1995], we now have a data base of velocities, bulk properties, and electrical properties. Many of these properties are constrained as a function of effective confining pressure and/or as a function of saturation.

Numerous correlations between measured parameters are apparent within the data-set. Some correlation involve the entire data-set, while others are restricted to samples from a given borehole and still others are restricted only to a given rock-type from a given borehole. Here we will concentrate on the dominant correlations which exist among the data-set as a whole. A more complete description of results is presented by Boitnott and Boyd [1996].

Seismic Properties

Compressional and shear velocities have been measured as a function of pressure and saturation on 17 samples from 11 depths in SB-15-D. The samples are representative of the two dominant

rock types, metagraywacke and argillite (metashale). The samples range in depth from 266.7m to 483.1m, which spans the proposed cap-rock/reservoir boundary.

A summary plot of velocity data for both SB-15-D and NEGU-17 is shown in Figure 1. In general, saturated compressional and shear velocities of SB-15-D samples are slightly lower than those measured on NEGU-17 samples. Dry shear velocities also exhibit this pattern, but dry compressional velocities of SB-15-D cores are not clearly distinguishable from those of NEGU-17 samples (dry velocity data not shown).

A negative correlation between compressional and shear velocities (at 30 MPa effective confining stress) with porosity (at room pressure) is apparent. Among SB-15-D cores, argillite samples exhibit higher porosity and generally lower velocities than metagraywackes. Note however that the velocity/porosity relationship is not strong among any subset of the data other than within metagraywackes from SB-15-D. The relatively high porosity of the SB-15-D argillites may reflect the presence of parting within the foliation, and thus may not be persistent at elevated confining pressures. The degree to which porosity is a controlling factor for velocities remains uncertain.

The effect of saturation on compressional and shear velocities is similar to that found for NEGU-17 samples. A clear weakening in the dynamic shear modulus with saturation is apparent, the effect being larger among argillites than among metagraywackes. As within the NEGU-17 data-set, among SB-15-D metagraywackes, shear velocity reduction with saturation varies from negligible to nearly 5%. Shear velocity reduction among SB-15-D argillites is much stronger than that observed in NEGU-17, with reductions ranging from 5% to 11%.

Electrical Impedance

Complex electrical impedance has been measured on all samples over a frequency range from 5 Hz to 8 MHz. All samples were saturated with distilled water. In general, SB-15-D cores have lower resistivities (low frequency) and higher dielectric permittivities (high frequency) than their NEGU-17 counterparts. A summary plot of electrical properties is presented in Figure 2. The strong negative correlation between relative dielectric permittivity (K) and low frequency resistivity (R) appears to be independent of rock type and well. This relationship is not an intrinsic relationship observed among other rocks, and thus appears to be indicative of composition and/or pore structure of the matrix material from The Geysers.

Correlations Between Properties

We have seen in Figure 2 the strong correlation between (K) and (R). Importantly both of these parameters correlate with shear velocity reduction upon saturation (see Figure 3). We postulate that the shear weakening with saturation is controlled by composition of the argillaceous material (possibly smectite content). High dielectric permittivity, low resistivity, and large shear weakening would all be consistent with presence of a hydrophilic clay phase.

Following this hypothesis, we postulate that among argillites, composition is the dominant controlling factor. This would suggest that the NEGU-17 argillite, which in comparison to SB-15-D argillites has high resistivity, low dielectric permittivity, and relatively little shear weakening, is compositionally different from the SB-15-D argillites. Along this same line of argument, compositional variations among SB-15-D argillites are apparent from the spread in values among these samples. Furthermore, for metagraywackes both argillite content (amount) and argillite composition control the shear weakening and electrical properties. The difference between NEGU-17 metagraywackes and SB-15-D metagraywackes may reflect different argillite composition (consistent with the differences between the argillites from SB-15-D and NEGU-17), while variations within metagraywackes from a particular borehole may reflect both variations in argillite content and/or variations in argillite composition. Quantitative petrographic analysis are required in order to test this hypothesis.

Electical Impedance versus Saturation

Electrical impedance versus saturation has been measured on 3 samples of metagraywacke from NEGU-17. The results indicate that the real part of the relative dielectric permittivity (K') can be fit as a simple linear function of saturation for all saturation levels. The linear relationship is a strong function of frequency. This is in contrast to the results of similar tests on sandstones (see Knight and Endres [1990]) where saturation effects on (K') are different at low and high saturations. The results on the NEGU-17 metagraywackes are similar to those for Westerly granite and thus may reflect a behavior characteristic of low porosity rocks which is different from that observed in porous sandstones. The simple relationship between K' and saturation indicates that measurement of K' may be useful for characterizing saturation levels in core and/or in boreholes.

FUTURE PLANS

Electrical impedance will be measured on brine saturated samples to further characterize electrical properties and to facilitate more direct use of measured values to field applications. Velocities, electrical impedance, and permeability will also be measured on selected preserved core to explore issues related to the importance of core preservation and to aid in extrapolating existing data to field conditions.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Lawrence Livermore National Laboratory	Reservoir characterization and assessment
Lawrence Berkeley National Laboratory	Interpretation and design of field seismic experiments

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Figure 1. Saturated compressional (V_{p_sat}) and shear (V_{s_sat}) velocities versus porosity for core samples from SB-15-D (squares) and NEGU-17 (circles). Dark symbols indicate metagraywacke and open symbols indicate argillite.

Figure 2. Logarithm of the low frequency resistivity versus logarithm of the real part of the relative dielectric permittivity (at 4 MHz) for core samples from SB-15-D (squares) and NEGU-17 (circles). Distilled water was used as the pore fluid. Dark symbols indicate metagraywacke and open symbols indicate argillite.

Figure 3. Relative change in shear velocity [$dV_s = (V_{s-sat} - V_{s-dry})/V_{s-dry}$] versus the $\log(R)$ and $\log(K')$ for core samples from SB-15-D (squares) and NEGU-17 (circles). Dark symbols indicate metagraywacke and open symbols indicate argillite. Large reduction in shear velocity with saturation correlates with low resistivity and high dielectric permittivity.

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 BACKGROUND AND STATUS

The Geysers Coring Project (GCP) was conceived and undertaken principally to address the virtual absence of direct porosity, permeability, and fluid-saturation measurements for The Geysers steam field. These data are important for effective near- and long-term predictions of reservoir performance and steam quality. Obtaining this information, however, requires core. Yet prior to the GCP only about 100 m of core (from 24 separate geothermal wells) had been collected from the resource. 237 m of new, continuous core was retrieved from the GCP drill hole, SB-15-D (a sidetrack to an existing Unocal Corporation production well; Fig. 1) during the coring phase of the project. The core was carefully documented and sampled on site under guidelines set forth in a site-specific core protocol and science plan. Selected samples were specially sealed and otherwise preserved at this time to inhibit the escape of contained fluids. Baseline geologic characterization of the core, as well as a full range of complementary investigations by the GCP's collaborating investigators, remain underway at this time. Preliminary results of these studies have been reported at various domestic and international forums, including the Geothermal Resources Council Annual Meeting, the annual Stanford University Reservoir Engineering Workshop, and the World Geothermal Congress. The core is available for sampling at ESRI's Geothermal Sample Library.

PROJECT OBJECTIVES

The GCP is a cost-shared endeavor involving the Department of Energy's Geothermal Division (DOE-GD), Unocal Corporation and other Geysers steamfield operating companies, and a group of collaborating investigators from universities, national laboratories, and various government agencies. The chief objective of the GCP is improved understanding, through continuous coring, of the nature of porosity, permeability, and (remaining) fluid saturation in The Geysers vapor-dominated geothermal system. The new data ideally will permit Geysers steamfield operating companies to make more accurate forecasts of the field's steam supply and quality. The coring phase of the project was completed in September 1994. Baseline geologic characterization of the core, and detailed core studies by the collaborating investigators, have revealed hitherto unknown aspects of The Geysers while addressing the project's stated scientific goals.

Technical Objectives

- Improve understanding of the following critical steam-reservoir parameters: (a) porosity and permeability controls; (b) nature, amount, and availability of remaining, indigenous, liquid water reserves; and (c) potential sources of chloride and noncondensable gases in produced steam.

Expected Outcomes

- More accurate characterized and quantification of porosity and permeability in The Geysers' reservoir rocks.
- Determination of the amount and configuration of the reservoir's remaining indigenous liquid water reserves.
- A better understanding of the sources of noncondensable gases and corrosive acids in produced steam.
- A clearer understanding of the evolution of The Geysers hydrothermal system, particularly: (a) the mechanisms by which the modern, vapor-dominated geothermal system evolved from its high-temperature, liquid-dominated precursor; (b) physical and chemical controls on the development of reservoir porosity; and (c) formation of the field's relatively impermeable caprock.

APPROACH

After multiple meetings and more than a year of careful planning, the coring phase of the GCP took place in late August to early October 1994. Coring operations were carried out utilizing a triple-tube coring and core-retrieval system. The triple-tube system permitted recovery of delicate, potential porosity elements like fracture stockworks and carbonate-dissolution networks in a condition approximating (as closely as possible) *in situ*. The system allowed for sealing of selected cores immediately upon retrieval to the surface, thereby minimizing the escape of contained fluids. These cores could be scanned by short-range remote-sensing methods for investigation of fluid quantities and distributions. The coring system also permitted recovery, by Unocal Corporation, of selected cores which were retrieved to the surface and frozen under simulated reservoir pressures -- a technique conceived to preserve indigenous fluids in their original configurations.

A broad range of detailed investigations of the core addressing principal project objectives is being carried out by the GCP's collaborating investigators. These studies, summarized in the project's site-specific science plan, include the short-range remote-sensing investigations (e.g X-ray CT scanning; MRI scanning) as well as others aimed at, for example, quantifying in detail the porosity and permeability of the retrieved core; extracting and measuring trapped, indigenous

reservoir fluids from the core; and deciphering The Geysers' hydrothermal history. These studies will be largely completed by the end of FY 1997.

RESEARCH RESULTS

Summaries of some of the individual research projects being carried out by the GCP science team can be found elsewhere in this volume. Our baseline geologic characterization of the core, undertaken in support of these efforts, has revealed surprising new aspects of The Geysers hydrothermal system and its complex geologic setting.

Readers will recall that because of unanticipated drilling difficulties, SB-15-D, rather than commencing coring deep in the so-called "normal" Geysers reservoir, penetrated instead the transition zone between the uppermost reservoir and its relatively impermeable caprock (Fig. 2). Both of these zones are superficially similar, consisting dominantly of late Mesozoic metagraywacke extensively disrupted by older, randomly-oriented, metamorphic quartz-calcite veins, and by younger, high-angle veins deposited in the geologically recent past by The Geysers hydrothermal system. The difference between the caprock and the reservoir rock is found in these young veins.

The Geysers hydrothermal veins in the SB-15-D core mostly show dips of greater than 70° (relative to planes normal to the core axis, itself inclined at 7.5°. They range in width from less than a mm to (rarely) several cm, and many are conspicuously vuggy. The vugs have formed as a result of incomplete filling of the host fractures by a variety of secondary phases (Fig. 2). At least at this high elevation in The Geysers, these vuggy veins are clearly the dominant porosity elements; minor porosity is also found as scattered carbonate-dissolution pores in the older quartz-calcite veins.

The vuggy Geysers veins consist principally of quartz, bladed calcite, and adularia, with various vertically zoned calc-silicates and layer silicates (Hulen and Nielson, 1995a, 1995b). The calc-silicates wairakite, epidote, and prehnite are largely confined to the reservoir portion of the core (Fig. 2). Veins in the caprock portion of the core are distinguished by containing abundant mixed-layer illite/smectite and minor chlorite/smectite, both layer silicates deposited late in the vein-mineral paragenesis. It seems clear that these expandable clays choke off what would otherwise be permeable, vein-controlled fluid conduits similar to those which act as steam channels in the underlying reservoir rock (Hulen and Nielson, 1995a).

Another intriguing finding from our baseline geologic characterization of the SB-15-D core: Both past (now sealed) and present fluid channels -- the abundant Geysers hydrothermal veins -- are clearly high-angle features (Fig. 3). This fact apparently conflicts with the findings of Beall and Box (1989) and Thompson and Gunderson (1989), who presented convincing evidence that steam-bearing fractures in the reservoir graywacke at The Geysers were principally lower-angle features. A possible explanation for this discrepancy is that SB-15-D, drilled into a shallow "bubble" at the top of the reservoir (e.g. Gunderson, 1990) is not representative of the reservoir as a whole. Still, many of the other Geysers graywacke-reservoir cores archived at ESRI do host relatively high-angle hydrothermal veins (though these are not in general as vuggy as those from

SB-15-D). It is our contention that another corehole, drilled deeper into the reservoir, would allow more definitive direct characterization of the field's permeability network.

Finally, in spite of the great care taken to retrieve core at close to *in situ* conditions, it was soon clear on site that many of the fractures in the SB-15-D core were artificial features, induced both by the drilling process itself and by cooling of the core from nearly 235°C to ambient temperature. Moreover, even though the clearly natural vuggy veins are high-angle features, their strike azimuths are unknown -- they could be randomly oriented, or they could be aligned. This missing information would be very useful for reservoir-engineering purposes, for targeting new production wells, and for maximizing injection strategies. Therefore, we suggest that, where feasible, borehole imaging logs be strongly considered in addition to continuous core for similar operations in the future.

FUTURE PLANS

Sufficient time has passed since completions of the GCP's coring phase that a collaborating investigators' working-group meeting should yield meaningful results while furnishing new guidelines for the overall research effort. Such a workshop is tentatively scheduled for spring 1996, possibly in the Santa Rosa, CA, area.

Toward the close of the project, we plan to organize and chair a special session of an appropriate scientific meeting (e.g. GRC or AGU) dedicated to results from the GCP. Presentations at this session will form the nucleus of a special issue of a peer-reviewed journal such as *Geothermics*.

INDUSTRY RESEARCH AND TECHNOLOGY TRANSFER

SB-15-D was completed as a sidetrack to an existing Unocal Corporation steam-production well, scheduled for conversion to an injector. The sidetrack has since been outfitted by Unocal for this purpose, and the GCP corehole should remain useful for replenishing this sector of The Geysers' depleted reserves.

The baseline geologic characterization and the effort of the GCP's collaborating investigators are furnishing valuable new insight into fluid-flow controls, the various types of porosity and permeability, and the nature of fluid saturation. This information should benefit not only Unocal but also the following Geysers steamfield companies: NCPA, CCPA, and Calpine Corporation. Since the modern vapor conduits penetrated by SB-15-D clearly once also focused the flow of hot water, much of the information being obtained by this project should also be generally applicable in hot-water-dominated systems on a global basis.

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Figure 1. Location Map.

Figure 2. Downhole mineralogy and vertical mineral zoning of selected, representative, Geysers hydrothermal veins in core from corehole SB-15-D. Qtz - quartz; Cal - calcite; Kfsp - Potassium feldspar (adularia); Wair - Wairakite; Prehn - Prehnite; Ep - epidote; Py - pyrite; Il - illite; Il/Sm - mixed layer illite/smectite; Ch - chlorite; Ch/Sm - mixed layer chlorite/smectite.

Figure 3A. Dip-angle distributions for Geysers hydrothermal veins in core from successively deeper intervals of corehole SB-15-D. Note predominance of high-angle veins in all intervals.

Figure 3B. Dip-angle distributions for all SB-15-D Geysers hydrothermal veins with vuggy porosity.

HYDROLOGIC CHARACTERIZATION OF FOUR CORES FROM THE GEYSERS CORING PROJECT

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KEY WORDS

pressure-pulse decay, permeability, slip flow, capillary pressure, laboratory measurement, vapor-pressure lowering, The Geysers

PROJECT BACKGROUND AND STATUS

The rock matrix in The Geysers geothermal field in Northern California is of very low permeability, and the transport of stored liquid water from the interior of matrix blocks to the fracture network appears to be the rate-limiting step for energy extraction. Operations therefore depend upon accurate descriptions of the fracture and matrix properties. During 1994, 237 m of core were obtained from well SB15D in The Geysers Coring Project (Hulen et al., 1995). This year, we have measured some properties of the reservoir rock and cap rock on plugs from the recovered cores.

PROJECT OBJECTIVES

The objectives of this project are to provide data to assist operators at The Geysers, by measuring important properties of reservoir rocks, and to relate these data to the mineralogy.

Technical Objectives

- Measure matrix absolute permeability
- Measure fracture permeability
- Determine capillary pressure curves
- Relate these properties to the mineralogy of the plugs

Expected Outcomes

- These data will improve the accuracy of numerical simulators used to plan operations at The Geysers.
- The correlation of mineralogy with hydrologic properties will permit hydrologic properties to be estimated from mineralogy.

APPROACH

We designed and constructed a gas-pressure-pulse decay permeameter to measure permeabilities as low as 10^{-22} m². In this method, the sample is initially equilibrated with small-volume (2 mL) reservoirs at each end. The test starts when a pressure pulse is applied to one end of the sample. Pressures in both reservoirs are recorded automatically, and the permeability is calculated from the rate at which the pressure pulse decays (i.e., the rate at which gas flows through the sample). In small pores, when the mean free path of gas molecules approaches the pore size, gas permeability is enhanced by "slip flow," which is quantified by the Klinkenberg b factor. Permeability measurements were done at pressures ranging from ambient up to 29 kPa (500 psi) to calculate this factor. Capillary pressure curves were measured for 18 small plugs by equilibrating them with controlled humidity atmospheres and calculating saturation from measured weight gain.

Mineralogical description of the plugs is based upon visual and microscopic examinations of plugs and thin sections, and by X-ray diffraction.

RESEARCH RESULTS

The matrix permeabilities measured were low (1 to 10 nanodarcy). Preliminary values for measured permeabilities are summarized in Table 1. The three upper cores represent The Geysers' relatively impermeable cap rock; the lowest core was collected from the immediately underlying, uppermost, steam reservoir. We found a 10-fold difference in permeability between the reservoir and caprock samples, but we also found a conductive fracture in one caprock sample. Presumably this fracture is blocked at scales larger than these plugs (2.54 cm diameter).

The capillary pressures (moisture tension) measured were high (100's of MPa) at moderate liquid saturations. Figure 1 shows the capillary pressure curves for plug 26-2, measured in both the wetting and drying directions.

All the cores investigated are fine- to medium-grained Franciscan-Assemblage (late Mesozoic) metagraywacke, consisting of elastic grains (avg. 0.4 mm in diameter) of quartz, albite, chert, intermediate-composition metavolcanic rock, and argillite embedded in a matrix of illite, chlorite, and "rock flour" compositionally identical to the elastic grains. The metagraywacke is very poorly sorted, and appears to have little primary intergranular porosity.

The cores contain two types of veins -- Franciscan metamorphic quartz-calcite veins; and late Cenozoic, Geysers hydrothermal veins deposited in the high-temperature, liquid-dominated geothermal system which "dried out" to form the modern steam field. Together, these two types of veins account for 1 - 3.5 % of the volume of the plugs extracted from the cores and used for this study. The Franciscan veins are dense, mostly non-porous, and firmly cemented to their wallrocks. The Geysers hydrothennal veins are fragile, vuggy, and easily detached from the vein walls. As a result they are commonly refractured along strike. Some of these fractures are clearly artifacts from drilling or cooling but others are believed to be indigenous features which could be important permeability controls in the steam reservoir. Some of the caprock veins which might otherwise be permeable, are discontinuously blocked by late stage hydrothermal clays in the cores.

FUTURE PLANS

The mineralogy will be correlated with the measured properties. Relative permeability will be calculated by combining these data with sorptivity measurements. Additional measurements will be conducted using samples selected in consultation with industry contacts.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

UNOCAL reservoir engineers follow this work closely. A paper will be presented at the 21st Stanford Workshop on Geothermal Reservoir Engineering, Stanford, California, January 1996 (Persoff and Hulen, 1996).

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Persoff P., and Hulen, J. B., Hydrologic Characterization of Four Cores from The Geysers Coring Project, in 21st Stanford Workshop on Geothermal Reservoir Engineering, Stanford, California, January 1996.

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Table 1. Permeability of plugs from The Geysers Coring Project

Run	Depth (m below ground)	Visible vein ?	Fracture effective aperture, (micron)	Matrix perme- ability (m2)	Klinken- berg constant (psia)
15-2	290	Y	1.6	-	-
26-2	319	N	-	1.30E-21	391
54-1	393	N	-	2.02E-21	3055
86-2	482	N	-	2.67E-20	58.6

Figure 1. Capillary pressure curves for sample 26-2 (caprock, not fractured). Curves are power-law fits.

MICROSEISMIC MONITORING AT THE GEYSERS

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KEY WORDS

microearthquake, injection, seismicity, geothermal monitoring, The Geysers.

PROJECT BACKGROUND AND STATUS

In March of 1990 LBNL, in conjunction with the Coldwater Creek Operator Company (CCOC, now CCPA) undertook the collection, analysis, processing, and interpretation of the microearthquake (MEQ) data from the 16-station, digital, 3-component, high-frequency CCOC array in place at the Northwest Geysers geothermal field. During the monitoring period injection occurred at two different sites, wells Prati 8 and 9. Processing of the data revealed a strong correlation between injection and seismicity as well as definition of the structure from inferring relationships between the velocity and attenuation properties and the system components (geologic structure, steam content, etc.). It was also concluded from this work that the injection-related seismicity was superimposed on a more general pattern of seismicity related to such factors as "natural" seismicity and effects of fluid withdrawal.

Current work involves MEQ monitoring in the southeast Geysers area (see Figure 1). As a continuation of the NW Geysers work an additional 13-station array was installed by LBNL in the SE Geysers area in mid-1993. This is a cooperative effort with several operators (UNOCAL, NCPA, CCPA, and Calpine). The objective is to more fully understand the earthquake mechanisms associated with reinjection activities. Prior to the installation of the LBNL digital array, UNOCAL had been operating an analog system in the region. Data from this array had shown a good correlation with injection activities (M. Stark, UNOCAL, pers. comm. 1995). Although the UNOCAL system has been very useful, the results from the NW Geysers array had shown that precision location of events required digital acquisition at higher frequency content using three-component data. The SE Geysers array was configured to monitor the injection test that started in the SE Geysers in mid-December 1993.

PROJECT OBJECTIVES

Technical Objectives

- Demonstrate the utility of high-resolution, multicomponent, microearthquake (MEQ) data for: (a) locating high-permeability paths in the reservoir, (b) aid in the location of in-fill wells, and (c) monitoring effects of condensate injection in real time.

Technical Objectives (continued)

- Develop a tridimensional model of the reservoir; including: (a) P- and S-wave velocity and attenuation structure, (b) Poissons ratio model., and (c) 3-D structural model using MEQ location for inferring flow paths.

Expected Outcomes

- Improved software for streamlining collection, processing and interpretation of MEQ data in a routine fashion.
- Linkage of hydrological/geological/geochemical data to MEQ processes.
- High-precision location for reducing uncertainty in well siting.
- Recommendations for utility of using digital MEQ arrays.

APPROACH

The approach is to use state-of-the-art digital electronics over a wideband data width to collect the data. The NW Geysers experience had shown us that wideband, digital data collection at high frequencies had yielded precision results in the location of events, as well as offering the potential for detailed analysis of source properties as a function of production parameters and reservoir dynamics. The current approach monitors a selected area of the field in detail at various times of injection. There has been continuous monitoring of seismicity in the SE Geysers with a three-component, digital (16-bit) wide band with (480 samples/sec) 13-station array. The data are telemetered to a central site where automatic detection occurs and the full waveform data are recorded on tape. The tapes are returned to LBNL for analysis. All events are processed for location, magnitude, and source properties using a 3-D velocity model developed from joint inversion methods (location and velocity structure). All events are hand-picked for P- and S-wave arrivals. The source mechanisms are developed from moment-tensor solutions using the first amplitudes of the P- and S-wave information.

RESEARCH RESULTS

Figure 1 shows the seismicity pattern associated with the SE Geysers injection experiment during March 1994-March 1995. The significant findings are:

- A complex relationship exists between seismicity and geothermal fluid production and injection activities.
- Events with a negative volumetric component to their moment tensor have principal axes consistent with the regional tectonic stress field. These events can be explained by a shear

crack plus closing tensile crack model. These events could be caused by loss of shear strength due to fracture deflation caused by steam extraction.

- Events with a positive volumetric component to their moment tensor have principal axes consistent with normal faulting. These events can be explained by a shear crack plus opening tensile crack model. These events could be caused by sudden local stress changes when water flashes to steam within the reservoir.
- The relationship between seismicity and steam extraction, water injection, and reservoir parameters is not a simple relationship. That is:
 - ▶ Events occur in clusters and in more diffuse patterns.
 - ▶ Most clusters are near active injection wells.
 - ▶ Some clusters occur near formerly active injection wells.
 - ▶ Some clusters are in production-only areas.
 - ▶ Some injection wells have no associated seismicity.
 - ▶ The area in Calpine leases with the highest flow rates also has highest pressure and a low level of seismicity.
 - ▶ The upper part of the producing reservoir is generally aseismic.
 - ▶ The base of the seismicity is roughly coincident with the base of the producing zone.
 - ▶ Events below the producing zone have vertical linear trends.
 - ▶ NE-SW linear trends correlate with directions of high permeability inferred from tracer test and other data.

FUTURE PLANS

Work in 1996 will involve a synthesis and analysis of data collected up to December 1995. The array will be put in a dormant state until three months prior to the next phase of injection (early 1997). UNOCAL will still be operating their array during 1996.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

This project is a joint LBNL/industry (UNOCAL, Calpine, and CCPA) project. The companies provide field support, injection and production data as well a list of seismicity recorded and analyzed by the Unocal array. Meetings are held periodically to discuss research directions and priorities.

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Figure 1. Study area for SE Geysers injection study showing MEQ station locations (triangles) and seismicity (crosses) for the period of March 1994 to March 1995.

HEAT-FLOW STUDIES AT THE GEYSERS

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KEY WORDS

heat flow, The Geysers, thermal conductivity, high-temperature reservoir, pressure.

PROJECT BACKGROUND AND STATUS

This project originated with industry concern over the unexpectedly rapid decline of steam production from The Geysers geothermal field. Pioneering studies of The Geysers geothermal field modeled the system as a nearly isothermal ($\sim 245^{\circ}\text{C}$) vapor-dominated reservoir (VDR; hereafter referred to as the "normal" reservoir) underlying an impermeable, liquid-filled caprock of varying thickness. In the early 1980's, exploration and development of the northwestern Geysers revealed the presence of a second, higher temperature vapor-dominated reservoir (HTR) underneath the normal reservoir (NR; Walters *et al.*, 1988). Although a number of wells penetrate the HTR, there is little information from the HTR, and the nature of the NR-HTR transition is practically a matter of speculation. Temperatures within the HTR exceed 350°C , and it could serve both as a producing reservoir in its own right and as a source of heat for re-injection into the NR. Unfortunately, high quantities of non-condensable gases and HCl, both of which cause significant production problems, have also been associated with the HTR.

The absence of precision temperature and pressure data from the HTR severely limits research into these problems. Detailed studies in the caprock and the interval between the NR and HTR may reveal variations in conductive heat flow due to temporal variations in the Geysers system. Consequently, the first phase of this project was focused on the acquisition of equilibrium temperature and pressure logs from idle wells which penetrate the HTR. The second phase has been focused on measuring the thermal properties of Geysers caprock and reservoir rock at temperatures and pressures equivalent to in situ conditions. These measurements are necessary for the determination of heat flow variations with depth in the system. The project is scheduled to be completed in early 1996.

PROJECT OBJECTIVE

The overall objective of this project is to acquire thermal data from The Geysers geothermal field in order to develop an accurate and comprehensive understanding of the nature and evolution of the system.

Technical Objectives

- Obtain precision temperature and pressure logs from wells at The Geysers, particularly those penetrating the High Temperature Reservoir in the Northwest Geysers.
- Measure the thermal conductivity of selected core samples of Geysers reservoir and caprock at temperatures and pressures representative of in situ conditions.
- Combining the above measurements into vertical profiles of heat flow and utilizing these profiles to develop models for heat transfer through the High Temperature Reservoir, the "Normal" Reservoir (NR) and the caprock.
- Establishing a heat flow database for The Geysers for use in regional studies and local exploration efforts.

Expected Outcomes

- An integrated model of the nature of the High Temperature Reservoir, along with the implications of this model for future research and exploitation.
- Transfer of precision temperature and pressure data to appropriate industrial partners.
- A reinjection strategy for stimulating production in the High Temperature Reservoir while reducing the amount of non-condensable gases and corrosives entrained with the produced steam.
- Location of The Geysers heat flow database as a site on the internet, with digital data available to the public through online access.

APPROACH

The technical approach applied in this research involves the acquisition of precision, equilibrium temperature and pressure logs from idle wells in The Geysers. These data are combined with thermal properties measurements on cores and cuttings for a determination of the temporal and spatial variability of heat transfer above and within the steam reservoir. Collaborative arrangements with other research groups and Geysers steam producers are necessary for the success of this effort.

RESEARCH RESULTS

In 1991 and 1992, with the assistance of investigators from Sandia National Laboratories (R. Jacobson, P. Lysne, J. Dunn), temperatures and pressures were measured in a number of wells in the NW Geysers. The temperature data were combined with thermal conductivity measurements on drill cores and cuttings in a vertical profile of heat flow. Rock thermal conductivity is significantly temperature-dependent, and room temperature conductivity

measurements on cuttings were transformed to in situ values via the method of Sass *et al.* (1992a). Results based upon this method were published in the Transactions of the Geothermal Resources Council (Williams *et al.*, 1993). In order to establish confidence in these original estimates of in situ thermal conductivity, measurements on core plugs from The Geysers have been made in a new high temperature and pressure apparatus capable of simulating in situ conditions (Sass *et al.*, 1992b; Williams and Sass, 1994; Williams and Sass, in press). These measurements confirm the accuracy of the corrections applied in Williams *et al.* (1993) and are summarized in a paper that will be presented at the 21st Stanford Geothermal Workshop.

The thermal conductivities of most major rock-forming minerals vary with both temperature and confining pressure, leading to substantial changes in the thermal properties of some rocks at the high temperatures characteristic of geothermal systems. In areas with large geothermal gradients, the successful use of near-surface heat flow measurements to predict temperatures at depth depends upon accurate corrections for varying thermal conductivity. Previous measurements of the thermal conductivity of dry rock samples as a function of temperature were inadequate for porous rocks and susceptible to thermal cracking effects in nonporous rocks. We have developed an instrument for measuring the thermal conductivity of water-saturated rocks at the temperatures from 20 to 350°C and confining pressures up to 100 MPa. A transient line-source of heat is applied through a needle probe centered within the rock sample, which in turn is enclosed within a heated pressure vessel with independent controls on pore and confining pressure.

Application of this technique to samples of Franciscan graywacke from The Geysers reveals a significant change in thermal conductivity with temperature. At reservoir-equivalent temperatures of 250°C, the conductivity of the graywacke decreases by approximately 25% relative to the room temperature value. Where heat flow is constant with depth within the caprock overlying the reservoir, this reduction in conductivity with temperature leads to a corresponding increase in the geothermal gradient. Consequently, reservoir temperatures are encountered at depths significantly shallower than those predicted by assuming a constant temperature gradient with depth. We have derived general equations for estimating the thermal conductivity of most metamorphic and igneous rocks and some sedimentary rocks at elevated temperature from knowledge of the room temperature thermal conductivity. Application of these equations to geothermal exploration should improve estimates of subsurface temperatures derived from heat flow measurements.

These results confirm the vertical decrease in caprock heat flow with depth in the Northwest Geysers noted by Williams *et al.* (1993). This interpretation of this decrease in terms of the transient thermal effects of a recent intrusion is consistent with studies of the evolution of the vapor-dominated system through investigations of fluid inclusions (Moore, 1992) and steam chemistry (Truesdell *et al.*, 1993).

Additional support for this study will come from analysis of a new Geysers heat flow database being assembled at the USGS office in Menlo Park. With the assistance of Mark Walters, an industry consultant, we have assembled heat flow data from more than 600 industry exploratory holes drilled throughout the Geysers-Clear Lake-Calistoga region. These data are critically important to any regional study of The Geysers geothermal field and its associated thermal

anomaly. The database is loaded into a Microsoft Excel spreadsheet and, after final editing and processing is completed, will be made available online through the internet.

FUTURE PLANS

Plans for the current fiscal year and beyond are focused on three objectives. The first objective involves continued logging of wells at The Geysers to establish the areal extent of decreasing heat flow with depth in the caprock. Logging efforts will involve a new insulated temperature and pressure memory tool acquired by INEL and operated for DOE by the USGS. The caprock study will also include additional conductivity measurements under in situ conditions. Operations to clean out obstructions in wells that penetrate the HTR may also take place. Removing existing obstructions will enable temperature and pressure logging of the HTR at a number of locations, provide access for downhole fluid sampling of the HTR, and restore some bridged wells to producible conditions. The second objective centers on The Geysers heat flow database. Once final editing is completed, a digital version of this database will be placed online for public access through the internet. Paper copies will also be available by request to the USGS. The third objective is a continuation of our efforts to model heat transfer in the NW Geysers. Successful thermal modeling will provide a reliable explanation for the observed heat flow variations, perhaps establishing an explanation for the nature of the NR-HTR transition.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Companies involved in collaborative efforts with this project in the present or recent past include Calpine, CCPA, Unocal, and various consulting groups.

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INTEGRATED RESERVOIR ENGINEERING CHARACTERIZATION OF THE SOUTHEAST GEYSERS

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KEY WORDS

The Geysers, reservoir engineering, reservoir characterization, Fetkovich analysis, injection

PROJECT BACKGROUND AND STATUS

A series of reservoir engineering studies have been conducted in the Southeast Geysers, Unit 13 area to evaluate historical injection response. A calibrated numerical model has been created that closely matches over 13 years of historical production, injection, and injection derived steam response. The calibrated model has been used to evaluate different future injection scenarios to gain insight into an optimized injection program. The Unit 13 injection studies were initiated in 1991 and are essentially completed. One of the major difficulties with reservoir engineering studies at The Geysers is the lack of characterization of the permeability distribution. Reservoir engineering practice has been to assume regions of constant permeability, or rely on the history matching process to estimate reservoir permeability. This latter approach utilizes many assumptions that need to be numerically tested. A large amount of production data exists for The Geysers at the California Division of Oil and Gas in electronic format. This data can be used to perform a production type decline curve analysis to estimate the permeability-thickness product and wellbore skin for each well's drainage volume, as well as empirical Arps decline curve parameters. This data is currently being analyzed for use and integration with other subsurface data to develop a detailed reservoir engineering description. A study area (Figure 1) has been selected in the Southeast Geysers which includes the Unit 13 model study area, as well as two other Industry/DOE cooperative injection projects, the C-11 and D&V 11. These cooperative injection tests have provided additional data for use in reservoir characterization.

PROJECT OBJECTIVES

The project objectives are to demonstrate the application and utility of the production type decline curve technique for vapor-dominated geothermal reservoirs. This information, when integrated with additional subsurface information, can be used to develop a detailed reservoir engineering description. This detailed reservoir engineering description can be used as a primary input for numerical studies of The Geysers, eliminating a degree of freedom in the history matching process to deduce reservoir permeability. The use of actual field production data as a standard geothermal reservoir engineering tool enhances our understanding of the reservoir. This last objective is of direct interest to users of geothermal reservoir engineering results.

Technical Objectives

- Extension of the Fetkovich type production decline curve technique to vapor-dominated reservoirs for routine reservoir performance monitoring.
- Demonstration and application of the type production decline curve technique to a specific portion of The Geysers field.
- Integration of the type production decline curve results with other subsurface information to develop a reservoir engineering description of the study area.

Expected Outcomes

- Demonstrate the utility of the production decline type curve technique for steam reservoirs.
- A map of the permeability-thickness product (kh) for the study area at The Geysers.
- A reservoir engineering description of the study area with sufficient detail to be a primary input to numerical models of The Geysers.
- An improvement in the reliability of reservoir engineering results at The Geysers. While a quantitative estimate is difficult to estimate, a 50% improvement in reservoir permeability is reasonable.

APPROACH

The older petroleum literature discusses the use of the empirical Arps equation Equation (1) to describe production decline using semi-log analysis.

$$q(t) = \frac{q_i}{[1 + b D_i t]^{1/b}} \quad (6)$$

The recent petroleum literature increasingly emphasizes the use of production decline type curve analysis, more commonly referred to as Fetkovich analysis.

In 1973, M. J. Fetkovich combined the analytical and empirical relationships, Equation (1) by defining a decline curve dimensionless rate Equation (2) and decline curve dimensionless time Equation (3). The technique is based on the governing equations for pressure transient analysis in response to a specific flow rate history. This combined approach resulted in the type-production decline curve of dimensionless time versus dimensionless rate.

$$q_{Dd} = \frac{q(t)}{q_i} \quad (7)$$

$$t_{Dd} = D_i t \quad (8)$$

This approach integrated the theoretical transient and empirical depletion periods of a well's production history and allowed a greater degree of sophistication in the analysis of a well's production decline. The type decline curve approach allows the determination of the Arp's exponent b without the use of a statistical regression and allows further insight into reservoir performance.

The calculation of permeability-thickness product (kh) within the well's drainage radius is accomplished by using the dimensionless rate Equation (4) during transient response:

$$q_D = \frac{141.3 q(t) \mu \beta}{k h (p_i - p_{wf})} \quad (9)$$

and another expression of the dimensionless decline rate Equation (5).

$$q_{Dd} = q_D \left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2} \right] \quad (10)$$

Equation (4) is combined with Equation (5) to yield the productivity factor Equation (6).

$$\frac{k h}{\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2} \right]} = \frac{141.2 \mu \beta}{(p_i - p_{wf})} \left(\frac{q(t)}{Q_{Dd}} \right) \quad (11)$$

The values for $q(t)$, q_{Dd} , and r_e/r_w are determined from the type curve match and the permeability-thickness product (kh) is calculated. The magnitude of the calculated kh value in Equation (6) is determined by the vertical displacement of the production data on the type curve match, with a larger kh resulting from the data shifted vertically down relative to the type curve. By inspection of Equation (6), the choice of r_D (dimensionless radius, r_e/r_w) has an impact on the calculated kh, with larger values of r_D resulting in greater values of kh.

The value of r_e can be estimated from the well spacing or estimated drainage radius and r_w' (the effective wellbore radius, adjusted for wellbore skin) is calculated using Equation (7) which yields the wellbore skin factor, s , adjusted for a drainage area shape factor, s_{CA} .

$$r_w' = r_w e^{-(s + s_{CA})} \quad (12)$$

In the case of natural gas production, the pressures are adjusted using the real gas potential, defined as Equation (8).

$$m(p) = 2 \int_p^{p_b} \frac{p}{\mu(p) z(p)} dp \quad (13)$$

Mannon and Atkinson noted the real gas potential of a dry steam was a fairly linear function and could be approximated by a series of curve fit equations. At a temperature of 450°F and pressures greater than 100 psia, Equation (9) could be used to approximate the integral in Equation (8).

$$m(p) = 19.94 p^{2.078} \quad (14)$$

The case for gas well is achieved by combining Equation (6) and Equation (9) is presented in Equation (10).

$$\frac{k h}{\left[\ln \frac{r_e}{r_w} - \frac{1}{2} \right]} = \frac{P_s T_r}{19.87 (10^{-6}) T_s [m(p_i) - m(p_w)]} \left(\frac{q(t)}{q_{Dd}} \right)_{match pt} \quad (15)$$

A variation of this technique has been used at The Geysers by Zais et. al, S. L. Enedy, Ripperda and Bodvarsson, and K. L. Enedy. S. L. Enedy presented a modification of the black oil Fetkovich equation, Equation (6) for use in a geothermal steam field by converting the steam mass production rate to an equivalent reservoir volumetric rate in stock tank barrels at a normalized constant producing pressure. Enedy's approach evaluated the physical properties of steam at an average pressure. For the typical range of vapor-dominated reservoir pressures, this simplifying assumption is reasonable. The approach outlined above using the real gas potential method is a more rigorous method, applied specifically to a gas reservoir.

The open record production data at The Geysers is available for over 400 wells and the production data, including rate, days on production, producing wellhead temperatures and pressures is available in electronic format from the California Division of Oil and Gas, Geothermal Resources Office, Santa Rosa, CA (DOGGR). Open record well files for over 350 wells were copied and an electronic abstract from the DOGGR database was obtained for use in this study. This large dataset is worth a careful application of this technique.

RESEARCH RESULTS

A series of simulations have been performed to establish the idealized behavior of a 40-acre, radial bounded vapor-dominated reservoir using "Geysers-like" properties. These simulations were conducted both for a homogeneous porous and a fractured reservoir conditions, at water saturations from 0 to 90%, with permeability varying from 1 to 1000 mD. A very strong capillary pressure relationship was used to approximate the strong "negative suction" of water adsorption.

The results of these runs are still being compiled, however several items are worth noting. The Arp's exponent b for a fractured, 100% dry steam case is about 0.3 and increases to a maximum of about 0.8 as the matrix water saturation approaches 100%. Secondly, in the presence of a boiling phase (water), the kh from the type decline curve method is about 20% higher than the simulation input. This is due to the very large apparent compressibility of a boiling phase, giving rise to an additional apparent kh due to boiling. Results from production data where liquid water is present and boiling will need to be adjusted for this effect.

The Fetkovich type decline curve technique has been used for a number of wells in a preliminary study. This technique is very sensitive to changes within a well's drainage volume, with both production and injection interference effects readily apparent. The injection interference provides a direct measure of the production response to injection. Standard practice at The Geysers has been to use semi-log production decline curve analysis to estimate the Arps decline parameters. When the production history of a well responding to injection is plotted as a semi-log, the onset of injection response is typically very subtle and hard to detect. When the same data is viewed using the Fetkovich method, the onset of injection response is clearly evident as a shift to the right. The application of the Fetkovich method can be used to monitor injection response and to allow a more accurate assessment of injection derived steam.

FUTURE PLANS

Future plans are to finish reviewing the simulation cases and verify the mathematical extension of the Fetkovich technique to vapor-dominated steam reservoirs. The production data of wells in the study area will be analyzed and integrated with additional subsurface data in the study area. The Fetkovich analysis of the study area is my thesis topic at Colorado School of Mines and will be completed by May 1996. Integration of the Fetkovich results with additional field data will be completed during FY 1996.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Calpine and NCPA have released data on over 20 closed record wells in study area to assist in this project and to provide a comprehensive data set for this study. Future water augmentation projects in the Southeast Geysers will require increasingly detailed reservoir engineering studies to optimize the usage of this additional water. The real time monitoring of the production response to injection provides the reservoir engineer an additional tool to optimize the use of limited injection water.

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NOMENCLATURE

b	harmonic decline parameter
β	formation volume factor, rbbl/stb
C_t	total system compressibility, psi^{-1}
D_i	initial production decline rate, month^{-1}
h	reservoir thickness, feet

K	one thousand
k	permeability, mD
$m(p)$	real gas potential, psia cp ⁻¹
P_D	dimensionless pressure
p_i	initial reservoir pressure, psia
P_{wf}	flowing bottom hole pressure, psia
q	flowrate, stb/day or Mscf/day
$q(t)$	flowrate at time t , stb/day or Mscf/day
q_D	dimensionless flowrate
q_{Dd}	decline curve dimensionless rate
q_i	initial flowrate, stb/day or Mscf/day
r_D	dimensionless radius, r_e/r_w
r_e	well drainage radius, feet
r_w	wellbore radius, feet
r_w'	effective wellbore radius, feet
s	wellbore skin factor, dimensionless
s_{CA}	drainage area shape factor, dimensionless
t	time, hours
t_D	dimensionless time
t_{Dd}	decline curve dimensionless time
z	real gas deviation factor
μ	fluid viscosity, cp
ϕ	formation porosity, fraction
v	specific volume, ft ³ /lbm

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Figure 1. Location map of the study area.

OPTIMIZATION OF INJECTION INTO VAPOR-DOMINATED GEOTHERMAL RESERVOIRS CONSIDERING THE EFFECTS OF ADSORPTION

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KEY WORDS

reservoir performance, injection, optimization, adsorption, The Geysers.

PROJECT BACKGROUND AND STATUS

This project concerns the effects of adsorption (and subsequent desorption) of water in vapor-dominated geothermal reservoirs. Prior experimental work in our laboratory has provided an understanding of the magnitude and characteristics of the adsorption phenomenon. This research program includes the development of practical reservoir engineering methods to include the adsorption phenomenon in optimization studies of vapor-dominated reservoirs. The investigation has placed specific emphasis on the production and injection characteristics of The Geysers steam reservoir. A large number of measurements of Geysers core materials over the past year have provided an understanding of the overall magnitude of adsorption and the way that adsorption depends on reservoir rock type. Results suggest that adsorption can be characterized by the rock's internal surface area. There is also indication that adsorption is more prominent within the felsite, although these results are still under investigation.

PROJECT OBJECTIVE

Technical Objectives

- Apply simulation models to analyze field performance and design of reinjection strategies.

Expected Outcomes

- Improved interpretation of field performance data and aid optimization of future production and reinjection operations.

APPROACH

Core samples from The Geysers have been collected over the past year, with the specific objectives of obtaining a fieldwide understanding of the variability of the adsorption phenomenon and characterizing the relationship between adsorption and rock type.

We are currently investigating the inclusion of the adsorption-desorption data into numerical models used for reservoir engineering performance matching and forecasting. These models will be used to develop an optimization procedure applicable to vapor-dominated geothermal reservoirs in general and The Geysers reservoir in particular.

PROJECT STATUS

Available numerical simulation models have been evaluated and are now ready to be integrated into the study. Optimization algorithms are in the process of development.

Experiments in earlier years 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 we determined the need to confirm these results using a different experimental procedure. These experiments are ongoing.

RESEARCH RESULTS

The work over the past year has yielded several very important results:

1. Experimental measurements on The Geysers cores have shown the relationships between different locations and rock types from the point of view of their adsorption characteristics. Surface area is a particularly important indicator variable.
2. The effects of adsorption on injection and on tracer transport have been analyzed, using analytical and numerical modeling.

PLANS

We will integrate the results on the adsorption characteristics of The Geysers as a function rock type into the injection optimization study. This study will undertake the optimization of injection strategy, considering the effect of the readsorption of the reinjected water.

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WATER ADSORPTION

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KEY WORDS

geothermal reservoir, adsorption, The Geysers, rocks.

PROJECT BACKGROUND AND STATUS

Any reliable model of the behavior of vapor-dominated geothermal reservoirs must include information about the amount of water present in the micropores and adsorbed on open surfaces. To estimate the size of the available resource and to predict pressure changes during operation, it is important to know what fraction of the water is present as adsorbed layers and capillary condensate with an equilibrium vapor pressure lower than that of bulk water. Operating experience suggests that adsorbed and pore water may act as either a source or a potential sink directly influencing the response to reinjection processes. This response may be difficult to predict if hysteresis phenomena inherent in condensation/evaporation of water in mesoporous systems are not taken into account.

The physicochemical complexity of interactions between molecules of a strongly polar substance (water) and various aluminosilicates and oxides forming a heterogeneous capillary system of pores with unknown shapes and size distributions (rock matrix) makes it impossible to predict with a reasonable certainty the water retention by the rocks at different temperatures and pressures. The most useful data would be those obtained at temperatures in the vicinity of the actual reservoir temperatures. The temperature in most of The Geysers reservoir is approximately 240°C, and a higher temperature reservoir is found in the northwest area of the field. The results of experimental measurements of adsorbed water published in the literature have been limited to about 150°C, with most of the experiments conducted at 120°C and below (Shang *et al.*, 1994a, 1994b, 1995).

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

- Rock samples were obtained and prepared.
- Samples were sent to an external facility where BET surface area analyses were made using nitrogen and krypton at 77 K. These analyses yielded surface areas and total pore volumes of the samples. Densities were also determined by the helium displacement method.

- The Oak Ridge National Laboratory (ORNL) isopiestic apparatus was completely overhauled in order to prepare it for adsorption measurements. This included detecting and eliminating remaining leaks, which were not a major obstacle in its previous applications, as well as modifications to achieve the highest possible weighing accuracy.
- The density of each sample was determined independently of the PMI analysis by measuring the buoyancy in compressed argon gas.
- The 150°C adsorption and desorption isotherms were determined for 12 Geysers rock samples taken from three different wells and ground to three different grain sizes. Approximately 20 values of p/p_0 from 0 to 0.98 were investigated. The time needed to reach equilibrium was estimated. At least 14 hours of equilibration time was allowed after each pressure change.
- The 200°C adsorption isotherm was determined for the same samples in a similar way.

At present, the 200°C desorption isotherm is being measured. It is expected that measurements at this temperature will be finished in early January 1996. Next, the 250 °C measurements are planned in the first quarter of 1996. Our preliminary results indicate that the isopiestic apparatus is suitable for making adsorption measurements with sufficient precision and reliability.

PROJECT OBJECTIVES

Technical Objectives

- Experimental determination of water retention per unit of mass by rocks from The Geysers geothermal field as a function of vapor pressure at temperatures from 150°C to 250°C when pressure is increasing ('adsorption' isotherms) and decreasing ('desorption' isotherms).
- Characterization of rocks from The Geysers using both the data obtained by us and BET surface area analyses done by an external laboratory (including determination of pore sizes and shapes), and quantitative correlation of the water retention phenomena (including temperature dependence).

Expected Outcomes

- Obtain accurate and reliable water retention data for representative samples of The Geysers rocks at the reservoir temperature (for the first time). These data will then be available for use in material balances in the reservoir models.
- Resolve the issue of the temperature dependence of the amount of water retained.

Expected Outcomes (continued)

- Expand the knowledge about the structure of The Geysers rocks and about water-rock interactions. Gain insight into the type of rock-water interactions that are present. The interactions may be chemical in nature (pertaining to the fraction of water which is irreversibly bound to the surface) or physical in nature (pertaining to the fraction of water which may be retained on the surface and in the pores, or released, depending on the reservoir pressure).

APPROACH

The ORNL high-temperature isopiestic apparatus is a unique facility capable of precise and accurate measurements of the change of mass of a sample under high-temperature and high-pressure conditions. This ability makes it an instrument suitable for measurements of adsorption by materials characterized by relatively small internal surface areas (such as The Geysers rocks). With this instrument, the parameter measured is the change of the mass of the solid with the addition of adsorbed water. The sorptometers used by other investigators for measuring adsorption on geothermal reservoir rocks rely on measurements of vapor pressure changes in vessels of known volumes. The total volume of the sorptometer is kept small to increase its sensitivity to relative pressure changes, but the small volume also makes the instrument more sensitive to leaks, temperature variation, and errors in calibration of the internal volumes of the sample chamber and the vapor chamber. In the isopiestic apparatus, the mass is measured by comparison to a set of standard weights placed inside the pressure vessel together with the samples. The densities of the samples, which must be known in order to correct for the effect of buoyancy, are measured inside the isopiestic apparatus by weighing the samples in vacuum and then in an atmosphere of compressed gas (e.g., Ar) of known density. The large volume of the isopiestic vessel (about 28 L) makes small leaks of less consequence. These characteristics of the isopiestic apparatus make it relatively easy to evaluate the time needed for reaching equilibrium, as the samples may be left under the same vapor pressure for many days and the change of mass with time can be monitored. The isopiestic apparatus is capable of, and has been previously used for, measurements at 250°C and 40 bar.

In conjunction with the water adsorption measurements, BET surface area analyses were performed by Porous Materials Inc. (PMI) on the same rock samples using nitrogen or krypton adsorption measurements at 77 K. Analyses of this type are standard for determining specific surface area and pore volume (also average pore diameter) of solids. These parameters are the most important in estimating water retention capability of a porous material. The same laboratory also determined the densities of the samples by helium pycnometry. Their results were then compared with our own density values obtained by measuring the effect of buoyancy in compressed argon.

RESEARCH RESULTS

The measurements were performed on cores taken from the producing steam reservoir. Well numbers and approximate depths are as follows (per Jeff Hulen of the University of Utah, Earth Science Research Institute who supplied the samples):

- NEGU-17, 8530-8530.5 ft (rubble)
- Prati State-12, 6261.7-6261.8 ft
- MLM-3, 4336-4336.3 ft.

The rocks were crushed and sieved. Three fractions were prepared from each core with the following grain sizes: 2.00 - 4.25 mm ('coarse'), 0.355 - 2.00 mm ('medium'), and 0 - 0.355 mm ('fine'). The surface areas as determined by PMI ranged from 0.64 to 3.52 m²/g. The examination of the BET surface analysis data showed, however, that the accuracy of these determinations may be too low to reliably draw conclusions about the differences in surface area between the three rocks and between their size fractions.

The PMI helium pycnometry results showed the densities of the fine fraction were smaller by up to 0.79 g/cm³ compared to the two larger fractions. Our measurements yielded fine fraction densities that were larger by up to 0.34 g/cm³ than those of the two larger fractions. The precision of our density measurements ($\pm 1\%$) was better than that of PMI ($\pm 3\%$). We used our density values to correct for the buoyancy effect in water vapor.

Four samples of each rock were loaded in the titanium cups of the isopiestic apparatus (the medium fraction of each of the rocks was loaded in two cups, so that repeatability of the measurements could be verified). Four of the remaining cups contained pure minerals (silica gel, chlorite, magnetite, and anatase). The data obtained on these standard samples, which have surface areas and water retaining capacities significantly higher than The Geysers rocks, can be compared with literature results. The last four cups contained the standard weights made of titanium.

A relatively long time was spent preparing the isopiestic apparatus for adsorption measurements. After the first trials the electromagnetic balance coil was replaced and modified in order to obtain higher weighing precision. All the seals were replaced, and the pathway for electric cables from the vessel was improved. The servo amplifier circuit was also modified to improve reliability and reduce measurement time. As a result, the repeatability of water retention measurements was improved, and is now estimated to be better than 0.05 mg/g for sample masses between 4 and 11 g. The vessel is now free of significant leaks, and it can be left for equilibration for several days with a negligible pressure change. Measurements at low p/p_0 (sub-atmospheric pressures) are now more reliable.

The amount of water adsorbed by The Geysers rocks at 150°C and $p/p_0 = 0.8$ varied from 0.8 mg/g for the coarse fraction of Prati State-12 rock to nearly 4 mg/g for the fine fraction of the

MLM-3 rock. The water retention capability was generally increasing in the sequence: Prati State-12 < NEGU-17 < MLM-3; and in the sequence: coarse < medium < fine. The fine fraction adsorbed significantly more water than either the medium fraction or the coarse fractions. The differences between the medium fractions and the coarse fractions were much smaller, sometimes of the same order as the differences resulting from the probable heterogeneity of the samples. We were able to directly compare our 150°C adsorption isotherms for MLM-3 rocks (either 'coarse' or 'medium' fractions or their median) with the 120°C isotherm (represented by a fit to an adsorption equation) measured by Shang *et al.* (1994a, 1994b) for the same rock, taken from nearly the same depth (4330 ft). The agreement is excellent for p/p_0 up to 0.8 and good above this value.

A characteristic feature of the results of Shang *et al.* is complete absence of closed or even nearly closed hysteresis loops for water adsorption, although they obtained closed hysteresis loops for nitrogen adsorption (Shang *et al.*, 1995). The desorption branches of all their isotherms are significantly higher than the corresponding adsorption branches and they remain so down to the lowest p/p_0 values. Our results at 150°C show closed or nearly closed hysteresis loops for all 'coarse' fractions and some of the 'medium' fractions. The shape of the hysteresis loops is of the type H3 according to the IUPAC recommended classification (Sing *et al.*, 1985). This type of hysteresis loop usually has been associated with adsorbents having slit-shaped pores. The 'fine' fractions all show large differences between the adsorption and desorption branches, persisting down to $p/p_0 = 0$, similar to the results of Shang *et al.* The dependence of water retention on the grain size of the samples is very strong for finely divided samples. We explain this behavior by the presence of 'fresh' surface in the crushed rocks. This surface is able to adsorb some amount of water irreversibly at high p/p_0 , and, as a result, the desorption branch is higher than expected at low p/p_0 . However, our results obtained thus far at 200°C seem to confirm this assumption. The adsorption isotherms at 200°C approximately follow the desorption isotherms at 150°C at low p/p_0 even for the fine fractions (the 'fresh' surfaces don't exist any more, as all the surface was saturated to capacity with chemically bonded water molecules during the 150°C run). It is expected that all the hysteresis loops for these samples will now be closed. If the samples were saturated with water before starting the first run, they would probably all show closed hysteresis loops at 150°C.

Taking into account the above considerations, our results do not confirm the increase in water retention at a given p/p_0 with temperature observed by Shang *et al.* between 80°C and 130°C for various rocks including samples taken from the MLM-3 well similar to our MLM-3 samples. Their observations imply that the process of condensation of water onto the surface of the rock and into its pores is slightly less exothermic than the process of ordinary condensation of water vapor on bulk water (with no surface effects). Additionally, the increased water retention effect observed by them increased with p/p_0 . This is inconsistent with our model, because as the adsorbed layers become thicker and the larger pores are being filled, the process should become increasingly similar to the condensation to bulk water, with no temperature dependence of water retention at a given p/p_0 . Our results indicate that the temperature effect is rather small - close to zero or slightly negative. This seems plausible, as the presence of the solid surface under the

adsorbed layers should be an energetic advantage for further condensation and should make the process more exothermic. Our new data indicate that there is at most a small decrease in adsorption with increasing temperature at high p/p_0 . This contrasts with the results of Shang *et al.* at lower temperatures, which indicated the strong increase in adsorption with increasing temperature at high p/p_0 described above. Since the initial state of the samples was different before the first (150°C) and the second (200°C) runs (the rocks were not previously exposed to saturated water vapor at elevated temperatures), the final conclusions will be easier to draw after the 250°C run is completed.

FUTURE PLANS

We will continue the measurements at 200°C, and in the first quarter of 1996 we expect to finish measurements on the 250°C isotherms. This last temperature is close to the actual conditions of the "normal" Geysers reservoir. The pore size analyses will then be made using mathematical models of capillary condensation (Gregg and Sing, 1982). We will also attempt to explain the observed dependence on temperature by calculating contributions of the known temperature effects. This may allow us to estimate water retention at even higher temperatures.

The results obtained thus far will be presented at the Twenty-First Annual Stanford Geothermal Reservoir Engineering Workshop in Stanford, California, January 22-24, 1996 and published in the workshop Proceedings.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The results are expected to be of interest to companies operating geothermal reservoirs where a vapor phase zone is present. The knowledge of the adsorption/desorption isotherms and of the hysteresis characteristics is considered to be essential in modeling the behavior of the reservoirs, including the reservoir response to reinjection processes.

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HEAT MINING TO EXTRACT HOT DRY ROCK GEOTHERMAL ENERGY: TECHNICAL & SCIENTIFIC PROGRESS

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KEY WORDS

Fenton Hill, flow testing, GEOCRACK, hot dry rock (HDR), logging, reservoir modeling, reservoir engineering, reservoir lifetime, thermal drawdown

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, NM 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. 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 about 8 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% (based on the injection rate) 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. The flow testing was suspended only because of budget constraints.

With the Fenton Hill HDR Test Facility on standby status during FY 1994, work was concentrated on reservoir modeling studies and passive reservoir studies that could be accomplished at low cost. Data from the LTFT were used to improve the GEOCRACK reservoir model being developed by Kansas State University to more closely simulate the behavior of the reservoir at Fenton Hill both during steady-state and transient flow operations. Temperature calculations were coupled to the hydraulic and mechanical computations of GEOCRACK to enable the model to predict the thermal effects of reservoir operations.

Simulations conducted with the modified version of GEOCRACK indicated that a large cooled region would develop after 40 years of circulation at Fenton Hill under LTFT conditions, but the cooling front would not have reached the production wellbore even after such a long term of continuous operation. In addition, GEOCRACK calculations showed that the flow rate through the reservoir at a constant applied pressure would at first decline, but after about a year would begin a period of continual increase. Unless restrained by active intervention, this flow increase would eventually lead to short circuiting. In brief, GEOCRACK, as modified to include thermal performance, predicts a long thermal lifetime and constantly improving productivity for the Fenton Hill HDR reservoir and similar HDR reservoirs that may eventually be developed around the world.

A few wellbore logging experiments conducted during FY 1994 confirmed that the primary injection zone at Fenton Hill is located at about 12,000 ft and that active flow paths within the reservoir extend some 1,500-2,000 ft above that point. In addition, inflow to the reservoir from the overpressured far field was measured as the reservoir pressure was allowed to decay, thus demonstrating that at least a portion of the water "lost" during circulation is actually being stored at the periphery of the fractured region of the reservoir. A series of static pressurization tests showed the nonlinear response of the reservoir "fluid volume" to changes in imposed pressure.

Finally, the response time of the Fenton Hill production well to pressure increases in the injection wellbore (after a total circulation period of about 9 months) was documented to be about 14 minutes.

PROJECT OBJECTIVES

Technical Objectives

- Work with private industry and other interested parties to address the remaining technical issues for producing energy from hot dry rock resources.

Expected Outcomes

- HDR technology transferred to private industry for application in both HDR and hydrothermal settings to advance geothermal reservoir productivity and increase the potential for development of the entire geothermal resource base.

APPROACH

The long-term flow test (LTFT) effort of 1992-1993 demonstrated that HDR heat mining technology can produce clean energy in significant quantities over an extended time. Results of the flow testing, although limited, were uniformly positive. Upon termination of the LTFT, the Fenton Hill HDR test facility was placed on standby status. 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. Development work during 1994 was concentrated on reservoir modeling and documentation of previous field results.

For FY 1995, the HDR budget was increased enough to permit the acquisition of a centrifugal injection pump and the implementation of a limited flow-testing program. The fall and winter months were spent preparing the site for flow testing, including procurement and installation of the new pump. A reservoir verification flow test (RVFT) was initiated in early May 1995 with the aim of first verifying that the system could be brought back into operation at the conditions in effect at the end of the LTFT, and then obtaining circulation data that would be important to the operation of an industry-led HDR project envisioned at that time.

RESEARCH RESULTS

Reservoir Verification Flow Testing (RVFT)

Test Protocol

In order to repeat the operating conditions prevailing during the LTFT and obtain maximum system productivity without reservoir expansion, the RVFT was run at a constant injection pressure of 3,960 psi. On the basis of controls applied at the production wellhead, the test was divided into four segments as follows:

Segment 1 -- A backpressure of 1,400 psi was imposed at the production wellhead for the first five weeks of circulation. This test segment simply re-established the steady-state operating conditions in effect at the end of the LTFT in 1993.

Segment 2 -- A backpressure of 2,200 psi was imposed at the production wellhead with continuous production. This segment evaluated the operation of the system with a smaller net pressure drop across the reservoir than that applied in Segment 1. In a commercial system, pumping costs would be reduced in direct proportion to decreases in the pressure drop across the reservoir.

Segment 3 -- A backpressure of 2,200 psi was applied at the production wellhead and the production wellhead was shut-in for a period of 25 minutes each day. Observations from the earlier part of this test and from flow testing in 1992-1993 showed that brief shut-ins of the production wellbore could enhance net energy production. The 25 minute daily shut-ins of Segment 3 were designed to illustrate this phenomenon under routine operational conditions.

Segment 4 -- A backpressure of 2,200 psi was imposed at the production wellhead for 20 hours a day, but for a 4-hour period each day, the backpressure was reduced in a programmed manner from 2,200 to 500 psi to temporarily induce a large, and essentially constant, increase in the production flow rate. This part of the test was designed to demonstrate that such intermittent flow increases could be employed to provide peaking power or load-following energy production from the HDR resource. The demonstration of such capability should greatly increase the interest in HDR by electric utilities because rapidly adapting to surges in electricity demand is one of their major concerns at present.

The injection pressure and production pressure profiles over the span of the RVFT are graphically illustrated in Figure 1. These two pressures constituted the primary control parameters applied during the RVFT.

Test Results

Power Production -- Table 1 shows representative power production rates during each of the 4 segments of the RVFT compared to Phases 1 and 2 of the LTFT and the short period of steady-state testing conducted after a sudden increase in reservoir flow was observed at the close of the

LTFT in 1993. The power-production rate observed during Segment 1 of the RVFT indicated that some residual effects of the sudden flow increase event persisted even after two years of reservoir dormancy. The most obvious process expected to occur during a long period of reservoir shut-in is temperature recovery at the surfaces of open joints within the reservoir. It thus appears at this time, that localized reservoir temperature profiles may have played an important role in the initiation of the sudden flow increase and in its subsequent mitigation.

The increased backpressure imposed on the system in Segment 2 of the RVFT resulted in a decline in power production on the order of 14%. This is in response to a 30% decrease in the driving pressure across the reservoir. Exactly how this driving-pressure decrease would translate into decreased injection pumping-power requirements in a practical HDR facility is not easy to calculate because that would depend on a number of factors including parasitic power requirements, the efficiency of the injection pumping equipment, and the degree to which the residual pressure of the fluid at the exit of the production well (1,400 psi in Segment 1 vs. 2,200 psi in Segment 2) could be recovered as useful power or, alternatively, maintained across a high-pressure surface plant.

Segment 3 of the RVFT once again demonstrated the value of briefly shutting in the production wellbore on a daily basis as power production in this Segment increased by more than 10% over that of Segment 2. This characteristic behavior of an HDR system is discussed in detail in a paper by R. DuTeau, 1993.

Segment 4 of the RVFT produced perhaps the most important data generated during this short flow test period. Operations during this segment unambiguously demonstrated that it is possible to produce power for several hours a day at a rate about 60% greater than the established baseload level. Remarkably, exercising the reservoir as was done in Segment 4 resulted in a baseload power-production level that was slightly higher than the reference steady-state production rate of Segment 2. The results of Segment 4 verify that HDR reservoirs can be operated to produce both baseload and peaking power and highlight the potential for this technology to fill a unique and important role in meeting the needs of the electric power industry.

Injection and Production Flow Rates -- The injection and production flow profiles over the term of the RVFT are illustrated in Figure 2. The figure shows that both the injection and production flow rates became increasingly stable as Segment 1 of the test proceeded toward equilibrium conditions. Note also that after each brief shut-in for pump maintenance, the production and injection flow rates tended to level out at slightly higher values. Our previous experience tells us that brief production shut-ins tend to enhance the steady-state production rate, and only after a relatively long period of continuous flow (on the order of weeks) does the steady-state flow rate gradually decline to the pre-shut-in value.

The imposition of a higher backpressure on the production wellhead at the start of Segment 2 was rapidly reflected in a decline in both the production and injection flow rates. When brief daily shut-ins were intentionally scheduled during Segment 3, an enhanced steady-state production flow rate was observed. In a practical HDR plant the improved production stability imparted to the system by this procedure could be achieved by scheduling brief shut-ins during periods of low

energy demand and sequencing them among the multiplicity of production wells that such a facility would no doubt utilize.

During Segment 4, the flow rate was enhanced by about 60% for a 4-hour period each day by dropping the backpressure on the production wellhead from 2,200 down to 500 psi in a controlled manner. When the production backpressure was subsequently methodically returned to 2,200 psi, the flow rate declined only to about the level it had been at just prior to the increased production period. Figure 3 is an expanded fluid production profile for a time frame including the final two high flow excursion periods of RVFT Segment 4. This figure illustrates the rapid adjustment of flow from one level to another and the stability of flow at each of the selected levels.

In this test, Segment 4 was run in the open-loop mode for 4 hours of enhanced production. The injection pressure was held steady at 3,960 psi throughout Segment 4. However, the injection flow increased significantly during the period of enhanced production, though not enough to accept all of the excess produced fluid. The higher injection flow rate slowly tapered off toward its normal level after the close of the enhanced production period with the net result that over each 24-hour time frame, the total injection and production flows remained in balance and the overall reservoir hydraulic properties did not change significantly.

In a commercial plant, it is anticipated that a closed loop operating strategy would be maintained during periods of increased production, with the injection pressure temporarily boosted as required to reinject all of the excess fluid produced. How would periodic but relatively brief excursions in the injection pressure affect the reservoir? This issue was among those scheduled to be investigated if it had been possible to continue with the RVFT.

Production Fluid Temperatures -- Figure 4 shows that the production temperature varied directly with the production flow rate throughout the test period. The apparent drops in temperature during all the shut-in periods have no physical meaning and are artifacts of the data collection and presentation process. However, the temperature increases shown during each of the 4-hour periods of increased flow in Segment 4 of the test are real. During these periods of enhanced production, the increased power output resulted from a combination of an elevated flow rate and a higher production temperature.

Because load following operations implemented by inducing periodic excursions to higher production levels from baseline production rates lead to only modest temperature cycling in the production wellbore (about 12°C in this test), the most perilous aspect of full on/off cyclic operations is avoided. Segment 4 of the RVFT not only showed the potential for using HDR energy systems in load-following applications, but also demonstrated that the most serious problem typically associated with cyclic operation of geothermal systems - excessive temperature cycling of the production wellbores - can be readily obviated by the application of an appropriate operating strategy.

As measured at the surface, there was no decline in the temperature of the produced fluid over the 2-month span of this flow test. The large HDR reservoir at Fenton Hill has now been operated for a total period of almost one year without a measurable decline in the temperature

of the production fluid. Unfortunately these operations have been intermittent and spread over a time period now approaching a decade. Even so, the data are extremely encouraging in respect to the development of HDR systems with the thermal lifetimes required for commercial viability.

Supporting Reservoir Analyses

Production Wellbore Logging -- Two wireline temperature logs were conducted during the course of the RVFT, on June 22 and July 10, 1995, respectively. A faulty amplifier setting during the first log caused the recorded temperature to be somewhat low and thus require some interpretation. This problem was corrected before the second log and, because the deviations due to the improper amplifier setup were well-understood, it was possible to correct the results of the first log with a high degree of certainty. The corrected data for the June log showed a mixed mean temperature of about 227° at the outlet from the production zone, while the next log conducted only 18 days later showed this temperature to be about 226°. There was thus an apparent temperature decline of about 1°C over the short time span between these two logs.

Figure 5 shows a typical temperature profile measured in logging through the open-hole interval of the production wellbore, with four specific depths indicated by the letters A to D. The inset to the figure summarizes the logging data at these specified depths for logs conducted since 1992. Based on the data of Figure 5, it appears that there may be a continuing trend toward a slight temperature decline in the production wellbore. The dynamic nature of the temperature profile within the open-hole region of the production wellbore as reflected in the changing temperature differences between points A and C (2.5°C, 2.2°C, 0°C, 0.3°C and -1.4°C, respectively) as time moves forward is also notable. Finally, the data indicate that over the span of the long shut-in period from May 1993 to May 1995, the temperature across the production zone tended to become isothermal (see data of June 22, 1995), almost certainly as a result of convection currents in the reservoir. As shown in the data of July 12, 1995, the convection effects were subsequently washed-out by the influence of the circulating fluid as the RVFT proceeded.

Tracer Measurements and Chemical Analyses -- Two tracer tests were carried out during the RVFT. The first was begun on June 6, about a month into the test and the second was initiated on July 11, near the end of the test period. The tracer data was complicated by the significant growth of flow through a leakage pathway in the injection wellbore during the period between the two tests (which resulted in a significant portion of the second tracer returning to the surface via that alternate pathway). The trend of the data, however, supported earlier findings that tracer "first arrival times" tend to lengthen as flow testing proceeds, ostensibly due to the closure of short flow paths that may have cooled somewhat.

Chemical analyses during the RVFT showed that the dissolved solids and gas content of the circulating fluid was very similar to that observed during the LTFT 2-3 years earlier. In fact, the chemical composition of the circulating fluid, with total dissolved solids in the range of 3,000-4,000 ppm and dissolved gases at a level of about 2,000 ppm (almost entirely carbon dioxide), has been remarkably stable over the entire term of flow testing at Fenton Hill.

Other Reservoir Testing

Low-Pressure Reservoir Flow Testing

Two low level flow tests conducted early in FY 1995 documented the operation of the Fenton Hill system under relatively low-pressure injection conditions. Production rates of approximately 22 gpm were obtained with injection at pressures in the range of 2,450-2,475 psi and backpressures on the production well of 1,100-1,200 psi. At these low flow rates, the temperature of the produced fluid dropped to about 100°C by the time it reached the surface.

Reservoir Pressure Maintenance

For the period of about 6 months ending in early March 1996, the HDR reservoir was simply maintained at a pressure of 1450 psi. Toward the end of this period, a careful measurement was made of the leakage from the reservoir to the far field. The data for the first 7 days of March showed that leakage to the periphery of the reservoir had declined as a result of extended, steady-state pressurization to a level of only 0.9 gpm. Although 1450 psi is well below the operating pressure of 3960 psi employed during the LTFT and RVFT campaigns, the low level of leakoff from the stimulated region of the reservoir observed during this extended pressurization experiment bodes well for low water losses after extended operations at any pressure level below that which induces reservoir growth as reflected in seismic activity.

Continuing Development of the GEOCRACK Reservoir Model

Improvement in Simulating Reservoir Flow Paths

In simulations with the two-dimensional (2-D), coupled thermal/fluid-flow GEOCRACK model, the horizontal joint spacings are specified in the range of 20-40 meters. Figure 6 shows a schematic vertical section of the Phase II HDR reservoir at Fenton Hill, with an arbitrary, 80-meter-thick horizontal slice highlighted.

Until this past year, fluid flow was simulated with the 2-D GEOCRACK model by arbitrarily setting the height of all the model rock blocks at 80 meters. At the same time, however, the specified fluid heights bounding the solid elements were being randomly varied across the lateral extent of the reservoir. Varying the fluid heights provides the range of permeabilities of discrete fluid flow paths needed to replicate the high degree of flow dispersion indicated by the results of tracer testing at Fenton Hill and gives the model a quasi 3-D aspect.

The tracer results showed that the Phase II reservoir is comprised of flow paths that vary fairly uniformly in residence time from a few hours to several weeks. This variability cannot be replicated by GEOCRACK using a simple rectangular array of interconnected flow paths if constant fluid element heights are specified. In particular, the longer residence-time flow paths imply the existence of very "deep" joint connections where the fluid velocity is very low. These would suggest the assignment of some very "deep" fluid heights by the model. However, it was found that specifying such "deep" flow paths when running a GEOCRACK thermal simulation

resulted in an excessive amount of rock block cooling if the heights of the rock blocks they bounded were not also adjusted to compensate for the "deep" flow paths.

To further illustrate this point, Figure 7 shows two views of a small portion of the 2-D GEOCRACK flow model for the Fenton Hill reservoir: Figure 7a is a plan view of the interconnected flow paths in a portion of the jointed reservoir. Figure 7b is an isometric view of the same flow paths indicating the variability in fluid element heights bounding the solid elements. With a constant rock block height, the high degree of variability of the fluid heights from joint to joint sometimes resulted in exaggerated thermal behavior in discrete portions of the reservoir. This phenomenon is easier to understand if one observes that, in some cases (in order to match the tracer results), a model rock block could be bounded by fluid elements with heights much in excess of the height of that solid element, leading to excessive cooling and an exaggerated thermal dilation of the rock block. Conversely, a nearby rock block could be bounded by overly short fluid elements resulting in reduced cooling and sustained high flow impedance.

To correct this problem, the specification of constant rock-block heights across the reservoir has recently been dropped. Now, each rock block created in the model representation of the reservoir has a height for heat transfer that is equal to the actual mean of its bounding fluid element heights. Specifically, the solid element in the middle of the plan-view flow geometry shown in Figure 7a would have a height equal to the mean of the heights of the six bounding fluid elements depicted in the isometric view (7b) of the figure. Although this change has entailed considerably more "bookkeeping" in executing the numerical solutions, it appears to have reduced the excessive degree of variability from model run to model run when several random distributions of fluid heights across the reservoir are employed.

Improvement in Simulation of Fluid Storage

A "far field" factor that increases the fluid capacity of the simulated reservoir has been incorporated into GEOCRACK to better replicate transient fluid storage. This factor accounts for the storage that we know occurs at the periphery of the reservoir. It has been possible to implement the "far field" storage concept simply by changing the boundary portions of the geometry of the rock-block mesh created by GEOCRACK, thereby maintaining the high-degree of replication of reservoir permeability characteristics that GEOCRACK has already demonstrated while at the same time improving the simulation of fluid storage. GEOCRACK now includes both improved heat transfer characteristics and improved treatment of fluid storage. Other GEOCRACK improvements under consideration include incorporation of a wellbore model and, in the longer term, conversion to three-dimensional geometry. In all these cases, "improvement" means better simulations of all aspects of the operating data obtained during both steady-state and cyclic flow testing at Fenton Hill in 1992-1993. Ultimately, the more refined version of GEOCRACK now being developed will be applied to redo reservoir thermal simulations already obtained for comparative purposes and to obtain more credible predictions of reservoir thermal lifetime.

Improvement in Simulation Efficiency

Work is also underway to increase the efficiency of GEOCRACK computer runs by the use of an advanced software package. In addition, the portability and world-wide availability of GEOCRACK are being addressed by making it more available to remote users via computer networks. GEOCRACK is currently being applied in HDR simulations by the Australian Geological Survey, American industry is evaluating it for a number of reservoir engineering applications, and it is being considered for use in studies of fluid flow in jointed rock at Sandia National Laboratories.

Development of Serious Leakage Flow from the HDR Reservoir

A small amount of fluid leakage from the large HDR reservoir at Fenton Hill to the surface via the annular space between the tubing string and the first casing string of the injection wellbore (designated EE-3A) had been observed since its completion in the mid-1980's. Tracer tests and other measurements had verified that the source of the leak was a reservoir connection to an uncemented portion of the wellbore at a depth of somewhat over 9,000 ft. Before June 1995, the rate of leakage varied with the reservoir pressure and other known factors, typically in the range of 2-6 gpm, in a manner that was generally predictable. Shortly after the initiation of the RVFT, however, the pressure at the outlet of the leakage flow at the injection wellhead began to rise. When this increasing pressure was relieved, the flow rate at first increased substantially, then tapered off for a few days, and finally began to rise once more.

By mid July 1995, an increase in pressure on the second annular space beyond the tubing string was observed. A breach in the first casing string was subsequently identified at a depth of 4,150 ft. Although these problems with the injection wellbore did not impact the scheduled flow testing in FY 1995, it would be imperative that the wellbore be repaired if additional flow testing was contemplated and the casing breach would have to be plugged even if the wellbore were simply plugged and abandoned. As this is being written, no final decision has been reached how to address this problem.

Remarkably, the significantly increased bypass flow rate to the surface via the annular flow path in the injection wellbore was not reflected at all in the output from the production well. In addition, even after an extended time period of shut-in, the pressure at the annular outlet did not rise to the level measured at the shut-in production well. These observations have led to the conclusion that the leakage flow is being derived from a segment of the reservoir only poorly connected to the main body of the reservoir that carries the production flow. Comparisons of pressure changes of the segments over time indicate that the main segment of the reservoir is about 1.5 times as large as the segment feeding the leakage pathway.

FUTURE PLANS

The work of FY 1995 was carried out under the assumption that the HDR technology developed at Los Alamos over a period of more than 20 years would be transferred to private US industry via a cost-shared project to construct and operate an HDR facility to produce and market power.

A solicitation designed to lead to the implementation of such a project was issued by the DOE early in FY 1995 (see below), but was withdrawn just after the close of the fiscal year. As this is being written, the future course of HDR research, development, and implementation in the United States is unclear.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The HDR Industry Solicitation

Early in FY 1995, the USDOE issued a solicitation requesting proposals from US private industry for a government-industry cost-shared project leading to the development of a facility to produce and market power derived from an HDR energy resource. Representatives of more than a dozen US firms attended a Pre-Award Conference convened by the DOE at Albuquerque, NM in late January 1995 to review the details of the solicitation and answer questions posed by potential bidders. By the close of the solicitation response period in April 1995, qualified bids had been received and accepted by the DOE.

In June 1995 a technical panel composed of geothermal experts from industry, academia, and government reviewed the bids, scored them, and sent forward a recommendation to the DOE Geothermal Division that a cooperative agreement be awarded to the winning bidder. After an extended period of consideration, the DOE Geothermal Division announced in October 1995 that the solicitation was being withdrawn and no award would be made. At the same time, the DOE pledged its continuing support for HDR technology development and stated that it intended to work with industry and other interested parties to resolve the remaining HDR technical issues. The specific technical issues to be addressed are still under consideration.

Withdrawal of the solicitation marked the closure of a significant period of intense industry interest in HDR technology. Although the solicitation itself did not go forward, it sparked the interest of a number of private groups not previously familiar with HDR technology and led to several novel proposals for the application of HDR technology by the private sector. The USDOE is putting off evaluation of all such proposals until after the completion of a review of HDR by the private geothermal industry, as represented by the Geothermal Energy Association (GEA), but some of the proposals are currently under consideration by other funding agencies.

Non-Solicitation Industry Interest

Organization(s)	Type and Extent of Interest
Envirocorp, Houston, TX	Use of HDR technology for waste treatment and chemical processing. Discussions ongoing.
Euro-US, Longmont, CO	Use of HDR technology for waste sludge treatment. Discussions and site visit.
Bovis, McLachlin, Pty. Ltd., Australia	HDR system to pre-heat feed water for coal-fired power plant. Continuing interactions, GEOCRACK reservoir model provided to Australian HDR workers.
PNOC, The Philippines	HDR applications in the Philippines. Visits to Los Alamos and Fenton Hill HDR site. Discussions ongoing.
UNOCAL Geothermal, Santa Rosa, CA	HDR fracture detection and mapping techniques to increase hydrothermal production. Joint work is planned.

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Table 1
Power Production Rates from the Large Fenton Hill HDR Reservoir

Date	Flow Test Phase	Power Production, Thermal MW
July 24, 1992	LTFT, Phase 1	3.9
April 13, 1993	LTFT, Phase 2	3.9
May 13, 1993	After sudden flow increase	5.4
May 31, 1995	RVFT, Segment 1	4.2
June 19, 1995	RVFT, Segment 2	3.6
June 28, 1995	RVFT, Segment 3	4.0
July 7, 1995	RVFT, Segment 4, 20 hrs	3.7
	RVFT, Segment 4, 4 hrs	6.2
	RVFT, Segment 4, 24 hr. average	4.1

Figure 1. The injection pressure was held constant over the entire course of the reservoir verification flow test (RVFT). Variations in the production backpressure were employed to investigate a number of practical operating scenarios for commercial HDR systems.

Figure 2. Steady-state flow conditions were rapidly established during the RVFT. Although increasing the backpressure to 2,200 psi led to somewhat decreased production, a small increase in the production flow was afterward achieved during the enhanced production portion of the test. The subsequent load-following experiments demonstrated that greatly increasing production for a few hours each day to meet peaking power needs could also significantly boost the overall energy output of the system.

Figure 3. This expanded production flow profile shows that HDR reservoir flow production can be rapidly and smoothly transitioned from a baseline to an enhanced level and back again. Note also the extremely stable flow rate achieved during both baseline and enhanced operations.

Figure 4. The production temperatures during the RVFT remained steady, declining or increasing only in conjunction with changes in the production flow rate. The increased production temperatures during high-flow periods of the load following experiments contributed to the large increases in energy output at those times.

Figure 5. A temperature profile across the open-hole interval of the production wellbore at Fenton Hill. The temperatures measured at points A, B, C, and D on a number of different dates are summarized in the inset table.

Figure 6. A cross-section of the Fenton Hill HDR reservoir. The shaded portion shows a horizontal slice of the reservoir as defined for use in the GEOCRACK model.

Figure 7. (a) A two-dimensional representation of a portion of an HDR reservoir as defined by the GEOCRACK model. (b) An isometric view showing the varying heights of the fluid flow paths bounding the rock blocks as assigned by GEOCRACK.

COOPERATION AND TECHNOLOGY TRANSFER BETWEEN LBNL AND THE CALIFORNIA DIVISION OF OIL, GAS, AND GEOTHERMAL RESOURCES

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KEY WORDS

technology transfer, reservoir simulation, Heber geothermal field.

PROJECT BACKGROUND AND STATUS

A numerical simulation model of the Heber geothermal field in southern California is being developed under a technology transfer agreement between the Lawrence Berkeley National Laboratory (LBNL) and the California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR). The two main objectives of the cooperation are: (1) to train DOGGR personnel in geothermal reservoir simulation using the TOUGH2-PC computer code (Antúnez *et al.*, 1994, 1995); and (2) to develop a subsidence-uplift module compatible with TOUGH2 (Pruess, 1991) to investigate the effects of production and injection operations on the ground surface subsidence and uplift phenomena observed at Heber. The Heber geothermal system is overlain by prime irrigated agricultural land, and any changes in ground surface elevation will drastically influence the effectiveness of the irrigation drainage system. Therefore, the need exists to control subsidence and uplift.

The DOGGR engineers were trained on the strategy and methodology used in the different stages of a numerical simulation exercise. Using data from the Heber field, they worked with LBNL personnel to construct a conceptual model of the natural-state for the system and a numerical model of the field. They are currently calibrating this model by matching its results against field data and the conceptual model.

The module to incorporate subsidence and uplift in the simulator is being developed by LBNL at the present time.

PROJECT OBJECTIVES

The objectives of this cooperative agreement are to develop a geothermal reservoir simulation capability in DOGGR and to incorporate a subsidence-uplift module in the numerical simulation studies. This modeling capability will provide a valuable and powerful tool to enhance the understanding of geothermal fields in California.

Technical Objectives

- Train DOGGR personnel in geothermal numerical simulation and in the use of the TOUGH2-PC computer code.
- Develop a module compatible with TOUGH2 to investigate the effects of production-injection operations on the ground surface subsidence and uplift phenomena in geothermal fields.

Expected Outcomes

- Develop DOGGR expertise in geothermal reservoir simulation.
- Enhance the tools and methodology available at DOGGR to evaluate geothermal field operations and development.

APPROACH

The DOGGR engineers have been trained at regular meetings of the cooperative group. During these meetings, numerical simulation theory was reviewed, practice exercises used the analyses of simulation results, and the group prepared and reviewed the content of input and output data sets and the presentation of the results in graphical form. The engineers were also given the materials for exercises to be completed before the following training meeting. The LBNL software was obtained to conduct numerical simulations in the DOGGR branch offices, and licensed commercial software was purchased. Questions and problems that arose were handled by phone, email, or FAX.

RESEARCH RESULTS

The DOGGR personnel are being trained in the different aspects of numerical simulation, including the gathering of the data required for a conceptual model, the construction of the corresponding numerical model, and its calibration and use as a predictive tool. The engineers were informed in the operation of TOUGH2-PC and the mechanics of conducting numerical simulations. The training included the use of preprocessing and postprocessing software packages to manipulate the input and output data and to present the output in graphical form.

LBNL and DOGGR engineers constructed a numerical model for the Heber geothermal field (see Figure 1), and are conducting independent numerical simulation runs required to calibrate the model against available pre-production pressure and temperature data.

FUTURE PLANS

After the completion of the initial-state calibration, the calibration of the model will be refined by matching the production history of the field, and the numerical model will be ready to be used as a forecasting tool. A TOUGH2-compatible module is being written to consider the subsidence-uplift effects caused by geothermal fluid production and injection operations. It will be completed during FY-1996. Several injection-production scenarios will be modeled to study which will minimize ground surface subsidence-uplift effects.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The LBL numerical simulator, TOUGH2, will be enhanced by the addition of a module to account for elastic deformation of sedimentary rocks. This module will compute changes in pore volume and in grid-block dimensions in response to pore pressure changes due to fluid withdrawal or injection and the compressibility of the rock-fluid system. The process by which this change in volume is transmitted to the surface (*i.e.* ground deformation) will also be considered.

Through this collaboration with DOGGR, LBNL is helping to disseminate the technology developed under DOE-funded programs. DOGGR personnel are developing reservoir simulation capabilities, increasing their forecasting confidence, and enhancing their understanding of geothermal fields under production.

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Figure 1. Areal gridding for the Heber geothermal field.

GEOHERMAL TECHNOLOGY ORGANIZATION INDUSTRY COOPERATIVE RESEARCH

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KEYWORDS

industry cooperation, cooperative research, cost-shared research

PROJECT BACKGROUND AND STATUS

INEL assisted the geothermal industry in forming the Geothermal Technology Organization (GTO) and in reaching an agreement with the Department of Energy (DOE) 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. GTO and the DOE-GTO agreement allow the industry members 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 and the organization 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 reservoir technology research program. Several of the projects have also received additional funding to broaden their original scope.

The DOE-GTO projects have included: 1. Development and interpretation of micro-seismic data at The Geysers; 2. Interpretation of injection tracer tests at The Geysers; 3. Characterization of subsurface fracture patterns in the Coso geothermal field; and 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.

PROJECT OBJECTIVES

GTO, an organization of geothermal companies, and DOE-ID (DOE Idaho Field Office) entered into an agreement in early 1988 wherein DOE and the members of GTO could share in the cost of geothermal research. The agreement specifies that technology development that can, in the short term, have a high probability of yielding benefits 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. INEL facilitates the screening of proposals and provides organizational support to GTO.

Technical Objectives

- Perform research that is cost-shared by DOE and the GTO.

Expected Outcomes

- Development of technology that industry would not be able to do alone.

APPROACH

Industry, researchers and the DOE suggest research topics to GTO. If GTO approves the project, it proposes the project to DOE. After DOE and GTO reach agreement on a project and the funding becomes available, DOE establishes suitable contracts or research agreements 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 AND VARIANCES

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 micoseismic 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 and by 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

Organization(s)	Type and Extent of Interest
Calpine Corporation California Energy Company Coldwater Creek Operating Company Northern California Power Agency Pacific Gas & Electric Company Unocal U. S. Navy	Recent sponsors (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 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.

PROJECT OBJECTIVES

Technical Objectives

- Facilitate the expansion of the U. S. geothermal industry into markets abroad
- 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

- Increased opportunities for U.S. companies to develop geothermal projects abroad.
- Compilation and development of conceptual models of foreign geothermal systems that can serve as analogues to U.S. fields.

APPROACH

Formal agreements between Department of Energy (DOE) and 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 Idaho National Engineering Laboratory (INEL) and Lawrence Berkeley National Laboratory (LBNL) is sponsoring trade missions and technical contacts with foreign geothermal developers, particularly in Africa, Central and South America and the Far East.

RESEARCH RESULTS

During FY 1995 the activities under this project were quite limited due to funding restrictions. However, an industry/DOE team worked with the Indonesian electrical utility PLN on a pre-feasibility study of sites for small, rural geothermal power. DOE also provided support to the Geothermal Energy Association on geothermal projects in Bolivia, Nicaragua and St. Vincent.

Only a small amount of work was carried out under the DOE/CFE agreement during FY 1994. Researchers at LBNL continued monitoring the geochemistry at Cerro Prieto to improve the understanding of changes in a geothermal reservoir due to extended production and injection. Oregon Institute of Technology Geo-Heat Center is assisting CFE with use of silica collected from production as a cement base. New cooperative research will be conducted with the participation of U. S. industry as much as possible. The agreement with CFE has lapsed and a revised agreement is under discussion.

The interaction with ENEL was limited to informal meetings before and after the time of the World Geothermal Congress in Florence, Italy in May 1995.

Various LBNL 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 will complete a prefeasibility study of a number of small geothermal sites in rural Indonesia. 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. DOE researchers will also initiate studies of core from an Indonesian geothermal field which will lead to a better understanding of the volcanologic processes associated with geothermal prospects in Indonesia.

Visits of foreign scientists to 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

MODEL DEVELOPMENT FOR CYCLE ANALYSIS IN ADVANCED HEAT REJECTION STUDIES

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KEY WORDS

computer-aided model, binary cycle, flash steam system, geothermal power plant, heat rejection system, economic evaluation, thermodynamic evaluation, off-design performance

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, the power plant must 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 then imperative to investigate heat rejection systems to produce economical electrical energy.

In FY1994, we developed models to evaluate cycle performance and impact on the levelized cost of energy (LEC) 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 for small, low temperature plants (4 production wells and <300°F). Additional baseline data will be incorporated during the next year into the model from the Next Generation Geothermal Power Plant Study currently being carried out under the direction of the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE).

Studies of heat rejection systems and their impact on cycles was carried out during FY1995. The tool mentioned above was updated to include different types of heat rejection temperatures and also to predict "off-design" performance of a system if the ambient conditions were changed from the design values. These enhancements have made possible studies on different types of heat rejection systems and their response to changing ambient conditions. In FY1996, the tool will be further expanded in its database of working fluids and economic data on different systems. In addition, dual-flash steam systems will be included in the model.

PROJECT OBJECTIVES***Technical Objectives***

- Produce a computer-aided method to rank systems with different configurations by evaluating their impact on LEC.
- Update the model to consider more working fluids (including pure fluids and binary mixtures) for the binary cycle.
- Analyze heat rejection system performance, working fluid performance for mixtures in binary systems with and without internal recuperation and comparison of binary with flash steam systems.

Expected Outcomes

- A computer-aided method to be used by the Geothermal Power Program to evaluate advanced systems.
- Different operating strategies to minimize water consumption along with LEC.
- Other studies involving binary cycles with different types of working fluids, with and without recuperative preheat of the working fluid with turbine exhaust, comparisons between binary and flash steam systems.

APPROACH

The approach taken is to apply a computer-aided "Value Analysis" as described in the Background section to binary cycles with various types of heat rejection systems, with and without internal recuperation. Flash steam systems will also be considered in the method. 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 FY1994, a computer program was developed which allowed changes in the levelized energy cost (LEC) to be determined for changes in small air-cooled, binary geothermal power plants with air-cooled condensers. The effects of component size change and their impact on LEC were determined for some low temperature applications.

In FY1995, this work was extended to include different types of heat rejection systems. Additional systems to be considered are:

- Shell-and-tube condensers with water cooled in an evaporative cooling tower,
- Shell-and-tube condensers with water cooled in an air cooler and then in an evaporative cooling tower,
- Series combinations of one of the air cooled systems over an evaporative water cooled system,
- Parallel combinations of the systems mentioned above.

This work will be extended in FY1996 to include studies involving binary cycles with recuperation, and dual flash steam systems. In addition, the binary working fluid database will be expanded and the economic database will be extended to include some of the results of the EPRI/DOE Next Generation Geothermal Power Plant Study (NGGPP). (The final report on this study will be available at the end of calendar 1996.)

The methodology will be updated to include economic data from the NGGPP study for higher temperature resources and larger plants. More choices of binary cycle working fluids will be available including many binary mixtures. Binary cycles with internal working fluid preheating with turbine exhaust and dual-flash systems will be added to the method.

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

In FY1996, the computer-aided model will be expanded to include: 1) Binary systems with recuperative preheating of the working fluid with turbine exhaust, 2) Greater choice of working fluids including binary mixtures, 3) Expanded economic data to include higher temperature resources and larger plants with data from the NGGPP study, and 4) Dual-flash systems.

Studies will be made on the effect of recuperation on LEC of binary systems, selection of binary working fluid to fit particular resource and ambient conditions, and comparisons between advanced flash steam and binary systems.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The computer program will be made available to industry when it is completed. The use of the NGGPP Study will give a baseline with which industry is familiar. The results of the studies will produce some "rules-of-thumb" in components such as heat rejection systems, the type of

working fluid to use in binary cycles at different resource conditions and the comparison of flash steam to binary systems.

The intermediate results of this project were presented at the 1995 Geothermal Program Review and comments were solicited from the industrial participants.

REFERENCES

The original "Value Analysis" work for geothermal power plants is discussed in the following report:

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IMPROVEMENTS IN BINARY CYCLE PERFORMANCE -- SUPERSATURATED TURBINE EXPANSIONS

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KEY WORDS

binary power cycles, turbines, supersaturated expansions, metastable turbine expansions

PROJECT BACKGROUND AND STATUS

The identified hydrothermal resources in the United States that are economically feasible for the commercial production of electrical power have been, or are being developed by the nation's geothermal industry. A large fraction of the nation's hydrothermal resources are only marginally feasible for the production of electrical power. To support the development of this energy resource, investigators in the INEL's Heat Cycle Research program have been working since the early 1980's to develop technologies that convert the energy in the hydrothermal resource into electrical power more efficiently. Lower power generation costs typically result from these more efficient cycles.

INEL has largely completed its efforts to identify concepts that produce significant performance improvements for binary power cycles. A cycle has been defined with a 20% improvement in the brine utilization (net power produced per unit mass of brine flow); the performance of this cycle approaches thermodynamic maximums. Field investigations at the Heat Cycle Research Facility (HCRF) validated the assumptions critical to achieving the performance improvement. They were also used to develop the technology base required to incorporate the advanced cycle concepts into the design of a commercial plant. The work on this advanced cycle has been completed.

One of the INEL analytical studies showed that brine utilization could be improved an additional 8% if the turbine inlet state points were modified to allow turbine expansions that "passed through" the two-phase region. The turbines in conventional binary plants are operated with sufficient superheat at the turbine inlet that the entire expansion process remains completely "dry". This operating constraint is applied to the turbine because of concern that any condensation forming during the expansion process would adversely affect the turbine's performance and/or damage (by erosion) its internal components. The INEL study suggested that condensation would not occur, and that if condensate droplets did form, they would be small and tend not to grow to a size that would cause damage or affect performance.

Before the closure of the HCRF in 1994, investigations were conducted at that facility to examine the condensation behavior of these metastable, supersaturated expansions and to determine their effect on turbine performance. The remaining issues to be resolved are currently being

investigated at a binary power plant operated by Mammoth Pacific Limited Partnership. The investigations at the Mammoth facility are examining the impact of these expansions on a commercial turbine over an extended period. At the conclusion of this extended test, turbine operating parameters will be defined that minimize the potential for damage, while allowing a binary plant operator to maximize the amount of power produced from a given flow of brine.

PROJECT OBJECTIVES

The objective of the Heat Cycle Research program is to reduce the cost of generating electrical power from marginal temperature hydrothermal resources. This is being accomplished by developing binary power cycle technologies that allow the cycle performance to approach thermodynamic maximums. The objective of the project investigation of metastable, supersaturated turbine expansions is to define the turbine operating conditions that increase the amount of power produced from a given amount of brine without damaging the turbine or affecting its performance.

Technical Objectives

- Define the conditions producing condensate formation and the operating parameters that will support a supersaturated vapor during the turbine expansion process.
- Determine the degree of supersaturation and/or moisture that can be tolerated during the expansion process without degrading turbine efficiency.
- Identify the effects of these metastable expansions on internal turbine components (rotor and nozzle/vane surfaces), and on turbine performance over an extended period of operation.

Expected Outcomes

- Metastable, supersaturated vapor expansions can proceed without adversely effecting turbine performance.
- Erosion effects of the supersaturated vapor are not significant up to the point of condensate formation.
- A turbine can operate for short periods of time with "wet" expansions without damaging its internal components. (These "wet" expansions would typically occur during a plant conditions when significant levels of liquid would be present in the working fluid as it is expanded through the turbine.)

Expected Outcomes (continued)

- The power production will be increased or the brine usage decreased (while maintaining the same power output) by reducing the conservatism in the amount of superheat maintained at a binary cycle turbine inlet.
- A mode of operation will be defined that could improve the brine utilization by up to 10%.
- The cost of electricity is projected to decrease by 3% to 5% for an increase of 8% to 10% in the brine utilization.

APPROACH

The investigation of the condensation behavior of the metastable, supersaturated vapor expansions were initially conducted at the HCRF. A converging-diverging nozzle was used to simulate the expansion in a turbine, and a droplet detection system was used to detect the presence of condensation in the expansion process. These simulated expansions provided investigators with information on the conditions producing condensation, the size of the droplets that formed, and the conditions under which the formed drops evaporated as the expansion continued. From the data generated, the degree of supersaturation attained before condensate forms can be identified.

Field investigations were conducted at the HCRF with both an impulse turbine and a reaction turbine; both turbines were prototype size. These tests determined the degree of supersaturation or moisture level sustained in the turbine expansion before the efficiency is adversely affected. During these investigations, the turbine operating conditions were closely monitored and controlled. At fixed operating pressures, the turbine inlet temperature was varied to control the degree to which the turbine expansion process was allowed to enter the two phase region. The turbines were operated at inlet conditions producing (as defined by the nozzle tests) "dry" expansions, supersaturated expansions, and "wet" expansions. The turbine performance was monitored at each test condition to define the point at which a degradation in performance occurred. This point was correlated with the nozzle tests to determine the degree of supersaturation or moisture level present in the turbine expansion. This process was repeated at different inlet and exhaust pressures, as well as with different working fluids.

To determine the long-term effects of these expansions on a turbine's performance and internal components, the investigations are continuing at a commercial binary power plant. This plant will be operated over an extended operating period with its turbine having a controlled degree of supersaturation in the expansion process.

Before starting an extended period of operation, the condition of the internal turbine components is to be documented, and the "baseline" performance of the turbine and plant established for a "dry" expansion process. The turbine inlet conditions will then be modified to provide the desired degree of supersaturation, and maintained for the duration of the test. The turbine

performance will be monitored over the test period to determine whether efficiency degrades with time. At the conclusion of the extended operation, the components internal to the turbine will be removed and examined for any abnormal wear or erosion.

At each phase of the metastable, supersaturated turbine expansion investigations, industry review and comment is solicited from turbine manufacturers, plant operators, and engineering-design firms active in the geothermal industry. With increased interest, these entities loan or donate materials and services to the investigation (in-kind contributions). The ultimate objective is to generate sufficient industrial interest to have the concept incorporated into the operation of a turbine in a commercial plant.

RESEARCH RESULTS

The initial investigations of the condensation behavior of the metastable, supersaturated vapor expansions and their effect on turbine performance were conducted at the HCRF prior to its closure at the end of 1994. Tests with an expansion nozzle and a droplet detection system confirmed that a supersaturated vapor was achieved during the simulated turbine expansion of an isobutane working fluid. It was estimated that the brine utilization in a commercial plant would increase by up to 10% at the maximum level of supersaturation achieved in these tests. Tests conducted with an axial-flow, impulse turbine and a radial-inflow reaction turbine verified there was no adverse impact on the performance at the levels of supersaturation achieved in the nozzle tests; the effects of these expansions on turbine performance are shown in Figure 1 for the axial-flow, impulse turbine and Figure 2 for the radial-inflow, reaction turbine.

The objective of these tests was to determine the impact of the supersaturated expansions on the performance of each type of turbine; it was not to compare the performance of the two types of turbines relative to each other. (There are a number of probable causes for the radial-inflow turbine efficiency being low; a similar type of turbine operating and tested at Mammoth Pacific has efficiencies greater than 85%.) The performance of the turbines did not begin to degrade until their expansions (as indicated by the nozzle tests) would have produced significant levels of condensate formation. The impulse turbine efficiency was not affected until the vapor leaving the turbine was "wet", i.e., the actual exhaust condition was within the two-phase region. The radial-inflow reaction turbine did not tolerate the same moisture level before its performance was affected; its efficiency began to degrade once the isentropic exhaust condition was within the two-phase region. The "wet" expansions data shown in Figures 1 and 2 correspond to an isentropic exhaust condition which on the dew point curve, or just outside the two-phase region. Similar results were obtained in both turbines for an isobutane working fluid and a 95% isobutane, 5% hexane mixture (see Figures 1 and 2).

During the testing at the HCRF, each turbine was operated for a few hundred hours. Although there did not appear to be any unusual wear on the impulse turbine components, there was erosion damage to the stationary internal surfaces (including the nozzles) in the reaction turbine. Discussions with the turbine manufacturer, an engineering firm, and a plant operator using a similar turbine suggested the erosion damage was due to small particulate entrained in the working fluid vapor; the particulate was residue from the plant construction activities. A similar

phenomenon had occurred at commercial plants; it was resolved by installing filters and/or separators upstream of the turbine.

While the results of the HCRF investigations showed the supersaturated expansions did not adversely affect performance, they did not resolve the question of the long-term impact of these types of expansions on the turbine. To address this issue, an agreement was reached in 1995 with Mammoth Pacific Limited Partnership to continue these investigations at one of its plants (MP-100) near Mammoth Lakes CA. The radial-inflow, reaction turbine at MP-100 will be operated at inlet conditions producing the supersaturated vapor expansions over an extended period to determine the long-term impact of these types of expansions. The turbine manufacturer and the engineering firm that designed the plant are involved in defining the conditions for the extended operation, and will participate in evaluation of the data generated and reporting the results.

The initial phase of this effort required examining the feasibility of operating the MP-100 plant at turbine inlet conditions producing the supersaturated vapor expansions. This plant was designed for the commercial production of electrical power; it was not designed with the same operation flexibility as the HCRF. The initial investigations at MP-100 indicated that it would not be feasible to operate the turbine at supercritical inlet pressures because of the associated decrease in electrical power production. It would be possible to operate with subcritical inlet pressures and inlet entropies comparable to those producing condensate formation in the nozzle tests at the HCRF. To achieve these conditions, it would be necessary to operate with $\sim 1^{\circ}\text{F}$ of superheat at the turbine inlet. This level of superheat is substantially less than that used during the normal operation of the MP-100 turbine ($\sim 8^{\circ}\text{F}$). The initial investigations at MP-100 suggested that this could be accomplished, and that the turbine could tolerate short periods of operation with "wet" expansions.

Based on the feasibility tests, the flow and inlet pressure conditions selected for the extended test were similar to those for which the turbine was originally designed. Mammoth initiated the procurement of a new turbine rotor and nozzle set based on the original design for the extended investigation. To minimize the risk to Mammoth, as well as to assure the condition of the components and establish their pre-test condition, the project will purchase these components from Mammoth. They will be installed once received during the first quarter of FY-1996.

FUTURE PLANS

During the first quarter of FY-1996, Mammoth Pacific will receive the new turbine rotor and nozzle set. Once the pre-test condition of these components is documented, Mammoth will install them in the MP-100 turbine. After establishing the performance of the turbine with these components using completely "dry" turbine expansions, the inlet conditions will be modified to provide the desired degree of supersaturation in the expansions. This will become the "normal" operating point for MP-100 for approximately 6 months. At the end of this period, a mutual decision will be made whether to continue the investigation for an additional 6 months (or longer). At the conclusion of the extended test, the turbine rotor and nozzle set will be removed and their post-test condition documented. The results of the investigation will be reported. If

the results of the investigation are favorable, it is expected that Mammoth Pacific will make similar modifications to the inlet conditions for the turbines at one or more of its other binary plants in the Mammoth area. The successful completion of this activity will result in the transfer of the technology to industry, and its initial commercial application.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Barber-Nichols, Inc.	Turbine manufacturer and engineering firm: assisted with field testing of the impulse and reaction turbines at the HCRF and subsequent data evaluation; provided (at no cost) equipment for the testing of the impulse turbine.
Mission Energy	Binary plant operator: provided review and comment on project investigations conducted at the HCRF.
Rotoflow Corp., Inc.	Turbine manufacturer: provided (at no cost) the rotor and nozzles for testing the reaction turbine at the HCRF; provided review and comment on HCRF studies; assisted the project in soliciting interest from geothermal plant operators for the extended test; providing turbine rotor and nozzle set (at a discount) for the extended test.
CE Holt Co.	Engineering firm: provided review and comment on HCRF studies; assisted in soliciting interest from geothermal plant operators for the extended test; providing engineering services, including data evaluation, to Mammoth Pacific during the extended operation test.
Mammoth Pacific LP	Binary plant operator: making its MP-100 plant available for the extended operation with the supersaturated expansions; providing operational and maintenance personnel for activity at no cost; foregoing any lost revenues during shutdowns and testing.

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Figure 1. Performance of Axial Flow, Impulse Turbine During Testing @ HCRF

Figure 2. Performance of Radial Inflow, Reaction Turbine During Testing @ HCRF

DEVELOPMENT AND TESTING OF ADVANCED DIRECT-CONTACT CONDENSERS

Desikan Bharathan
National Renewable Energy Laboratory (NREL)

KEY WORDS

direct-contact condensers, hydrogen sulfide abatement, back pressure, non-condensable gas handling

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 MW_e from the Geyser 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 carry-over of steam with the non-condensable gases which must be vented. Over the years, PG&E has pursued different approaches to improve condenser performance with limited success. PG&E recognized the potential merit of NREL-developed condenser concepts for gaining substantial improvement in the condenser performance and is interested in developing those concepts into workable hardware.

NREL, the Department of Energy (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 non-condensable gas handling characteristics of these advanced condenser concepts. These condenser developments will be applicable to all steam power plants. The potential for improvement of plant heat rate is as much as five percent.

NREL and PG&E are working under a CRADA (Cooperative Research and Development Agreement) to demonstrate the use of advanced design techniques and designs to improve thermal performance and scavenging of non-condensable gases in direct-contact steam condensers thereby improving the utilization of geothermal steam resource and reducing emission of non-condensable gases.

The work to be carried out was divided 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 April 1996.

Phase I was carried out in FY 1994 by NREL. Phase II was implemented in FY 1995, with the definition of design and costs by March 1995, and the Go/No go decision for this project was made in July 1995, by PG&E with a go ahead for the project.

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 condensers, 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 and to retrofit one of the Units at the Geysers for performance verification.

Expected Outcomes

- Upon retrofit of the existing condenser, the condenser back pressure will be lowered significantly; this retrofit is estimated to have a pay-back period of less than two years.

APPROACH

Phase III. Engineering Design and Installation

Initial efforts in this Phase will allow PG&E to 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.

This third phase will be carried out during FY 1996.

During Phase III, 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 plant 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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DEMONSTRATION OF ECONOMIC BENEFITS OF A BIPHASE TURBINE IN A GEOTHERMAL APPLICATION

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KEY WORDS

biphase turbine, cooperative agreement, demonstration, flash plants, energy conversion

PROJECT BACKGROUND AND STATUS

The Douglas Energy Company was awarded a cooperative agreement through the Golden Field Office to demonstrate the economic benefits of a Biphase topping turbine. This patented device separates the steam from the brine and generates power from each phase. For a flash steam power plant, the Biphase turbine can recover useful work that would otherwise be dissipated in the flash process.

The Biphase turbine concept has been proven through an earlier DOE sponsored project. At Roosevelt Hot Springs, Utah, a Biphase turbine accepted the full flow from a geothermal well during a 4000 hour demonstration. The unit generated 1600 kW and demonstrated a 20% increase in power output when compared to a single flash steam turbine. However, the design of this Biphase turbine included three rotors, each rotating at different speeds, which increased the cost, complexity and maintenance to an unacceptable level. This unit's design also converted only the brine's kinetic energy to shaft power. Therefore, the benefit of the Biphase turbine was limited on high enthalpy wells (i.e., wells with a high steam fraction) by the inability to generate power from the steam phase.

An advanced Biphase turbine was developed to overcome the previous unit's limitations. The three rotors were replaced by a single rotor and impulse steam blades were added. The single rotor Biphase turbine design was proposed in response to a solicitation entitled "Demonstration of Economic Benefits of Improved Electrical Power Generating Systems for Geothermal Applications." Following a competitive process Douglas Energy was awarded a cooperative agreement to demonstrate the advanced Biphase turbine.

The program proposed by Douglas Energy was divided into two phases. Phase 1 involved operating a 12 inch diameter, sub-scale Biphase turbine on a slip stream from a geothermal production well. The small turbine would be operated on low, medium and high enthalpy flows. Phase 2 would incorporate the lessons learned from the small turbine into a full size unit that would be manufactured and operated in a commercial geothermal flash steam power plant environment.

Phase 1 of this program is completed. California Energy Company provided access to a geothermal well at Coso Hot Springs in California. The sub-scale Biphase turbine operated in each of the high, medium and low enthalpy regimes. Three 250 hour tests provided valuable information and operating experience. An analytical model developed by Douglas Energy was verified and the operating experience brought about several design changes to the full size unit.

Phase 2 is well underway. The lessons learned have been incorporated and the full size Biphase turbine is being manufactured. The new unit will be demonstrated at Cerro Prieto, Mexico and is expected to generate approximately 1 megawatt of electricity.

PROJECT OBJECTIVES

The objective of the above mentioned solicitation was to support geothermal projects that would demonstrate economic benefits of improved electrical power generating systems. Within that context, the overall objective of this project is to demonstrate the affordability of the Biphase turbine. This includes, the capital costs to purchase and install as well as the maintenance required to operate and service the unit.

Technical Objectives

Phase 1: Testing of the Sub-Scale Biphase Turbine

- **Gain operational experience through testing the sub-scale unit.** The 12 inch diameter Biphase turbine (12RSB) had been tested previously with water and air. However, no amount of laboratory testing can match field testing. California Energy Company provided access to a geothermal well at Coso Hot Springs. Due to some innovative piping arrangements this well was used for all three (high, medium and low) enthalpy tests.
- **Validate the analytical model and use it in designing the full scale unit.** Douglas Energy had developed a model to predict the efficiency of the turbine. From the data gathered, the computer model was able to be validated and used in the design of the full size unit. The model showed agreement to within 20% over the range of steam fraction from 0.07 to 1.0 and pressures from 33 to 117 psia .
- **Measure power generated from the steam impulse blades.** 100% pure steam was used for the high enthalpy test so that the steam blades input could be measured directly. A water-brake dynamometer was used to measure the power from the Biphase turbine. This allowed for greater control and accurate measurements.
- **Demonstrate the variability of the Biphase turbine by changing the two-phase nozzles for different flow conditions.** That is, a different set of nozzles, specifically designed for the flow conditions, were used for each test.

Technical Objectives (continued)

- **Demonstrate the computerized control system.** The Biphase system was instrumented and control equipment put in place for automatic control. The control system is designed so that one operator could control many Biphase units from a remote location. The control system used during phase one will also be used for the full size unit.

The objectives of Phase 1 have been met. Operational experience has been gained in a geothermal environment. Improvements to the advanced Biphase turbine have been realized. The modeling codes used in the design process have also been validated.

Phase 2: Manufacturing, Installation and Operation of the full Size Unit

- Incorporate the following lessons learned from Phase 1 into the design of the full size, 30 inch diameter unit:
 - ▶ **Install hydroblast scale removal system** - No scale formation occurred in the nozzles or on the nozzle side separator during Phase 1. However scale formation was observed on the diffuser side of the separator. A hydroblast scale removal system was installed and proved to be effective.
 - ▶ **Install upstream rock/sand catcher** - The geothermal well at Coso Hot Springs had been inactive for a period of time and was unstable when it was activated for testing. A great deal of debris, including sand and rocks, periodically entered the turbine, causing some seal and bearing problems. The rotor and steam blades were undamaged by the debris.
 - ▶ **Use corrosion resistant material** - The rotor and steam blades will be manufactured from HY-80. Parts exposed to high velocity brine will have a high density plasma spray coating of Inconel 718 or will be fabricated from that alloy. Previous experience has shown Inconel 718 to be resistant to both corrosion and erosion.

Expected Outcomes

- Demonstrate economic benefits of the Biphase turbine.
- Demonstrate increased efficiency. Addition of the Biphase system at the chosen well is expected to increase the power production by 45%.
 - ▶ The well to be used at Cerro Prieto is currently operating at a well head pressure of 790 psia. At this pressure, a flowrate of 312,000 lb/hr is produced with a steam fraction of 45%. The flow is flashed to 125 psia and sent to the steam turbine. The steam from this well produces 7410 kW.
 - ▶ The system to be installed at Cerro Prieto is shown in Figure 1. The two-phase flow from the well enters the Biphase turbine at 750 psia and is expanded in the nozzles to 444 psia generating 1080 kW shaft. The separated steam is expanded further in the back pressure steam turbine to 126 psia generating an additional 3520 kW shaft. The separated brine flows to the existing separator and is flashed to 125 psia. The steam then flows to the Cerro Prieto steam turbine where it will produce an additional 6610 kW giving a total output from this well of 10,760 kW electric output.
- Demonstrate continuous operation - The operational period for this project is two years.

APPROACH

A cutaway of the sub-scale Biphase turbine used in Phase 1 of this project is shown in Figure 2. From the well, ten two-phase nozzles direct the two-phase high velocity jets tangentially onto the inner surface of the rotating separator. Centrifugal force separates the brine from the steam as the brine forms a film on the separator surface and is slowed by friction to the velocity of the rotor. After slowing and transferring the torque to the rotor, the brine flows through transfer holes to the other side of the disc supporting the separator. The brine enters a diffuser which is immersed into the brine layer where the velocity is slowed converting the kinetic energy into pressure. The brine exits the turbine and flows to a disposal pit.

The separated steam flows through a row of impulse blades adding to the torque of the turbine. The steam leaving the impulse blades exits the turbine and is discharged to the atmosphere.

The full size Biphase turbine (30RSB) is shown schematically in Figure 3. From the rock catcher, the two-phase flow enters the two inlets, 1, to the Biphase turbine. An internal splitter, 2, divides the flow into four equal streams, each feeding a two-phase nozzle, 3. The eight two-phase nozzles are formed by a contoured insert which can be removed and replaced through an external port, 4. The flow is accelerated in the nozzle, forming a two-phase jet, 5, which is separated on the rotary separator surface, 6.

The separated liquid, 7, is slowed to the velocity of the separator by frictional forces, converting the momentum to torque. The liquid subsequently flows through holes, 8, in the separator disc to the opposite side where it enters a diffuser, 9. The flow is decelerated to convert the remaining velocity head to pressure and exits through a port, 10, in the casing.

The separated steam, 11, flows through axial impulse blades, 12, converting the steam kinetic energy to power. Steam subsequently exits through the steam port on top.

The Biphase 30RSB has conventional labyrinth seals with a clean water seal wash to reduce scaling. Ceramic bearings, cooled with clean water, will be used to provide the straddle mounted rotor with the required stiffness.

The operating speed is 3600 rpm, enabling direct drive of the generator.

The parties involved in this project and their respective responsibilities are as follows:

- ▶ Douglas Energy - Project manager and developer of the Biphase turbine.
- ▶ Department of Energy - Project management through Cooperative Agreement.
- ▶ California Energy Company - Provided geothermal well during phase 1 activities.
- ▶ California Energy Commission - Providing loans to Douglas Energy.
- ▶ Comision Federal de Electricidad - Providing geothermal well at Cerro Prieto for full size Biphase turbine.
- ▶ Biphase de Mexico - Mexican partner will install and help operate the Biphase system.

RESEARCH RESULTS

The performance of the sub-scale turbine was monitored continuously during its operation. The wide fluctuations in flowrate, steam fraction and pressure produced a wide range of operating conditions.

The turbine efficiency, defined as the gross shaft power (measured by the dynamometer) divided by the isentropic enthalpy difference from inlet to exit is shown in Figure 4. The efficiency varied from 10% at the lowest enthalpy values to 46% at the highest enthalpy. These values were obtained where the ratio of steam blade to jet velocity was between 0.18 and 0.25. However, the optimum steam blade efficiency occurs at a value of 0.5.

The measured power output vs. the predicted power output is shown in Figure 5. The power was measured over a range of steam fraction from 0.07 to 1.0 and pressures from 33 to 117 psia. The two highest measured power points were obtained using 100% steam with nozzles designed for steam only.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Douglas Energy Co. has performed a pre-feasibility of the Biphase turbine to generate additional power at existing geothermal plants. One application is to generate power from high pressure wellheads. In the Philippines the average increase in power was 15%. In Mexico the average was found to be 22%. The additional power is generated without drilling any additional wells and further exploiting the resource. The total installed cost was estimated to vary between \$500-\$700/kW, depending on additional piping requirements. When compared to spending \$1000-\$1500/kW to build a flash steam plant, the Biphase turbine looks very cost effective.

In a non-geothermal application, the Biphase turbine has been licensed to Carrier Corporation for worldwide refrigeration applications. Environmental considerations require the use of chlorine-free, high pressure refrigerants in air conditioners. These new refrigerant fluids are not as efficient as the fluids they have replaced. Part of the inefficiency results from flashing. Douglas Energy designed and manufactured a two-phase turbine for energy recovery in industrial air conditioners using R134A refrigerant. The Biphase turbine was installed in a large chiller and tested by Carrier at their Syracuse factory. An efficiency in excess of 50% was measured. In a centrifugal chiller the Biphase turbine replaces the expansion valve and generates power while chilling the refrigerant. The addition of the Biphase turbine will make the Carrier air conditioning units efficient as well as environmentally safe.

In the oil and gas industry, Biphase Energy Co. has entered a joint venture with Kværner a.s. Studies of conventional off-shore separation equipment have shown a fivefold reduction of footprint and weight is possible. The size reduction is achieved while generating power from the previously wasted two-phase flow energy. The first unit sold under the agreement has been installed in a proprietary system to reduce VOC emission during off-shore loading of tankers. This unit will generate power and separate inert gases from the crude oil. Laboratory tests have shown a 90% reduction in emissions.

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Figure 1. Biphase System at Cerro Prieto, Mexico

Figure 2. 12RSB Biphase Turbine, Nozzle Side, Isometric 1/4 Cutaway

Figure 3. Schematic of 30RSB Biphase Turbine

Figure 4. Measured and Predicted Efficiency Variation with Inlet Enthalpy

Figure 5. Measured Power Output Variation With Predicted Power Output

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 BACKGROUND AND STATUS

A solicitation was issued by 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 (see Figure 1). After a competitive process, Exergy was selected for an award.

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% more efficient than existing geothermal binary power plants.

Exergy is currently in negotiations with the Sacramento Municipal Utility District (SMUD) for a power purchase agreement. Initially, Exergy who has teamed with Far West Capitol had planned to enter into a power purchase agreement with Sierra Pacific, the local utility. However, due to circumstances beyond their control, Sierra Pacific was unable to enter into a long term agreement. Therefore, Exergy and Far West Capitol have been active in looking for other options. If the negotiations with SMUD are successful, this may be one of the first applications of wheeling power from a geothermal power plant to a utility across another utility's (PG&E's) transmission line.

An Environmental Assessment (EA) is being prepared by DOE. The EA will cover the land area that the power plant will be sited and the immediate vicinity in Steamboat Springs, Nevada, which is approximately 10 miles south of Reno. Studies have been done to investigate the potential environmental effects to the following environmental categories:

- Socioeconomic
- Land Use
- Geology
- Hydrology
- Biological Resources

- Cultural Resources
- Potential Accidents.

Environmental impacts to all of the above environmental categories were analyzed and determined to be insignificant. Any potential environmental impacts have been reduced by incorporating mitigation measures or project design features. Some concerns were raised regarding cultural resources, federally listed endangered plant life (Steamboat Buckwheat) and the geothermal resource itself. Based on studies targeting each of these concerns and an evaluation of construction and operational activities, no adverse impacts are anticipated for these resources.

As of January 1996, the EA is ready to be reviewed by the State of Nevada. After their comments are incorporated and/or resolved the DOE expects to publish the EA and issue a Finding of No Significant Interest (FONSI). Once the FONSI has been issued and the Power Purchase Agreement has been obtained, the detailed plant design work and construction will begin.

PROJECT OBJECTIVES

The objective of the solicitation through which this project was selected was to support geothermal projects that would demonstrate economic benefits of improved electrical power generating systems. Within that context, the objective of this project is to demonstrate the affordability of a geothermal power plant utilizing the KCS11 version of the Kalina cycle.

Technical Objectives

- Generate 12.5 MWe using the Kalina cycle that will be supplied 330°F brine flowing at 3600 gpm from two production wells.

Expected Outcomes

- Efficiency improvement over organic Rankine cycle geothermal power plants. The use of a mixture of ammonia-water allows the excess heat exiting the turbine to be used to vaporize a substantial portion of the working fluid. A conventional geothermal binary power plant utilizes the organic Rankine cycle and does not use any regenerative heating. That is, the heat exiting the turbine is transferred to the environment through the condensers. The Kalina cycle would therefore transfer substantially less heat to the environment.

Expected Outcomes (continued)

An efficiency improvement would also mean that more electricity is being produced per pound of brine. Compared to a conventional binary power plant, the Kalina cycle can produce the same amount of electricity with less brine. That translates into fewer wells needing to be drilled and maintained.

- Demonstrate the economic benefits of the Kalina cycle power plant. This power plant will be a commercial operation. Therefore, the developers interest in operating this power plant is to convert the geothermal heat to electricity cheaper than by any other means available.

APPROACH

Exergy has brought together a team with the expertise and ability to make this project a success. The team members and their respective responsibilities are as follows:

- ▶ Exergy - Technology licensor and technical consultant.
- ▶ Far West Capitol - Lessee and developer of the geothermal resource and power plant operator.
- ▶ Atkinson - Engineering, design and construction of the power plant.
- ▶ Department of Energy - Project management through Cooperative Agreement.

FUTURE PLANS

The future plans of this project will proceed as follows:

- ▶ Detailed Engineering and Design
- ▶ Plant Construction
- ▶ Testing and Start-up
- ▶ Commercial Operation

REFERENCES

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Figure 4 - Schematic of Kalina Cycle System 11 (KCS11)

EVALUATIONS OF ADVANCED COATING MATERIALS

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KEYWORDS

corrosion protection, coatings, polymers, polymer matrix composites, polyphenylene sulfide, flame spray application technology.

PROJECT BACKGROUND AND STATUS

Corrosion and scale deposition continue to adversely affect geothermal plant operating costs, energy conversion efficiency, and utilization factors. To combat corrosion, portland cement-based materials are sometimes used as liners on brine piping systems, but the alkaline nature of the cements prevents their use with acidic fluids. Other conventional protective barrier materials such as epoxies, polyesters and acrylics, or metallic claddings, are limited by the thermal and/or hydrolytic stability of the plastics, and the costs for the latter.

Since the general utilization of high alloy steels is cost prohibitive for most geothermal plants, current practice is to attempt to minimize corrosion and the scale deposition rate by plant design and subsequent operation that may not be optimum for energy conversion and fluid injection. For example, it is well known that lowering the pH of hypersaline brines can significantly reduce silica scale deposition. This would allow greater temperature differentials across the heat exchangers, reduce plant size and complexity by elimination of the clarifiers, and decrease the amount of potentially toxic waste sludges that must be disposed of at ever increasing costs. Unfortunately, the lowering pH option is constrained by increased corrosion problems which can only be solved by the use of prohibitively expensive construction materials. Low cost, acid resistant and hydrothermally stable coating systems that can be used for new plant construction and for the retrofit of existing plants are needed.

Another, but lower priority, materials need which if solved would reduce plant operating costs, is for insulative corrosion resistant liners which could be factory applied on the inside of pipe sections. Materials meeting these criteria would provide corrosion protection and reduce the required amount of external insulation. Installing insulation is a labor intensive, expensive operation. A secondary benefit would be that heat losses to the pipe wall would be reduced. The resulting higher temperature at the brine/liner interface may result in reduced susceptibility to scale deposition and its adherence to the liner may be lower, thereby decreasing descaling costs.

This task was started in FY 1995 and is being performed as a cooperative cost-shared effort with geothermal energy firms.

PROJECT OBJECTIVES

The objective of this task is to optimize and field test polymer and polymer matrix composites, developed in other Geothermal Materials Development tasks, as corrosion protection systems for geothermal energy processes.

Technical Objectives

- Develop and field test low cost, acid resistant and hydrothermally stable corrosion protective coating systems that can be used for the retrofit of existing plants and for new plant construction.

Expected Outcomes

- Significant reductions in plant construction costs and complexity by elimination of the need for clarifiers.
- Increased electric generation efficiency and plant utilization factors.
- Enhanced environmental acceptance due to reductions in solid waste generation rates.

APPROACH

The project objectives are being met by the performance of a multi-phase effort that is cost-shared with geothermal energy and/or other industrial partners. In Phase 1, specific coating needs will be identified and performance specifications defined. Phase 2 will consist of the selection of potential candidate polymer and composite systems developed in other program tasks, and optimization of them for the specified end-use application. Field testing of coupon size samples will also be conducted in this phase of the effort. Contingent upon these results, Phase 3 will identify potential commercial sources and development partners for the technology. Field testing of coated prototype and full-scale process components at the Salton Sea KGRA and other locations will be conducted in Phase 4. Contingent upon these results, Phase 5 will consist of economic studies and the completion of technology transfer.

RESEARCH RESULTS

A cost-shared effort with the Magma Operating Company (presently owned by California Energy) for the testing of advanced coating systems at one or more of their Salton Sea geothermal plants was initiated.

In preliminary tests to determine the technical feasibility of using flame spray techniques as a means for applying polyaryl-type polymer coatings, metal coupons representing piping and turbine housing materials were supplied to the Flame Spray Laboratory operated by the Materials

Sciences Department at the State University of NY at Stony Brook (SUNY-SB). Two polymers, polyphenylene sulfide (PPS) and polyphenyletheretherketone (PEEK) are being used in these initial tests. Initial experiments to determine the optimum PPS particle size for spraying and to evaluate application techniques are underway. The work to date has shown that PPS can be sprayed with a butane torch, flame spray torch, and plasma. Parameters such as substrate preheat temperature, flame temperature and particle size are being evaluated. Based on the results obtained, it appears that high quality coatings suitable for demonstration are achievable. One major stumbling block has been the particle size of the PPS feedstock. A size distribution between 50 and 100 microns appears necessary, and this has been obtained by laboriously grinding larger particles. A major supplier of PPS resins is cooperating with us in our attempt to obtain larger quantities of properly sized material.

Work to prepare coated pipe sections for field testing commenced. Four 60-cm lengths of 25-cm diam carbon steel pipe will be used in these tests. One of the pipe sections contains a welded joint so that the ability to protect welds from corrosion can be ascertained. At BNL it is planned to dip-coat one section with PPS and another with PEEK. At SUNY-SB, PPS will be applied on two sections including the welded one. Flame spray technology will be used.

FUTURE PLANS

FY 1995 initiated laboratory testing of industry-supplied metal coupons that were coated with BNL selected corrosion protection systems will be completed. Based upon these results, field testing of coated pipe sections and other components will be initiated at the Salton Sea and The Geysers.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
California Energy Co.	Research collaborators for corrosion protection for plant components. Potential user of technology.
Pacific Gas & Electric	Research collaborators for corrosion protection of dry cooling tower components, turbine blades and 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, design studies, fouling coefficient, economics, heat transfer, mild steel, polymer cement composites, silicon carbide, thermal conductivity

PROJECT BACKGROUND AND STATUS

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 GD 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 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 could possibly 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 will also become possible.

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 then 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. It was later shown that the addition of high temperature antioxidants 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.

In FY 1994, a 75 day field test of carbon steel tubing lined with a thermally conductive polymer composite (PCL) was conducted under conditions that simulated those in a bottoming cycle in a multi-stage flash geothermal process. The heat exchanger consisted of four 6-meter lengths of 2.54-cm o.d. x 1.24 mm wall tubing lined with a 0.76-mm layer of the PCL. The hypersaline brine inlet and outlet temperatures were 108° and 89°C, respectively. Concurrently, AL-6XN control tubes were evaluated under similar temperature, pressure, flow and brine composition conditions.

In FY 1995, analyses of the heat transfer, fouling and corrosion resistance performance of the PCL were completed. Preliminary design and cost studies for utilizing the composite in full scale shell-and-tube heat exchangers were also conducted. A second field test using PCL modified by the inclusion of antioxidants is planned for FY 1996.

PROJECT OBJECTIVES

The 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). If successful, low cost substitutes for high alloy tubing will be identified and reductions in the rate of scale deposition on heat transfer surfaces will be obtained.

Technical Objectives

Development of a material meeting the following criteria:

- Heat transfer and fluid-flow characteristics similar to those of AL-6XN tubing.
- Fouling coefficient <50% of AL-6XN when used in brines typical of the Salton Sea KGRA.
- Cost not more than twice that of mild steel.

Expected Outcomes

- Electric generation capacities in geothermal flash processes could be improved by 10% with the availability of cost-effective materials for use in bottoming cycle heat exchangers.
- Low temperature geothermal resources 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.

APPROACH

The work is being performed as a collaborative effort between BNL, NREL and private industry. 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 are also performed at BNL.

Engineering analyses and heat transfer tests are conducted by NREL. The work includes measurements of heat transfer coefficients, cost estimates, and the management of field testing. NREL also coordinates technology transfer activities.

A geothermal company provides the field test site, operating personnel and ancillary equipment. Tests in an environment typical of that in a bottoming cycle application in a flash process are being performed. Design and economic studies are then conducted by a heat exchanger manufacturer.

RESEARCH RESULTS

In FY 1995, BNL completed the post-test analysis of PCL and AL-6XN control tubing after completion of a 75 day field test exposure to flowing hypersaline brine under heat exchange conditions. In separate tasks, NREL evaluated the fouling and heat transfer characteristics and arranged for the performance of design studies and economic estimates. These NREL tasks are documented separately.

The BNL results from post-field test evaluations performed on four 3-meter sections of PCL tubes and on equal length sections of AL-6XN tubes that were cut from the 6-meter tubes are summarized below:

- After 75 days of exposure, the PCL and AL-6XN tubes were both found to contain a layer of scale ~3.2 mm in thickness. In general, the deposition of scale in the tubes was found to increase as the temperature of the brine stream decreased. Measurements also indicated that the deposition of scale on the PCL tubes was, on average, ~8.5 percent greater than that deposited on the AL-6XN tubes. The increased thickness of the scale in the tubes was probably due to the fact that the scale adhered more readily to the surface of the PC liner than to the AL-6XN.
- A visual examination of the PC liners indicated that the liners were still securely bonded to the tubing, and there was no evidence of any voids or delaminations between the liner and the tubing.
- Shear bond strength test results indicated that the bond of the liner to the carbon steel tubing had not deteriorated as a result of the exposure tests. After 75 days of exposure, the PCL had an average bond strength of 8 MPa, compared to an average control value of 7.9 MPa. A visual examination of the interior surface of the tubes

after the liners had been pushed out indicated that there was no apparent evidence of corrosion at the interface of the liner and the tubing.

- Test results indicated that the bond of the scale to the surface of the liner was almost as high as the bond of the liner to the tubing. The average shear bond strength of the scale to the PC liner was 7.8 MPa.
- The average strength of the bond between the scale and the AL-6XN tubes was measured to be 1.2 MPa. A visual examination of the interior surface of the tubes after the scale had been pushed out indicated that there was no apparent evidence of corrosion at the interface between the scale and the AL-6XN tubing.

In conclusion, the results of the post-field test evaluation indicated that the PCL tubes were in good condition, and that they performed as well as the AL-6XN tubing.

FUTURE PLANS

Laboratory R&D to evaluate the effectiveness of the use of antioxidants as a method for reducing scale accumulation on composite lined heat exchanger tubing will be completed. Based upon the laboratory results, four 6 meter lengths of tubing containing antioxidants will be prepared for use in a second field test. The conditions for this test will probably be similar to those for the FY 1994 test, and the results will quantify the benefits of antioxidant additions. Tubing samples will also be provided to heat exchanger manufacturers for use in work to define potential methods for the joining of tubes to tube sheets in shell and tube heat exchangers.

INDUSTRIAL INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
California Energy Co.	Possible CRADA participant. User of technology.
Hughes-Andersen Heat Exchangers, Inc. Babcock & Wilcox	Heat exchanger manufacturer.

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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 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 1990, BNL initiated cost-shared work with geothermal companies active at The Geysers which focuses on low cost solutions to these difficult materials problems. The 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 1995, a series of field tests of coating systems for well casing had been completed with the Central California Power Agency (CCPA), and evaluations of pipeline 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, such as rotor housings, was underway.

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

Attainment of the project objectives will result in the following:

- Wells that presently cannot be operated due to excessive maintenance costs or environmental/safety concerns may be restarted.
- Service life expectancies of fluid production, transmission and electric generation components will be increased.
- Cost-effective methods for water conservation will be available, thereby resulting in reservoir life extensions due to increased fluid reinjection.

APPROACH

The approach 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

Laboratory and field testing efforts being performed as cost-shared activities with geothermal companies active at The Geysers were continued. Current industrial participants are the Pacific Gas and Electric Company (PG&E) and the Northern California Power Agency (NCPA). Of interest to PG&E are corrosion protective coatings for turbine components, and dry cooling towers. Polymer-matrix composite-lined steam transmission piping tees are being evaluated for NCPA. Details of these activities are summarized below.

Turbine Components

Flame spray-applied coatings on five metal substrates of compositions representing those currently used in turbines by PG&E at The Geysers are being evaluated. Components of interest are wheel pieces, buckets, diaphragm bodies and diaphragm partitions. New materials and specimens cut from parts removed from turbines used at The Geysers are included in the test matrix. Data from the latter will yield insight regarding the performance that may be expected when coatings are field applied to the components during routine maintenance operations.

Work to evaluate flame spray variables for polyphenylene sulfide (PPS) and other high temperature polymeric coatings is being conducted as part of a cost-shared effort with the Materials Sciences Department at The State University of New York at Stony Brook. Experiments to determine the optimum PPS particle size for spraying and to evaluate application techniques are underway. The work to date has shown that PPS can be sprayed with a butane torch, flame spray torch, and plasma. Parameters such as substrate preheat temperature, flame temperature and particle size are being evaluated. Based on the results obtained, it appears that high quality coatings suitable for demonstration are achievable. One major stumbling block has been the particle size of the PPS feedstock. A size distribution between 50 and 100 microns appears necessary, and this has been obtained by laboriously grinding larger particles. A major supplier of PPS resins is cooperating with us in our attempt to obtain larger quantities of properly sized material. Once received, coating of the PG&E turbine component samples will commence.

Laboratory evaluations of PPS coatings dip-applied to cold rolled steel and aluminum substrates were started. It was determined that coating thicknesses of >0.12 mm are needed to achieve long-term corrosion protection. With steel, it was determined that the formation of water insoluble FeS and ZnS reaction products at the PPS/steel interface enhances bonding and durability. These compounds are produced by interactions during the application process between S originating from the PPS and Fe in the steel.

A moderate rate of oxidation of the sulfide in PPS was found to play a key role in ensuring that PPS coatings protect aluminum in wet, low pH environments. The formation of a discontinuous, intermediate layer of $\text{Al}_2(\text{SO}_4)_3$ as the interfacial reaction product between Al_2O_3 at the top surface of aluminum and the oxidized PPS enhances the bond strength at this interface.

Dry Cooling Tower Components

Prototype sections of polymer coated finned-tube heat exchanger tubing 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 (PPS) and vinyl ester resin - trimethylolpropane trimethacrylate applied to surface modified and "as-received" metal surfaces were used for corrosion protection. Visual inspections were made after approximately 2, 5, and 10 mo, and no signs of blistering, chalking or delamination were apparent on any of the coated samples. All of the samples were reported to be in an "as new" condition. These tests are continuing.

Piping Systems

In March 1992, two polymer cement (PC) lined 30-cm diameter pipe tees were installed by NCPA in a steam transmission line where the conditions are as follows: flow rate 13,640 kg/hr, temperature 173°C and pressure 0.83 MPa. Both tees were visually inspected after approximately 12 mo exposure. At that time, some fine cracks and small regions of disbondment of the liner were noted, but in general both tees were in good condition. Therefore, the test was resumed and it has continued without interruption for a total exposure time of 44 mo as of December 1995. Since filters located downstream of the tees which are monitored routinely have not collected any pieces of the PC liner, it is expected that no gross erosion or delamination has occurred. At the next plant shutdown, both tees will be removed for examination.

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

Organizations	Type and Extent of Interest
NCPA	Research collaborators for corrosion protection for transmission piping. Potential user of technology.
PG&E	Research collaborators for corrosion protection of dry cooling tower components, turbine blades, rotor housings. Potential user of technology.

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FIELD TESTING OF THERMALLY-CONDUCTIVE, CORROSION-RESISTANT LINERS

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KEY WORDS

materials testing, materials development, polymer concrete lining, heat exchangers, industrial coatings

PROJECT BACKGROUND AND STATUS

A major concern in the utilization of geothermal resources, for producing low cost electricity, is the scaling and fouling of the heat exchanger surfaces used in binary geothermal power cycles. The formation of scale can help to accelerate the rate of corrosion at the heat exchanger surface and can drastically reduce the effectiveness of this heat transfer surface. 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. In addition, it is believed that this PC lining may be able to reduce the level of scale buildup, thus reducing the rate of fouling of the heat transfer surface.

A collaborative effort between NREL and an industry partner, which began in 1993, sought to quantify the heat transfer, anti-corrosion, and anti-scaling properties of a set of Polymer Concrete Lined (PCL) heat exchanger tubes provided by BNL. These field tests were concluded in November 1994 after a total of 75 days in brine service. The data gathered during the test were analyzed to determine the heat transfer and pressure drop performance of the PCL tubes. Both the PCL tubes and the high alloy stainless steel (AL-6XN) tubes were removed from the heat exchanger and examined to determine the anti-corrosion and anti-scaling performance of each. In addition, an economic analysis was conducted to ascertain the cost savings potential of PC lined heat exchangers.

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 conduct a series of field experiments for quantifying the heat transfer, anti-corrosion, and anti-scaling properties of tube liner materials, polymer concrete (PC) to date, in geothermal brine service. This task is important to the geothermal industry because it provides an alternative to the high cost of heat exchanger tubes made from corrosion resistant materials, such as titanium and high alloy stainless steel. In addition, it has the potential to reduce operational and maintenance costs of general process piping in brine service.

Technical Objectives

- Characterize the heat transfer, anti-corrosion, and anti-scaling properties of industrial polymer coatings, such as the polymer concrete lining developed at BNL, in relation to the currently available corrosion resistant metal alternatives.
- Identify potential difficulties arising from normal operations with a lined heat exchanger instead of a more conventional heat exchanger, employing corrosion resistant materials.
- Identify the significant manufacturing issues raised in the commercial production of lined heat exchangers, using the polymer coatings under consideration, and propose possible remedies and solutions.
- Assess the economic advantages of lined heat exchangers over heat exchangers employing corrosion resistant materials like titanium and high alloy stainless steels.

Expected Outcomes

- Thermal and mechanical data for use in designing full-scale heat exchangers used in binary geothermal cycles.
- General cost data, which can be used to gauge the overall costs associated with the fabrication of lined heat exchanger.
- Manufacturing techniques and processes for use in constructing lined heat exchangers in a commercial production environment.
- New heat exchanger lining materials that will lower the cost of electricity generation and extend the life of the primary heat exchangers.
- Similar coatings that could significantly reduce the operational and maintenance costs associated with general brine service piping and well casings.
- An additional outcome of this project could be the development of appropriate coatings that could be used to extend the life of the plant's rotating equipment that must be periodically repaired as a result of corrosion and erosion damage.

APPROACH

The approach taken in this task is to work closely with industry partners and BNL to develop, field test, and analyze polymer liner systems that provide viable alternatives to expensive corrosion resistant metals for geothermal heat exchanger tubing and service piping. Previous tests

of a polymer concrete liner material developed by BNL were conducted under a Cooperative Research and Development Agreement (CRADA) between NREL and one of its industry partners. This CRADA enabled field testing of the PCL material in the presence of an aggressive geothermal brine, which was provided by the industry partner at one of their geothermal power plants. Plans are currently underway to establish a new research agreement between NREL, BNL, the current industry partner, and a new industry partner to develop, test, and manufacture new polymer liner formulations. The steps taken by NREL for achieving the objectives of this task include:

- A detailed analysis of the thermal and mechanical data obtained over the course of the long-term field tests concluded in November 1994.
- Post field test examinations of the PCL and AL-6XN tubes to gauge the impact of the geothermal brine on fouling and corrosion in the tubes.
- Hydroblasting tests of the scaled PCL tubes to determine the cleaning potential of PC lined tubes.
- An economic study that quantifies the potential cost savings associated with heat exchangers constructed using PC linings in lieu of exotic corrosion resistant materials.
- An assessment of the manufacturability of full-sized lined heat exchangers. NREL is working closely with U.S. firms knowledgeable in the areas of advanced materials and industrial coating technology, and heat exchanger construction to assess and evaluate manufacturing issues related to lined heat exchangers.
- Development of research plans and industry partnerships to develop and test new and existing types of organic polymer linings that exhibit some or all of the properties cited previously.

RESEARCH RESULTS

Early testing of the PC lining, by BNL researchers, indicated that the lining was capable of protecting pipes exposed to an aggressive brine environment. In addition, the relatively high measured thermal conductivity of the material ($k_{pcl} = 3.7$ Btu/hr-F-ft) pointed towards its use in protecting heat transfer surfaces exposed to aggressive brines. Estimates indicated that if this PC material was used as a liner on carbon steel ($k_{cs} = 26$ Btu/hr-F-ft) and this liner was made suitably thin (approximately 30 mils) then the overall thermal conductivity of the composite heat transfer surface was comparable to that of high cost corrosion resistant metals like titanium and high-alloy stainless steels ($k_{AL} = 8.2$ Btu/hr-F-ft), having the same wall thickness.

In FY 1990, Idaho National Engineering Laboratory (INEL) and BNL in conjunction with a geothermal industry partner conducted a series of field tests involving a counterflow heat exchanger lined with the PC material and exposed to an aggressive geothermal brine. These field tests experienced numerous difficulties and were terminated after only 30 hours of operation, due

to plugging of the heat exchanger tubes. An examination of the tubes following the termination of the field tests found that a non-uniform application of the PC liner was the primary cause of the poor performance and rapid plugging. A technical report (1) containing the complete results of these field tests was provided to all the involved parties by INEL, in FY 1993.

NREL resumed the field testing of PCL heat exchanger tubes in FY 1993, along with BNL and the original geothermal industry partner. By the time these field tests resumed, BNL had devised a method of fabricating PCL tubes with a uniform liner thickness of 30 mils. In these tests the performance of the PCL tubes were compared to a control case using AL-6XN tubes. These tests utilized the original test skid that was built by INEL for their field tests back in 1990. The test skid contained two parallel counterflow heat exchanger loops, each 80 ft. in length. The field tests began in the summer of 1993 and were not concluded until November 1994. This time period is considerably longer than the 100 days of testing that had been envisioned as a result of several technical difficulties and delays that surfaced in both the test skid and the brine delivery system from the geothermal power plant. A total of 75 days of process data was obtained over this entire period.

Analysis of the thermal and mechanical data over the 75 test days (2) found comparable heat transfer and pressure drop performance for the PCL and AL-6XN tubes. The test results demonstrated that under similar operating conditions the overall heat transfer coefficient for the PCL tube was about 9% lower than for the AL-6XN tube. Pressure drop data found a similar rate of increase for both types of tubes, indicating a similar rate of fouling and scale buildup for both sets of tubes.

Following the conclusion of testing in November 1994, the PCL and AL-6XN tubes were removed from the heat exchanger test skid for further analysis. Approximately half of the PCL tubes and all of the AL-6XN tubes were sent to BNL for a detailed analysis of the PCL performance. The other half of the PCL tubes were sent to a commercial hydroblasting outfit to determine the cleaning potential of a PC lined heat exchanger surface.

Post field test examinations by BNL (3) found that the PC liner successfully protected the carbon steel tube from corrosion. Measurements of the scale-liner bond strength in the PCL tube found that it was more than six times the strength of scale-tube bond in the AL-6XN tube. Furthermore, measurements of the scale buildup found that the scale layer in the PCL tube was approximately 8.5% thicker than the one in the AL-6XN tube. This would seem to indicate that the scale bonded more readily to the surface of the PC liner, contrary to what was originally anticipated. Measurements of the bond strength between the PC liner and the carbon steel tube found it to be essentially the same as the bond strength between the scale and the PC liner. It is believed that a new formulation of the PC liner that was recently developed at BNL will drastically reduce the bond strength of the scale to the PC liner.

Hydroblasting tests indicated that geothermal scale deposited on the current formulation of PC lined tubes could not be consistently cleaned without destroying the liner in the process. A predictable pattern of pressure and flow rate that would result in a consistent removal of the scale only, leaving the underlying PC liner intact, could not be identified. Based upon the results, it

was concluded that the unpredictable nature of the scale removal was a result of a scale-liner bond strength similar in magnitude to the liner-tube bond. This conclusion was supported by the measurements made by BNL.

An economic study was commissioned with a geothermal heat exchanger manufacturer to determine the potential cost savings of a PC lined heat exchanger over one constructed using corrosion resistant metals (4). The corrosion resistant material selected for this study was titanium, which at the time of the study had the lowest material cost of the four compatible materials identified by the geothermal industry partner. The study was meant to identify cost targets for a PC lined heat exchanger. The analysis of the PCL heat exchanger included PC material costs and all standard heat exchanger fabrication costs, but did not include the costs associated with applying the PC material. It was, therefore, meant to be used to determine the maximum allowable cost of applying the PC liner that would still result in an attractive cost reduction. The study found that the titanium heat exchanger was close to three times as costly to manufacture as a PCL heat exchanger minus the PCL application costs, which we will call the base cost of the PCL heat exchanger. If we assume a 50% price target for the PCL heat exchanger to be selected over the titanium alternative, the total costs associated with the application of the PC liner must be less than half the base cost of the PCL heat exchanger.

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

Preparations for a new set of field tests are underway to evaluate the new formulation of PCL that has been developed at BNL. This new set of tests may also include testing of two additional liner materials in their current commercial formulations or a slightly modified formulations.

A new research agreement is currently being negotiated between NREL, BNL, and the previous geothermal industry partner. Negotiations are also underway with a US-owned industrial coatings firm to develop and test new and existing organic polymer coating for use in geothermal brine applications. With the help of this new industry partner, manufacturing issues relating to the application of such protective coatings in a production environment will be resolved, resulting in more accurate cost estimates for a lined heat exchanger. This would eventually lead to the fabrication of a pilot scale lined geothermal heat exchanger and ultimately to production units.

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ADVANCED HIGH TEMPERATURE CO₂-RESISTANT LIGHTWEIGHT CEMENTS

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KEYWORDS

calcium aluminate cements, phosphate containing compounds, flyash, acid-base reactions, mechanical properties, carbonation, lightweight, pumpable, well completions

PROJECT BACKGROUND AND STATUS

The quality of the cementing phase of a geothermal well completion often establishes the life expectancy of the well. Improperly designed cement jobs can result in blow-outs and casing corrosion or collapse. In addition to the need for cements which, upon curing, yield the necessary physical, mechanical and chemical characteristics, their slurry precursors must have rheological properties that permit placement. Low slurry densities (~ 1.2 g/cc) are desirable to minimize the frequency of lost circulation episodes when attempts are made to cement in weak unconsolidated rock zones with very fragile gradients.

During the period 1978-84, BNL under Department of Energy (DOE) Geothermal Division sponsorship 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, thereby 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 5 years, and in one case, resulted in a collapsed well casing within 90 days. Solving these materials problems, which could seriously constrain the development of the world's geothermal resources, is the goal of the current cement research activity.

As of December 1995, several cement formulations that meet many of the design criteria have been identified. Laboratory characterizations are underway. Industrial collaborators (Halliburton Services and Unocal) have been identified and they are participating in ongoing engineering-scale tests and downhole evaluations.

PROJECT OBJECTIVES

The objective of the project is to develop and field test lightweight, low-cost, CO₂-resistant, non-portland based cementitious materials that can be used for geothermal well completions.

Technical Objectives

Design criteria for the cements being developed in this program are as follows:

- Slurry density, approximately 1.3 g/cc.
- Pumpability, 4 hr at 100°C.
- Carbonation rate, <5% after 1 yr in brine at 300°C containing 500 ppm CO₂.
- Compressive strength, >5 MPa at 24 hr age.
- Bond strength to steel, >0.07 MPa.
- Water permeability, <0.1 m Darcy.

Expected Outcomes

- Decreased costs for well completions due to reductions in lost circulation control episodes.
- Increased well life to >20 yr.
- Reduced environmental concerns regarding blow-outs.
- Permit development of higher temperature, higher CO₂ content brines.

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 I consists of fundamental work to synthesize non-portland cement-based materials and to elucidate the interactions that occur between them and a number of lightweight inorganic and organic 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 CO_2 -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

Cost-shared R&D between BNL, Halliburton Services and Unocal was continued. The results confirmed that 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 hr in hydrothermal environments up to 300°C , high strength (>58 MPa), durable and CO_2 -resistant cement pastes are produced. Measurements of the CaCO_3 concentrations after autoclave exposure to a 0.05 Na_2CO_3 solution at 250°C for 120 days indicated values generally of <0.4 wt%. A conventional portland cement-based well completion material will form approximately 10 wt % CaCO_3 after only 7 days exposure to the same environment. Upon laboratory exposure to extremely harsh conditions ($>1.5\%$ CO_2 , 300°C), some carbonation-induced decomposition of calcium phosphate cements was noted. It was also determined that the rate of carbonation obtained upon exposure to hot water containing CO_2 gas is essentially the same as that in Na_2CO_3 -laden hot water. Experimentally, it is easier and safer to use the latter.

The incorporation of inorganic and organic microsphere fillers into the calcium phosphate cement matrix (CPC) produces a lightweight, moderate strength and highly durable cement. Aluminosilicate-based hollow microspheres, with a density of 0.67 g/cc and a particle size of 75 to 200 m, produced 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 hr at 25°C due to chemical interactions between the microspheres and the cementing matrix formulation.

Although the calcium phosphate cements are extremely resistant to carbonation at CO_2 concentrations up to those present in geothermal fluids currently of interest, care must be taken to insure that reactions with filler materials are not induced. For example, data from well tests performed at a depth of 2440 meters on lightweight cements containing glass and ceramic microspheres indicated that both of these inorganic-based microspheres reacted chemically with the cement hydrates. These reactions resulted in the formation of numerous microcracks and subsequent strength loss. The fluid temperature and pressure for these tests were 257°C and 16.3 MPa, respectively. BNL laboratory data confirmed these downhole results. In the BNL studies, lightweight calcium phosphate cements containing mullite microspheres exhibited 70% reductions in strength after 6 mo autoclave exposure to a 0.05 M Na_2CO_3 solution at 250°C .

Chemically inert organic-type microspheres were found to be promising fillers for use with calcium phosphate cements to produce lightweight, CO_2 -resistant cements. As an example, slurries containing hollow acrylonitrile microspheres had a density of 1 g/cc and produced a cured cement which upon autoclave exposure at 250°C for 6 mo. retained 73% of its initial strength. Optimization of this formulation is in progress.

Recent BNL studies have identified blast furnace slag and class F flyash combinations as promising cementing material additives. Since they both are industrial by-products, they are inexpensive. They are also highly reactive with $(\text{NaPO}_3)_n$ solutions and exhibit rapid hydration rates. Preliminary BNL studies using high alumina cement/blended class F flyash cement mixtures modified with $(\text{NaPO}_3)_n$ solutions produced cements with compressive strengths >27 MPa after curing for 7 days at 300°C. The cost of this formulation is estimated to be 70% lower than that derived from $(\text{NaPO}_3)_n$ modified high alumina cement slurries. Studies of the phases formed, microstructure developed, carbonation rate, and changes in strength and permeability after long-term exposures to CO_2 solutions at 250°C have been started.

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.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Halliburton Services	Cement properties characterization, pumpability studies, economic evaluation.
Unocal	Field testing.

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ADVANCED BIOCHEMICAL PROCESSES FOR GEOTHERMAL BRINES

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KEY WORDS

biochemical processing, decontamination, metal recovery, new products

PROJECT BACKGROUND AND STATUS

In 1987, an R&D program was begun at 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, microorganisms have been identified which can interact with toxic metals (including trace radionuclides) in geothermal residual sludges and convert them into soluble species for subsequent reinjection or concentration. The biochemical activities of these organisms served as models for the development of economic detoxification processes for geothermal waste treatment. The new technology reduces significantly the cost of surface disposal of sludges derived from geothermal brines. Concurrent processes to concentrate and recover valuable metals and salts are also being developed. Currently, the process removes better than 80% of total metal concentration in less than 24 hours. The solid residue from this treatment can be subjected to a secondary treatment leading to a depigmented product with applications potential in other industries. The aqueous product from the primary process can be used for metal recovery. Economic and regulatory significance of the new technology is clearly defined by the following information.

In 1985, the graded cost for type II-I disposal was \$200 per ton and \$75 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% removal of the metals represented a 60% saving. The cost of disposal and the long term liabilities are continuously increasing, while the available space for disposal is diminishing. For example, at BNL, recent disposal cost of a similar sludge was \$500 per ton. The corresponding non-regulated waste disposal cost was \$100 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 (\$2052 per ton). On the other hand, removal of the metals leaving radium alone produces waste costing \$76 per cubic foot to dispose of (\$10,800 per ton). 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, (c) adjusting to specific needs as demanded by different chemistries of geothermal sludges and brines, (d) production of fillers from the de-pigmented byproduct. The benefits are both environmentally and economically attractive. Not only is the detoxification less expensive, but the end products are useful. The emerging biotechnology could find applications in other industries, particularly in the treatment of similar geochemical materials.

PROJECT OBJECTIVES

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. High disposal costs and the long-term liability associated with hazardous waste disposal provide the incentive for this study. Development of economically and environmentally acceptable methods for disposal of geothermal wastes and conversion of by-products to useful forms is being pursued.

Technical Objectives

- 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 such as fillers and construction materials.
- 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

- A 25% or more reduction in disposal costs and less long-term liability associated with hazardous waste disposal.
- Conversion of geothermal sludges and brines into environmentally acceptable feedstocks, together with the metal salts recovery option.
- Integration of the biochemical processing recovery and recycling options into a geothermal power producing plant.

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 reduce significantly the high disposal cost and the long-term liability associated with hazardous waste disposal.

(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 pooled with bulk brines and be 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 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. Metals such as chromium, copper, manganese, and others, can be removed with 80-90% efficiencies. A laboratory-scale pilot plant has been constructed and is being used for the optimization of processes. 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, CRADAs and collaborative arrangements are in place.

RESEARCH RESULTS

The fourth comparative study of the agitated tank vs. fluidized bed type bioreactor was completed. For practical purposes, i.e., space restraints, the agitated tank is being used for routine studies. The two types of bioreactors are interchangeable in the BNL process.

Using a 40% loading and several hours residence time, a preliminary economic evaluation has also been completed. The results have been used to develop a computer program for the advanced biochemical processing of geothermal residual sludges. Differences in the cost of various processes stress further the importance of loading, residence time, the type of bioreactor,

biocatalysts production, process options and recycling. This study has also indicated the importance of process quality control and appropriate monitoring needs.

A first generation pilot-plant has been constructed and is being automated. A secondary process for the removal of radionuclides has been identified and is currently optimized. Sludge loadings of up to 40% are practical and at temperatures of $>50^{\circ}\text{C}$ fast rates of 10 hr or less have been achieved. Studies at elevated temperatures have confirmed that particular attention has to be paid to construction materials, compressors, pumps and other equipment needed for an efficient detoxification process.

The study of metal and salts recovery processes is very promising and indicated that an 80% to 90% metals recovery is possible from a small concentrate. The final aqueous phase meets drinking water standards. A complementary potassium and sodium chloride option is also very promising.

A process for the production of fillers has been designed. This process converts the bulk of the predominantly silica rich final residue into a new commercially viable feedstock.

FUTURE PLANS

Collaboration with industry will be expanded, e.g., cost-shared ventures. Complete process variables verification. Use best results from optimization studies for operating and field construction cost analyses. Continue "quality control" as per Salton Sea experience.

Additional and continuing attention is given to the environmental requirements and management of trace radionuclides. Conduct routine radioactivity measurements in the analysis of residual sludges with particular attention to radium.

Perform kinetic studies of biotransformation process at elevated temperatures particularly focused on short residence times and radionuclides removal. Optimize secondary processes particularly de-pigmentation technology.

Use laboratory plants to process and evaluate different types of sludges as supplied by industry, for example, MAGMA, P.G.&E. and others.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
California Energy (CECI) C.E. Holt Company	One on one collaborative effort. Confidentiality Agreement signed. BNL assists the industry in their analytical chemistry needs and selected technical studies. The industry consults and exchanges materials and information. Field trials of a prototype biochemical process will be conducted by CECI at their site.
CET Environmental P.G.&E. Services	A CRADA between BNL and CET Environmental Services is in place. In this CRADA, CET will scale up a modified version of BNL's biochemical process specifically geared to the type of wastes generated by the Geysers types of operations. P.G.&E.'s management at the Geysers Geothermal Field have already identified the site for field testing of this process and their sludge waste stream.
EER, Inc., CA ENSOL, Inc., CA	CRADA

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APPENDIX 1

ECONOMICS OF BIOCHEMICAL WASTE TREATMENT PROCESSES

Previous and ongoing studies have shown that there are at least ten key process variables, ranging from the reactor size to the recycling of biocatalysts, which are essential in the determination of the cost-efficiency of the bioprocesses considered. In addition to these variables, several other parameters have to be evaluated and costed into the design of the overall biochemical process. Currently, the most efficient primary process utilizes two biocatalysts whose production and the rate of delivery influence the size and the number of bioreactors needed to be operational. In Figure 1, a process for the treatment of 5294 kg/h of geothermal sludge at a 40% loading and a residence time of 5 h in the biochemical reactor, requires an input of 946.5 kg/h of each of the biocatalysts. The rate of the Biocatalyst 1 production is fast and that of Biocatalyst 2 is slow. This fact influences the cost of productions. Further, a 50:50 or 85:15 mix of the two biocatalysts influences significantly the economics of the process. Three additional factors have to be also taken into consideration: (1) recycling of the biocatalysts, (2) recovery of valuable metals, (3) recovery of salts such as sodium chloride and potassium chloride, and (4) production of fillers. Options 3 and 4 generate revenues which offset the cost of initial investments as shown in Figure 2. Table 1 shows significant savings which can be achieved by different biocatalyst mixes and recycling. Further combination of the biocatalyst mixes and the potash recovery option, as shown in Table 2, makes possible to accomplish additional monetary gains by total processing of various byproducts generated in the operation of a power plant.

Figure 1. Total biochemical process for geothermal sludge (5130 ib/h). Treatment: Biocatalyst 1 (50%): Biocatalyst 2 (50%).

Figure 2. Biochemical processing for geothermal sludge and brine. Scenario C: Combined processes for sludge and brine.

**Table 1. Cost Comparison for Different Biocatalyst Mixes
and Corresponding Total Bioprocess Costs Per Metric Ton of Sludge**

	*BC1:BC2	BC1:BC2	BC1:BC2
	50:50	85:15	85:15 (3 recycles)
	250 gal/h: 250 gal/h	425 gal/h: 75 gal/h	106.25 gal/h: 18.75 gal/h
BC1			
Capital Cost (CGR)	1,838,000	2,556,000	1,196,000
Annual Treatment	1,097,000	1,778,000	820,000
Fee	145	138	255
Unit Treatment Fee (\$/metric ton culture)			
BC2			
Capital Cost (CGR)	7,017,000	2,573,000	1,002,000
Annual Treatment	3,683,000	1,687,000	736,000
Fee	486	743	1,298
Unit Treatment Fee (\$/metric ton culture)			
BC1 + BC2			
Capital Cost (CGR)	8,855,000	5,129,000	2,199,000
Annual Treatment	4,449,000	3,466,000	1,556,000
Fee	316	229	411
Unit Treatment Fee (\$/metric ton culture)			
Total Bioprocess Costs Including Biocatalyst Production			
Capital Cost (CGR)	10,195,000	6,493,000	3,415,000
Annual Treatment	5,882,000	4,578,000	2,614,000
Fee	316	246	140
Unit Treatment Fee (\$/metric ton sludge)			

*BC = Biocatalyst

**Table 2. Total Biochemical Process Profit Estimates
Including Potash Plant Option for a 50-MW Power Plant**

BC1:BC2	Net Gain in \$ Millions/year
50:50	1.83
85:15	2.74
85:15 3 cycles	5.51

GEOTHERMAL POWER ORGANIZATION

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KEY WORDS

industry advisory group, geothermal energy conversion, cost-shared research

PROJECT BACKGROUND AND STATUS

The Geothermal Power Organization (GPO) was formed in 1993 to serve as an advisory group of geothermal industry professionals working on energy conversion technologies and equipment. The formation of the GPO involved the consolidation of the functions of the former Energy Conversion Panel (ECP) and the Technical Advisory Group (TAG). Since its inception, the GPO has provided an effective forum for discussions on the research needs for the geothermal industry and the promotion of geothermal energy for the production of electricity in a cost-effective fashion. The GPO has promoted an active exchange of ideas that provides industry response and guidance on the DOE Geothermal Division energy conversion program.

As a result of the members' active involvement in the GPO and at the bi-annual meetings, a fundamental change in the structure of the organization was instituted by DOE to assist the industry in pursuing cost-shared research and development with DOE. Efforts over the last year have centered upon investigating the various options for establishing a cost-sharing capability, and then implementing the most appropriate mechanism that met with agreement from the GPO members and the DOE. Significant strides have been made in moving the process forward, and as a result, a Memorandum of Understanding and a new, more structured organizational charter have been developed and are currently under review. The signing of the MOU should take place in January, 1996.

PROJECT OBJECTIVE

The objective of GPO is to provide industry-driven research objectives and guidance in advancing state-of-the art of geothermal energy conversion technology supported by DOE.

Technical Objectives

The Geothermal Power Organization provides a forum for:

- The presentation of proposals for industry projects related to geothermal technology for sponsorship by members of the GPO.

Technical Objectives (continued)

- Exploring the level of members' interest in potential technological problems to aid in developing future industry sponsored projects.
- Advising the geothermal industry, academic organizations and other research-oriented groups of the needs and interests of GPO.
- Facilitating the development of laboratory and research results related to geothermal energy conversion technology.
- Providing critical analyses of the technical aspects and direction of the energy conversion programs in the DOE Geothermal Division.

Expected Outcomes

- Project proposals submitted to GPO for consideration of cost-shared funding by industry and the DOE Geothermal Division.
- Development and promotion of priority research areas through cooperative research partnerships.
- Continued active participation by GPO members in exchanging information and ideas about energy conversion issues both at the GPO meetings and through informal channels.
- Increased visibility for the energy conversion sector and the important contributions that can be made by it in reducing costs of geothermal power.

APPROACH

Currently, the coordination and management of the GPO are done by NREL, with oversight provided by the DOE Geothermal Division. After signing the MOU, GPO will be managed by one of the industry members of GPO, with less involvement of the DOE and NREL. Meetings are held twice a year to solicit feedback from the geothermal industry, discuss research priorities, 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 the institution of a cost-sharing capability for the geothermal industry with the DOE Geothermal Division. Research projects will be proposed by the industry members at the next GPO meeting

(April, 1996), and with approval of funding by DOE, the highest priority projects will be initiated in 1996.

FUTURE PLANS

Bi-annual meetings will continue to be planned and carried out during the Geothermal Resources Council annual meeting (Fall) and the DOE Geothermal Program Review (Spring). Providing that cost-sharing funds are available from DOE, proposals will continue to be submitted by industry and projects undertaken that further the goals and objectives of the GPO.

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. Currently, there are approximately 25 active members of the GPO.

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DIRECT USE

GEOHERMAL DIRECT HEAT UTILIZATION ASSISTANCE

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KEY WORDS

aquaculture, direct use, district heating, greenhouses, heat pumps, industrial, low temperature resources, space heating, technical assistance

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 are 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 678 MWt representing an annual energy utilization of 2,747 TJ/yr, including heat pumps (Lienau, 1994). This growth is the result of 18 direct heat projects in five states and the equivalent of 72,700 3-ton geothermal heat pumps. The Geo-Heat Center provided technical assistance to 14 of the 18 projects and to 78 commercial geothermal heat pump projects.

PROJECT OBJECTIVES

The objectives of this project are to conduct direct-heat applied research and development and to provide assistance to stimulate utilization of the nation's large low-to moderate-temperature (<90° to 150°C) geothermal resource base.

Technical Objectives

- Provide technical assistance to developers of geothermal direct use projects for space heating, geothermal heat pumps, greenhouses, aquaculture and industrial applications.

Technical Objectives (continued)

- 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.

The success of this project will mean more rapid penetration of geothermal direct use into the energy sector.

Expected Outcomes

- Energy savings and reduced emissions of airborne pollutants and greenhouse gases due to more geothermal direct-heat projects on-line. For example, a 457 m, 82°C geothermal well producing 3 MWt (500 gpm) saves 28 TJ/yr of energy and reduces SO₂ by 0.1 kg, NO_x by 0.6 kg and CO₂ by 687 kg per hour compared to a natural gas boiler plant.
- Determine the cost of geothermal supplied heat in a similar fashion to that used for conventionally fueled sources. For the example above, the geothermal unit cost is \$1.86/10⁶ Btu and for natural gas \$6.14/10⁶ Btu with a simple payback of 1.2 years.
- Transferring the lessons learned in the Klamath Falls marketing program to some of the other district heating systems which have not achieved similar levels of customer saturation.
- Increased awareness of geothermal direct-heat developments and opportunities by publication of Bulletins on geothermal projects, technical papers, software, tours, and other educational materials.

APPROACH

The Geo-Heat Center's approach is to provide technical assistance to prospective geothermal users on resource data, preliminary engineering design, analysis of operational problems and technical information. The program is designed to introduce the potential user and engineering consultant to geothermal direct-heat applications. The presence of a proven and reliable source of technical advice to the consultant is critical in promoting their initial involvement with an unfamiliar resource. The Oregon Institute of Technology provides a cost share of 14.3% 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 for analysis (usually eight hours/project unless prior approval for additional hours are received from DOE). Engineering and economic assistance has been provided to a broad range of clients, from homeowners interested in geothermal space heating and municipalities engaged in geothermal district heating projects, to industrial concerns adapting geothermal resources to meet process energy needs. During FY 1995, the program handled 326 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) developing a spreadsheet for the cost evaluation of geothermal supplied heat in a similar fashion to that used for conventionally fueled sources, and (2) marketing program for cities with geothermal district heating systems.

Geothermal Cost Evaluation

In order to be seriously considered as an alternative in any project, an energy source must be easily characterized in terms of cost, both capital and unit energy cost. Historically, this has been a difficult hurdle for geothermal energy. Its costs vary with the depth and character of the resource, number of production and injection wells, and a host of other parameters. As a result, even in cases where developers are interested in using geothermal, identifying its costs has been a cumbersome process. To address this problem, a spreadsheet has been developed which allows potential users to quickly evaluate the capital cost and unit energy cost of accessing a geothermal resource (Rafferty, 1995).

Using resource, financing and operating inputs, the spreadsheet calculates the capital cost for production well(s), well pump(s), well head equipment, injection well(s), and connecting pipelines. These capital costs are used along with the quantity of annual energy to be supplied and financing information to produce a unit cost of energy. Unit costs for operation (maintenance and electricity) are added to arrive at a total unit cost in \$ per million Btu for geothermal heat. To put this value into perspective, similar costs for an equivalent sized gas boiler plant are also calculated. These values can then be compared to determine the relative economic merit of geothermal for any specific set of circumstances. This information is particularly useful at the conceptual stage of a project when decisions as to fuel source are typically made by the developers.

Consider a local economic development agency in an area of known geothermal resources as a general example of the use of the spreadsheet. The economic development agency may wish to determine the relative economic merit of geothermal use for a new industrial development as a function of required well depth. Output from the spreadsheet can be used to develop the curve illustrated in Figure 1. This graph assumed a 3 MWt load at two different load factors: 20% representing greenhouse or multi-building district heating, and 30% representing an industrial

process load. Even for this relatively small load, conditions are favorable (simple payback less than 5 years) for geothermal for all applications up to a well depth of 762 m without injection and for higher load factor (30%) with injection. For lower load factor (20%) applications, a well depth of up to 425 m with injection provides simple payback for less than 5 years.

Marketing Geothermal District Heating Systems

In the early 1980s, several geothermal district heating systems were installed with DOE sponsorship. Several of these were installed in small towns (Klamath Falls, OR; Susanville, CA; Pagosa Springs, CO; and Elko, NV) which lacked the infrastructure to market the energy. For a variety of reasons, a large portion of the capacity of these systems remains unsubscribed (Rafferty, 1994).

As a result of this situation, a marketing strategy for the systems was developed. The strategy is designed to address the following issues:

- Rates,
- Customer retrofit costs,
- Financing,
- System reliability, and
- Manpower requirements.

One of the issues with which the strategy had to deal with competition with low natural gas rates. When the geothermal systems were first installed, the plan was to equip each customer with an energy meter with the billing based upon geothermal at a percentage of natural gas. The savings for the customer resulted from two considerations: (1) the cost difference between natural gas and geothermal, and (2) the efficiency losses in the gas furnace. The new strategy eliminates the use of energy meters in favor of a flat-rate billing approach. The flat rate is based upon historic fuel bills for the building. This data is weather normalized using a computer spreadsheet developed especially for this purpose. The flat rate is simple, it is negotiable (usually about 50% of the gas bill), reduces cost (no energy meter) and can be a guaranteed value for a period of the contract.

To reduce retrofit costs, the new marketing plan eliminates the requirement for a customer heat exchanger. New customers are connected directly into the distribution loop water used as the building heating medium. For a customer with a 235 kW load, the elimination of the heat exchanger and associated components would reduce retrofit costs by 25%.

Some of the states operate tax credit and loan programs for renewable energy projects. For example, Oregon offers two programs which have been used in the marketing plan. The program offers business a 35% tax credit on costs associated with connecting to the geothermal district heating system and the Small Energy Loan Program.

Issues on the reliability of the geothermal district heating system operation were discussed at public meetings and with potential customers. This approach has generally proven to be an effective strategy.

Finally, most of the municipalities lack the manpower to do an effective marketing of the systems. The Geo-Heat Center has provided initial retrofit estimates and developed a life-cycle cost analysis for customer evaluation along with the fuel use weather normalization. Municipal engineering departments have been provided directions on how to evaluate buildings for inclusion in the district heating system. For example, the City of Susanville has decided to use this marketing approach and assistance has been provided to Boise on evaluating buildings.

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 for FY-96 will include economics of moderate density geothermal district heating systems, strategies for greenhouses and continuation of the geothermal district heating marketing strategy.

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 1995 from individuals, companies and municipalities:

Type of Interest	Number of Requests
Space and District Heating	45
Geothermal Heat Pumps	78
Greenhouses	19
Aquaculture	17
Industrial	6
Resource/well	63
Equipment	40
Other	58
Total	326

Technology transfer activities included: publication of the GHC Quarterly Bulletin (v.16, n.1-4), which includes technical articles and a geothermal progress section. A Geothermal Library of

5,164 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 1,091 publications were requested during the fiscal year, 15 technical papers were prepared, 15 presentations were given at conferences, 7 tours of local geothermal facilities were conducted, and 13 geothermal progress monitor reports were prepared.

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Figure 1. Cost effectiveness of a 3-MWt geothermal system vs. a gas-fired boiler plant.

LOW-TEMPERATURE GEOTHERMAL RESOURCE ASSESSMENT PROGRAM

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KEY WORDS

direct use, collocation, low-temperature, resource inventory, state teams

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-temperature (20° to 150°C) geothermal resources. In 1992, DOE funding came through the Idaho National Engineering Laboratory as contracts to the Earth Sciences and Resources Institute (ESRI), Oregon Institute of Technology (OIT) and Idaho Water Resources Research Institute (IWRRI). OIT began subcontracting to the state geothermal resource teams (State Teams) which had been selected to complete the resource inventory. IWRRI completed the resource inventory for Idaho. Figure 1 illustrates the geographic extent of this program.

The last major effort to assess the national potential of low-temperature geothermal resources occurred in the early 1980s. Since that time, substantial resource information has been gained through drilling for hydrologic, environmental, petroleum and geothermal projects, but there had been no significant effort to compile information on low-temperature resources. ESRI coordinated efforts with the state teams to complete the digital databases, reports, and resource maps. ESRI issued a revised water sampling manual and completed ten fluid chemistry analyses allocated to each state. In July 1993, ESRI and Utah Geological Survey hosted a meeting of the state teams to standardize data formats and to resolve problems and procedures. ESRI and OIT have reviewed state team reports, databases, and maps for errors and clarity. A comprehensive final report is being prepared that will summarize state team resource evaluation, inventory, recommendations, collocated resources and a method to evaluate the relative economic merit of geothermal energy at the sites.

PROJECT OBJECTIVE

The objective of this program is to encourage increased utilization of the nation's low-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).
- Identify communities collocated with resources.
- Prioritize the more favorable resources for in-depth studies.
- Provide outreach to communities that have resource development potential through distribution of data, information and technical assistance.

Expected Outcomes

- An updated geothermal resource inventory will be available for ten western states. The data will be available in hard copy, a digital database, and new resource maps.
- A designated state agency or university group with current geothermal expertise will be available to assist local economic development agencies, community planners or industrial developers for these ten states.
- Identification of communities collocated with a resource of >50°C and within 8km.
- Those resources most suitable for near-term development will be identified and prioritized for additional technical studies.

APPROACH

State geothermal resource teams (State Teams) initiated their resource evaluation and database compilation efforts in late 1992 and early 1993, and completed these inventories and reports in 1994 and early 1995. The state teams reviewed essentially all available sources of information on water wells and geothermal literature to arrive at the new inventory. The most productive sources of information included the USGS's on-line water information from the National Water Data Storage and Retrieval System (WATSTORE), the 1983 USGS database file GEOTHERM, and previous state geothermal resource maps. State agency files of water well records submitted by drillers were key data sources for some states, as were open-file and published reports by state agencies. With very few exceptions, the databases do not include sites with only bottom-hole temperature or temperature gradient and heat flow sites. The data were checked for accuracy of site location, to the extent practical, and numerous corrections were made to previously published locations. Water analytical data were checked by evaluation of charge balance.

An important part of the assessment was to complete a statewide collocation study of geothermal resources and communities in the western states in order to identify and encourage those

communities to develop their geothermal resources. The State Teams databases were searched for all the wells and springs with temperatures greater than or equal to 50°C. From that list a Paradox database was compiled which contained 18 data fields. The information included within the data fields are the collocated city, latitude and longitude, resource temperature, number of wells within the area, typical depth, total flow for all the resources within the area, typical use, and weather data.

RESEARCH RESULTS

Table 1 summarizes the catalog of 8,977 thermal wells and springs for the 10 western states; an increase of more than 82% compared to the previous assessment of 1980 to 1983. Each data entry in the inventory is a separate thermal well or spring. For purposes of this inventory and report, the State Teams have often selected a single well or spring to represent several (2 to 20) wells or springs within a small area (generally <1 km²) within the same geothermal resource. Thus the true number of thermal wells and springs represented by this inventory is substantially greater than the numbers reported here.

To improve our reporting, the State Teams were asked to identify the number of distinct hydrothermal resource areas represented by the wells and springs in the inventory. A distinct resource area may be less than 1 km² in areal extent, in the case of a few wells or springs in a small, fault-controlled resource, or more than 100 km² in the case of extensive thermal aquifers such as in the Snake River Plain or Columbia Plateau. More than 900 low- to moderate-temperature resource areas are indicated, and perhaps a greater number of isolated (single) thermal wells or springs. The final reports, maps, and databases generated by the State Teams document the present knowledge of the resource base and its utilization and potential in some detail.

The State Teams and OIT Geo-Heat Center have documented direct-heat use of geothermal fluids at nearly 360 sites, including space and district heating, industrial applications and resorts/spas. High-priority resource study areas (48) have been identified, together with high potential for near-term direct-heat utilization at 150 new sites. The number of commercial and residential direct-heat users and the total energy use have increased dramatically in one decade. Even greater resource utilization would be expected without the competition of low-priced natural gas. With proper conservation and utilization of our geothermal resources, they will be there to serve us when natural gas and other fuel types are less competitive. Several problem areas have been identified however, where the heat or fluid content of these resources are largely wasted and additional monitoring, reservoir management, and possibly regulation is warranted.

The collocation study identified 271 cities in the 10 western states that could potentially utilize geothermal energy for district heating and other applications. A collocated community is defined as being within 8 km of a geothermal resource with a temperature of at least 50°C. Over 1900 thermal wells were identified by State Teams as having temperatures greater than or equal to 50°C and 1,469 are collocated with communities. Figure 2 is a representative state map of collocated communities in Idaho, that is similar to those developed for the other nine states.

In one specific project, ESRI and the Utah Geological Survey (UGS) extended the temperature and water level monitoring study of five observation wells in the Newcastle, Utah, geothermal resource. Observations continued on a quarterly basis until September 1995, concluding a two-year monitoring effort. The observations provide important background data for future numerical modeling efforts and qualitative evaluations of the impact of the rapidly developing greenhouse industry upon the Newcastle geothermal resource. Substantial temperature and water-level variations have been observed to date. Permeable zones within the thermal aquifer tend to become warmer during prolonged fluid production in the heating season, and three observation holes show substantial water-level declines during the irrigation season. No adverse effect on greenhouse fluid production or long-term changes to the thermal aquifer are indicated by the observations to date.

FUTURE PLANS

Although this direct-heat compilation of resource data indicates the tremendous potential for expanded utilization, many high-priority areas need further resource and engineering studies. More specifically, for 48 high-priority sites these include:

- Geophysical exploration (10 sites)
- Confirmation drilling (12 sites)
- Hydrologic testing (11 sites)
- Comprehensive assessment (8 sites)
- District heating feasibility (12 sites)
- Industrial heating feasibility (7 sites)

We recommend a Phase 2 Low-Temperature Program, funded by DOE, to complete these studies. It is most important to support and maintain a local geothermal expertise (i.e., a State Team) to provide resource information and initial guidance to developers, in each of these states.

In addition, the states of Alaska, Hawaii, Nebraska, North Dakota, South Dakota, Texas and Wyoming need to update their low-temperature resource assessments and to establish new digital databases.

In the future we hope to continue R&D on improving methods for locating low- and moderate-temperature geothermal resources and on siting successful test and production wells. Part of this work will encompass development of better well-testing methods and better hydrologic models of these hydrothermal resources. These tasks are expected to pay off in further discoveries of resources and in better methods to evaluate reservoir production and ultimate-development capacity at an earlier stage in the development cycle than is now possible. This will further stimulate development of this greatly under-utilized and environmentally-benign resource.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Numerous inquiries have been received by state resource teams, the Geo-Heat Center and Earth Sciences and Resources Institute regarding geothermal resource location, quality, and suitability

for development. County Economic Development agencies listed below have collocated communities within their service areas, and they have been provided resource data and technical assistance information.

Organization(s)	Type and Extent of Interest
County Economic Development Agency (62 contacted) County Chamber of Commerce (50 contacted)	Resource data and direct heat development potential
Milgro Nurseries, Inc., Utah	Sustainable fluid production at Newcastle greenhouse development

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Table 1. State Geothermal Database Summary: 1992-95 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
1. Thermal Well/ Springs	1995 PGA	1,251 501	989 635	157 125	1,537 899	267 68	457 796	359 312	2,193 912	792 315	975 368
2. Moderate Temp. Wells/Springs (100°C: T=150°C)	1995 PGA	0 0	32 48	0 0	20 0	0 0	16 35	10 3	88 79	3 3	1 1
3. Low Temp. Wells/Springs (20°C: T=100°C)	1995 PGA	1,251 501	957 587	157 125	1,517 899	267 58	441 761	349 309	2,105 925	789 312	974 367
4. Low Temp. Resource Areas (20°C: T=150°C)	1995 PGA	35 29	58 56	93 56	54 28	33 15	300 300	30 24	200 151	161 64	17 10
5. Space and District Heating Sites	1995	2	23	16	16	9	11	2	44	2	-
6. Industrial Appl. Sites (Dehydration, Greenhouses, Aquaculture, etc.)	1995	4	15	6	17	4	9	5	6	7	-
7. Resort/Spa Sites	1995	4	55	18	17	15	15	6	17	9	5
8. Areas, Collocated Communities	1995	14	70	15	51	18	30	12	32	23	6
9. Areas, High Priority Resource Study	1995	3	7	6	5	4	4	4	5	4	6

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

Figure 1. Geographic extent of the new resource assesment identified in bold outlines.

Figure 2. Collocated communities in Idaho.

ENVIRONMENT

SOUTHEAST GEYSERS EFFLUENT PIPELINE AND INJECTION PROJECT

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KEY WORDS

pipeline, injection, The Geysers, steamfield, effluent, wastewater

PROJECT BACKGROUND AND STATUS

The geothermal steam resources at The Geysers in northern California are being depleted faster than originally anticipated. Of the 1,800 megawatts of installed generating capacity, a significant drop in output has occurred due to insufficient steam. Steam pressure in the reservoir has dropped from an original pressure of 500 psia to pressures below 100 psia in some areas.

The project consists of a 29-mile pipeline that will carry 7.8 million gallons per day of treated wastewater and lake make-up water to the southeast Geysers geothermal steamfield for injection into the reservoir. The injected fluid will increase the steam produced for power generation. The Lake County Sanitation District (LACOSAN) sees the project as a long-term environmentally-superior method of wastewater disposal for the communities of Clearlake, Lower Lake, and Middletown. The steam suppliers and power plant operators regard the project as a way to reduce the rate of decline in steam production and to augment power generation.

LACOSAN and the U.S. Bureau of Land Management have prepared a consolidated Environmental Impact Report and Environmental Impact Statement for the project. The Bureau of Land Management was the lead agency for the NEPA portion of this joint environmental document because it manages federal geothermal leases at The Geysers that will receive effluent. LACOSAN was the lead agency for the state CEQA portion of the environmental review because of the project's wastewater facility focus.

Final engineering plans and specifications have been completed, and ground was broken for the first segment of pipeline on October 6, 1995. Construction bidding for the remaining segments will occur during January-March 1996. Construction is expected to be underway concurrently at multiple locations throughout 1996, with completion and start-up expected in early 1997.

PROJECT OBJECTIVES

The objectives of the project are to reduce the decline in power production at The Geysers and to provide an environmentally-superior method of wastewater disposal.

Technical Objectives

- Construct a 29-mile, 20-inch diameter buried pipeline to carry 7.8 million gallons per day of treated wastewater and lake make-up water to the southeast Geysers geothermal steam field.
- Inject wastewater into The Geysers reservoir to increase steam production.

Expected Outcomes

- Up to 70 megawatts of additional power output capacity will result from the project. Annually, this could equate to as much as 625,000 Mwh of electricity.
- Power plant longevity will be extended.
- The 1991 California Regional Water Quality Control Board Cease and Desist Order and associated building moratorium will be lifted as a result of implementing treatment plant improvements and the disposal of wastewater into The Geysers reservoir.

APPROACH

LACOSAN will construct the effluent pipeline and upgrade the Middletown Wastewater Treatment Plant (MWTP) and the Southeast Regional Wastewater Treatment Plant (SRWTP). The public/private financing plan uses county wastewater funds, federal and state financial assistance, and Geysers operators' funding for construction. The Geysers operators will also spend additional funds on secondary pipelines and injection facilities within the Geysers steamfield.

The main effluent pipeline will be owned and operated by the Lake County Sanitation District up to the point of delivery. Unocal, Calpine, and NCPA will own and operate the final reach of pipeline, and the three lift pump stations in The Geysers. NCPA will use the effluent-based steam in its own power plants, and PG&E will purchase effluent-based steam from Unocal and Calpine for its power plants.

As shown in Figure 1, the pipeline will begin at the SRWTP north of the city of Clearlake and end in the southeast portion of The Geysers geothermal field, between PG&E's Unit 13, NCPA's power plants in southern Lake County, and the Unit 18 and 20 steam fields in Sonoma County. The project will also include a make-up water intake and piping from Clear Lake to the SRWTP treated effluent reservoir. The pipeline will also be connected to the MWTP and will receive effluent from this facility. Much of the distribution system piping and all of the injection wells are already in existence.

Treated effluent will come from the City of Clearlake and surrounding areas, including the communities of Lower Lake and Middletown. In the early years of operation, more make-up water will come from Clear Lake. As the volume of effluent increases in the pipeline from population growth, the volume of lake water will decrease.

RESEARCH RESULTS

Construction groundbreaking took place on October 6, 1995, and start-up of the pipeline is expected to occur in January 1997. The participants are planning an initial testing and evaluation phase that will include monitoring of all operational aspects and reporting of performance variances, if any, from predicted results.

FUTURE PLANS

The project schedule is shown in Figure 2.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Northern California Power Agency Calpine Corporation Unocal Geothermal and Power Operations Group Pacific Gas and Electric Company	Industrial partners

Additionally, the project receives and responds to numerous technology transfer inquiries from industry, academic, environmental, and other interest groups. Project staff regularly make presentations at various professional and public interest forums to disseminate project information.

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Figure 1
S.E. GEYSERS EFFLUENT PIPELINE

Figure 2
PROJECT SCHEDULE

	1995			1996												1997
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Reach 1: Clear Lake to SERTWP	—	—	—	—	—	—	—	—	—	—						
SERTWP pump station					—	—	—	—	—	—	—					
Lake pump station							—	—	—	—	—	—	—			
Lake intake										—	—	—				
Reaches 2-4: SERTWP to Middletown							—	—	—	—	—	—	—			
Reach 5: Middletown to Geysers							—	—	—	—	—	—	—			
Control system													—	—		
Final tests														—	—	
Start-up																—

SILICA WASTE UTILIZATION

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KEYWORDS

silica, Cerro Prieto, utilization, bricks

PROJECT BACKGROUND AND STATUS

The Geo-Heat Center has been investigating the use of waste silica from the Cerro Prieto geothermal field for several years (Lund et al., 1995). The Cerro Prieto geothermal field has an installed capacity of 620 MW, and in the process generated 6,800 tonnes/hr of brine consisting of 5 to 6 tonnes/hr of silica. Since the geothermal fields of the area extend into the Imperial Valley of California where waste silica is produced from an additional 420 MW of geothermal power generation, it is hoped that this research would also be applicable to the U.S. side of the border.

The conclusions from the original research (Lund et al., 1994, 1995) were that (1) the silica-lime mixtures had low strength and weather resistance, but high insulating properties, (2) additions of fibers to the silica-lime mixtures increased the strength, (3) silica-cement mixtures had high strength and weather resistance, but lower insulating values, (4) silica-asphalt mixtures were not suitable for road surfacing, and (5) silica-cement mixtures appeared to have application as road surfacing material.

The shortcoming of the original research was that the silica was obtained from evaporite deposits at a silencer. Since this source was not typical of the majority of silica waste at Cerro Prieto, additional material was obtained from their disposal ponds that cover 12 km² of area.

This project was started in July 1995 and should be completed by October 1996. The project is about 50% completed.

PROJECT OBJECTIVES

This project is investigating the utilization of waste silica from the evaporation ponds at Cerro Prieto geothermal field in Mexico. The main objective is to mix various combinations of hydrated lime, portland cement, and plastic fibers with the waste silica to determine their suitability for use as insulating bricks in low-cost housing.

Technical Objectives

- Produce mixes by combining the silica with various additives to determine their suitability for use as insulating bricks in low cost housing.
- Field test a wall of bricks constructed from the most suitable combination of silica and additive.
- Evaluate the design of a pilot fruit dehydrator constructed at the Los Azufres geothermal field in central Mexico.

Expected Outcomes

- Utilization of waste silica produced as a result of geothermal power generation.
- Demonstrate the advantages of starting a brick and tile manufacturing process utilizing the waste silica, based on (1) low cost and (2) high insulating value (low thermal conductivity).
- Demonstrate the advantages of using geothermal energy in fruit dehydration

APPROACH

Two silica samples were obtained from different locations in the Cerro Prieto disposal pond, and will be referred to as Sample 2 and 3, respectively, in this summary.

The silica is combined with the various additives: hydrated lime, cement, hydrated lime with fibers, and cement and hydrated lime in different proportions. The mixtures are formed into 7.60 cm by 5.10 cm by 15.2 cm brick molds for flexural testing and 5.10 cm square molds for compression testing. The samples are then allowed to cure for 7, 14 or 28 days by a moist or heat curing method. The moist curing method is in a water bath held at a temperature of 25°C. The heating method places a sample within a sealed container held at 60°C. Following the allocated curing time, the bricks are tested for flexural strength by a three point loading method. and the cubes are tested in compression. The samples are then dried and subjected to a 10-day weathering cycle. A weathering cycle consists of the sample being subjected to simulated rain by spraying until the sample is submerged in water and held at this state for 12 hours; then, it is placed in a oven at 60°C for an additional 12 hours.

RESEARCH RESULTS

Silica

The new silica samples have higher moisture contents, more visible individual crystals, and are coarser grained than the previous material obtained from the silencer. The higher moisture content was due to the material being sampled under water in the disposal ponds. The specific gravity of the new samples are slightly lower at 2.27 (2) and 2.18 (3) versus 2.29 for the original work. The composition is almost entirely silica with no significant trace minerals. As a result, the bricks and cubes have specific gravities that are 15 to 40 percent higher than in previous work.

Hydrated Lime

The silica-hydrated lime mixtures again produced the lowest specific gravities, thus indicating that they will have the best insulating values (low thermal conductivity).

The results of the 7-day flexural strength testing are shown in Figure 1. The result of the previous testing (Lund et al., 1995) are labelled at "1" and the two current samples as "2" and "3". In the phase II testing it became apparent that there was something wrong with our testing procedure since the 14-day and 28-day strengths were less than the 7-day strength. This is contrary to classical testing of lime mixtures (Transportation Research Board Committee on Lime and Lime-Fly Ash Stabilization, 1987), where strengths increase with the time of curing. This anomaly in our test results was not so evident in the original testing, but is readily apparent with the Phase II mix designs in Figure 2.

Upon a detailed investigation, it appears that our samples were drying out in the oven which prevented adequate curing and produced minute thermal cracks in the bricks. The longer the curing time the more thermal cracks that were produced. The samples then failed along these thermal cracks.

Because of the strength of lime-stabilization is both time and temperature dependent, the mixture design process is complicated. For curing lime stabilized samples, temperatures above about 23°C (considered ambient temperature) are used to accelerate formation of pozzolanic reactive products and thus reduce the need for long term curing and to estimate long term strengths. However, if elevated curing temperatures are too high, the pozzolanic compounds formed during laboratory curing could differ substantially from those that would develop in the field. Curing at 60°C is generally the highest temperature used and produces long term results in a short period of time (Townsend and Donaghe, 1976). Curing mixtures at 40°C, 50°C and 60°C is equivalent to producing 28-days strength in 69, 32 and 12 hours respectively (Biswas, 1972). Recent research indicates that elevated curing temperatures in excess of 50°C should be avoided, with 40°C recommended without introducing pozzolanic reactive products that significantly differ from those expected during the field curing (Transportation Research Board Committee on Lime and Lime-Fly Ash Stabilization, 1987).

Based on the above finding, two changes in our procedure were introduced 1) heat curing at 40°C instead of 60°C, and 2) curing in a moisture-proof plastic bag instead of tape-sealed pans. The results of this revised procedure can be seen in Figure 1. Mix design 2P was cured at 40°C in a tape sealed pan, and mix design 2Q was cured at 40°C in a moisture-proof plastic bag. The 7-day sample of 2P lost 40 grams of water while the 2Q sample lost 6 grams of water during curing as is evident in Figure 2. The lower curing temperature produced higher strengths and the moisture-proof bag curing produced higher strengths at 14- and 28-days. The results from mix 2Q are probably a better indication of what can be obtained in the field, providing that moist curing is achieved. The sample "3" mixes were all cured at 40°C.

Portland Cement

Cement stabilization produced higher strengths as compared to those obtained from the original testing (Figure 3). The strengths are approximately twice that of the corresponding silica-lime samples. The flexural strengths appear to be more dependent upon the amount of mixing water used, as the lower water/cement ratios produce higher strength. Additional testing was performed concerning the water/cement ratio. Mix 2N and 2O were mixed with the same proportions; but, 2N had 20% more water added which produced a higher water/cement ratio for 2N. From Figure 3, it is evident the strength is lower for 2N than 2O. Specific gravities of the new samples were as much as 40 percent higher than in the original testing.

Portland Cement and Hydrated Lime

The results from the combined cement and lime stabilization produced strengths between those obtained from just lime or cement alone (Figure 4). The silica:cement:lime ratios of 2:1:1 by weight should be compared with either the lime cement ratio of 1:1, and the 4:1:1 compared with 2:1. There appears to be no advantage to using this mixture unless the cost of lime is considerably less than cement, and strengths higher than those obtained from just lime stabilization are desired.

Hydrated Lime and Plastic Fibers

Approximately eight grams of plastic fibers, varying between 1.4 and 2.7 percent of dry weight of sample, were used to provide additional flexural strength to the lime stabilized samples. This produced significantly higher strengths than those samples cured at 60°C and only slightly higher strengths when compared with those cured at 40°C. However, the fiber samples were all cured at 60°C, thus additional testing will be performed at 40°C.

Weathering

The new samples performed well during the wet-dry weathering test. The "2" samples ranged from 2.3 to 47.0 percent loss, compared to the original samples which ranged from 3.7 to 100 percent loss. Most of the original silica-lime samples failed (average 91.0 percent lost); while, the "2" samples averaged a 15.9 percent loss. With the advent of a lower curing temperature for

the silica-lime "3" samples, thus minimizing thermal cracking, it is estimated that they will perform better than sample "2."

FUTURE PLANS

- Further testing of the silica samples.
- The thermal conductivity will be tested by USGS in Menlo Park, California.
- Field test of a wall of bricks constructed from the most suitable combination of silica and additives.
- Chemical analysis of the silica by Brookhaven National Lab and Tasman Pulp and Paper in Kawerau, New Zealand.
- Investigate the construction of low-weight roofing tiles.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization(s)	Type and Extent of Interest
Maxtile, Inc. 17141 S. Kingsview Avenue Carson, CA 90746	In the process of contacting manufacturing plants in Mexico City. Possible relocating of plant to Mexicali, Mexico.
Tasman Pulp and Paper Co., Ltd. Private Bag Kawerau New Zealand	Interest in use in the paper industry.
Several operators of geothermal power plants in Imperial Valley	Informal discussions waiting on results of research.

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Figure 1. 7-day strength for silica-lime mixtures.

Figure 2. Flexural strengths for Samples 1 and 2.

Figure 3. 7-day strength for silica-cement.

Figure 4. 7-day strength for silica-cement-lime.

THE GEOTHERMAL HEAT PUMP CONSORTIUM'S NATIONAL EARTH COMFORT PROGRAM

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KEY WORDS

geothermal heat pumps, ground-coupled heat pumps, geothermal heating and cooling systems, Geothermal Heat Pump Consortium, National Earth Comfort Program

PROJECT BACKGROUND AND STATUS

In 1990, DOE identified Geothermal Heat Pumps (GHPs) as a major renewable energy technology which offered the nation significant energy savings. In 1993, the U.S. Environmental Protection Agency concluded that geothermal heating and cooling technologies represented a major opportunity to reduce air pollution through use of renewable energy. EPA also found that geothermal technology was becoming increasingly competitive and provided excellent comfort, reliability and aesthetic amenities. EPA recommended the formation of a national, utility-based consortium to take advantage of this opportunity for cost-effective pollution prevention.

The U.S. Department of Energy immediately began laying the groundwork for such a market mobilization as part of Action 26 of President Clinton's Climate Change Action Plan of October 1993. DOE worked with the Edison Electric Institute, EPA, the Electric Power Research Institute (EPRI), International Ground Source Heat Pump Association, the National Rural Electric Cooperative Association and industry to incorporate the Geothermal Heat Pump Consortium (GHPC) in late 1994 to implement the National Earth Comfort Program.

The GHPC recruited 119 utilities as dues-paying members in 1995. In addition, well over 100 manufacturer and trade allies were recruited as well. From these organizations, officers and members of GHPC's Operating Committees were recruited, and strategic planning was begun in each Operating Committee. Meanwhile, GHPC completed its staffing, and provided sufficient definitization of its project priorities to receive assistance funding from both DOE and EPA.

PROJECT OBJECTIVES

Geothermal heat pumps substantially reduce heating, cooling and water heating bills, and cause less pollution than other available heating and cooling technologies. However, geothermal systems usually have higher capital costs than conventional technologies, consumers and commercial facility managers know little about them, and contractors generally do not actively promote them. The Geothermal Heat Pump Consortium is a partnership of utilities, geothermal manufacturers, HVAC vendors and public agencies whose objective is to overcome these market

barriers and increase market penetration of geothermal heat pumps tenfold to 400,000 per year by 2001.

Technical Objectives

- Reduce cost of loop installation by 25-50% by the end of this decade through development of new loop, drilling and trenching technologies.
- Develop advanced design tools and substantially increase number of architects, engineers, HVAC contractors and builders that are trained in the design and installation of geothermal systems.
- Effectively demonstrate and document the economic, environmental, comfort and reliability benefits of geothermal systems for consumers, commercial facility managers, building owners and public officials.
- Develop and implement "technology transfer" mechanisms to be employed by GHPC-member utilities, manufacturers and vendors.

Expected Outcomes

- Advance current loop designs or develop new loop systems that reduce installation time and cost and perform as well or better than today's prevalent loop configurations.
- Develop improved loop installation procedures, drilling and trenching equipment that reduce installation time and cost.
- Develop equipment performance ratings that accurately reflect the performance benefits of integrated functions (i.e., explicitly taking water heating benefits into account).
- Successfully demonstrate and document geothermal system reliability and energy performance in a variety of residential, commercial and public-sector applications.
- Develop 6 to 8 regional training centers that utilize the most up-to-date training facilities and curricula, and successfully train thousands of technicians in the effective sale and installation of geothermal systems.
- Improve and update residential and commercial geothermal system design tools.
- Demonstrate and transfer effective market-pull technologies and strategies to GHPC members through Model Utility Geothermal Program demonstrations.

Expected Outcomes (continued)

- Achieve widespread recognition of geothermal as a viable, desired heating and cooling technology among homeowners, landlords and facility managers.
- Substantially increase employment opportunities in the drilling and excavating industries.

APPROACH

Analysis of the HVAC market identified three major types of barriers to the increased market penetration of geothermal heating and cooling systems in the U.S. As a result, three Operating Committees were formed within GHPC to formulate, coordinate and implement aggressive responses to each of these areas.

First Cost Competitiveness

Geothermal systems cost as much as \$2000-\$5000 more than conventional heating and cooling systems in a typical residential application. However, for some commercial sized buildings geothermal systems have the lowest first cost. Even though their energy efficiency and maintenance savings leads to lower overall *life cycle* cost compared to conventional technologies, their first cost premium constitutes a significant market barrier for most systems. The First Cost Competitiveness (FCC) Committee's approach to reducing the capital cost of geothermal systems involves investigation of new, improved loop configurations, installation techniques, drilling/trenching equipment and developing innovative financing packages. It also is supporting technical work to improve the understanding of soil conductivity, grout performance, and advanced (hybrid and integrated) system design and performance.

Infrastructure Strengthening

Today there are insufficient numbers of distributors, contractors, architects, engineers, builders developers and realtors who know and recommend or install geothermal systems. The Infrastructure Strengthening (IS) Committee's goal is to create a market infrastructure of trained and experienced contractors, developers, architects and engineers sufficient to achieve GHPC's annual sales goal of 400,000 units by 2001 with advanced residential and commercial design tools, competitive pricing, a high degree of installation quality and reliability, and support from a rational framework of environmental, licensing, building code and other regulations.

Technology Confidence Building

A key barrier to geothermal technology is the fact that, even though it has been technically proven through the installation of over 250,000 systems to date, it is still unknown and unproven to end users in many markets. The goal of GHPC's Technology Confidence Building (TCB) Committee is to help build a self-sustaining market for geothermal by effectively communicating

their benefits to all important market stakeholders. TCB's approach is to provide cofunding for Model Utility Geothermal Program Demonstrations and Pilots. Through support for innovative utility program design, demonstration and transfer, GHPC will help its member utilities learn which program designs, communication and public education strategies are most effective in yielding demand for geothermal systems. In return, cofunded utilities will provide their own significant resources to the effort, and share program designs, deliverables and lessons learned. GHPC will complement this with a national effort to increase awareness about geothermal among key market influences, commercial building developers, realtors, national home builders, appraisers contractors, builders, architects and engineers.

RESEARCH RESULTS

During 1995, GHPC went through the process of member recruitment, organization building, staffing and strategic planning, leading to launch of the National Earth Comfort Program during the second half of the year. The following tasks were carried out:

Benchmarking Studies

To ensure effective program launch, GHPC performed several benchmarking studies to study present market conditions and formulate recommendations for overcoming key market barriers. Benchmarking studies on utility HVAC programs and financing alternatives to rebates provide timely insight on cost-effective utility program designs and public education strategies. Comprehensive research on the dynamics of the space conditioning market was carried out, providing recommendations about what awareness and education activities will be most effective for key market stakeholder groups. Similarly, benchmarking studies on existing technical training programs and geothermal design tools are providing a solid foundation for infrastructure strengthening efforts to begin in 1996. All of GHPC's benchmarking studies produced draft reports in 1995, with final reports to be completed in January 1996.

Projects Selected and Initiated

GHPC's early planning process led to identification of several projects that could be started up immediately. Contracts were successfully awarded for the following projects:

Field Demonstration of New Loop Technology

During 1995, GHPC initiated a field demonstration of a patented, "multiple parallel" loop configuration technology for both vertical and horizontal ground loops. Developed by ClimateMaster, this technology has the potential for reducing loop installation costs by 25% or more without compromising performance, while taking much of the responsibility for on-site design and fabrication from the installation contractor.

Grout Research

GHPC is supporting research at South Dakota State University on the performance and environmental impact of cement as an alternative grouting material. This is in response to interest by some state water protection agencies in requiring cement grout in lieu of bentonite.

ASHRAE Study on Antifreezes

During 1995, GHPC initiated cofunding for an important ASHRAE study on the environmental impacts of loop antifreeze materials. The study's findings, expected in 1996, will provide guidance to water protection regulators and the loop industry.

Compilation of State and Local Codes and Regulations

In 1994 the National Rural Electric Cooperatives Association (NRECA) initiated research at University of Idaho to compile and analyze state drilling regulations, and develop model regulations. GHPC is expanding this effort by extending the research to include local jurisdiction regulations and open-loop borehole regulations; and by compiling and analyzing state and local building codes for their treatment (if any) of geothermal systems.

Research on Pumping Pressure and Head Loss

Lack of information on the pressure drop associated with geothermal loop components (the pipe, pipe joints, and fittings, such as U-bends and Tees) can lead to oversizing of circulating pumps, thereby increasing capital cost and reducing operating efficiency. GHPC and Phillips Driscopipe, a manufacturer of geothermal loop pipes, are cofunding work at University of Alabama that will lead to publication in late 1996 of head loss tables for geothermal systems.

Duke Power Residential New Construction Pilot

GHPC selected Duke Power for a cofunded Model Utility Program pilot that combines several elements to build market infrastructure, increase public awareness, and reduce the first cost of geothermal in the single-family home market. Duke Power's contractor, the Alternative Energy Corporation of North Carolina, will train builders and HVAC contractors to build efficient and healthy homes utilizing geothermal systems. Duke will also evaluate and verify geothermal performance in its territory through monitoring, and will provide public education.

Minnesota Power Demonstration of Integrated Gas Station/Retail/Car Wash System

GHPC is cofunding a demonstration of a geothermal installation at a combination gas station/convenience store/car wash. The geothermal design, unprecedented in this climate, will provide space conditioning, refrigeration, hot water, and radiant slab heating and deicing for the car wash. Minnesota Power will produce an installation video, performance data, and a case study.

Plumas Sierra Rural Electric Cooperative Retrofit Pilot

Plumas Sierra serves many planned recreational communities in California that are experiencing a rise in full-year residency, and which get heating from electric resistance, air source heat pumps, propane and wood. GHPC will assist Plumas Sierra in implementing a unique, community-based awareness and education effort. A number of homes that convert to geothermal will be monitored for energy savings. Plumas Sierra will also analyze the degree to which recent revisions in local regulations is causing a rise in the cost of loops.

FUTURE PLANS

During FY96, GHPC will complete or make substantial progress in all of the above projects. Benchmarking reports and research findings will be reported fully to all GHPC members, and summaries will be made available through GHPC's National Information Resource Center and Web Site. In addition, the Operating Committees plan to initiate the following projects:

First Cost Competitiveness

- Field test innovative loop designs in addition to project already underway;
- Acquire residential and commercial field data and prepare case studies;
- Identify data gaps and monitor several commercial facilities to overcome them;
- Evaluate opportunities for reducing drilling costs;
- Analyze long-term heat build-up effects on system performance and the environment, leading to improved system designs;
- Develop low-cost ways to determine thermal conductivity of soils;
- Design commercialization project for drilling rigs and/or associated equipment that enhance vertical drilling productivity by 25-50%;
- Assess potential for loops that are integrated with other building components; and
- Improve understanding of heat transfer in hybrid commercial systems.

Infrastructure Strengthening Committee

- Establish 3-4 regional, state-of-the-art technician training centers;
- Develop and update training curriculum materials;
- Augment or update residential and commercial design tools; and

- Initiate process at Air Conditioning and Refrigeration Institute (ARI) to produce certification procedures and ratings for integrated geothermal systems.

Technology Confidence Building Committee

- Initiate 2-4 major Model Utility Geothermal Program Demonstrations;
- Initiate 3-5 smaller Utility Geothermal Program Pilots; and
- Report on the load shape benefits of geothermal for electric utilities.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organizations	Type and Extent of Interest
119 Electric or Dual Utilities	Dues-paying members in 1995
150 Manufactures and Trade Allies	GHPC non-dues paying members
International Ground Source Heat Pump Association (IGSHPA)	Board member; provides advice and guidance from perspective of research community and industry
Electric Power Research Institute (EPRI)	Tailored collaboration arrangement for members; cofunding of research efforts; Board Member
Edison Electric Institute (EEI)	Support for GHPC start-up; Board Member
National Rural Electric Cooperative Association	Resources for various R&D projects; Board Member
ASHRAE	75% cost share of antifreeze environmental study
ClimateMaster	Greater than 75% cofunding of new loop technology commercialization
Phillips Driscopipe	60% cost share of head loss algorithm study
Duke Power	70% cost share of pilot
Minnesota Power	50% cost share of installation monitoring demonstration and case study
Plumas Sierra Rural Electric Cooperative	60% cost share of retrofit and loop costing pilot
Philadelphia Electric Company	Cofunding for monitoring and case study for geothermal redevelopment project

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GEOTHERMAL HEAT PUMP CASE STUDIES

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KEYWORDS

case studies, ground coupled, ground source, groundwater, heat pump, performance, utilities, national assessment

PROJECT BACKGROUND AND STATUS

Geothermal heat pump (GHP) 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. Geothermal heat pump (GHP) systems can help meet the challenge by increasing our energy efficiency, with resulting benefits in better load management, to customers in lower utility bills and to society in a cleaner environment (Pratsch, 1992).

Electric utilities are the ultimate market target 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 was completed in October 1995.

PROJECT OBJECTIVES

The objectives of this program were to provide information on geothermal heat pump (GHP) performance and the status of electric utility companies in promoting the technology.

Technical Objectives

- Determine what existing monitored data (metered) are available on GHP installations for residential, school and commercial buildings.
- Determine seasonal energy use, savings patterns and economics of GHP systems with competing energy systems in typical residential and commercial situations.
- Develop information that will include electric utility marketing, incentive programs, barriers to market penetration, number of installations in utility service area and benefits to utilities.
- Evaluate temperature changes in loop fluid at a system near Helena, Montana through two household heating seasons.

Expected Outcomes

- Database of monitored GHP systems for residential and commercial applications.
- Efficiency improvements, energy use, demand savings and economics of GHP systems compared with competing energy systems in typical residential and commercial situations.
- Information on electric utility and rural electric cooperative programs to implement GHP into demand-side management programs.

APPROACH

The Geo-Heat Center's approach was to compare as many types of like case studies taken from as many sources as possible. Information was collected for 256 case studies, mainly from utilities throughout the United States. The information extracted from the case studies were compiled into a database. The database was organized into general information, system information, ground system information, system performance, and additional information.

Information was developed on the status of demand-side management of geothermal heat pump programs for about 60 electric utility and rural electric cooperatives on marketing, incentive programs, barriers to market penetration, number of units installed in service area and benefits.

Under agreement with the Montana Power company, separate meters were installed at a Helena, Montana, residence to monitor energy consumption of the heat pump, the electric hot-water heater, and the auxiliary strip heater. The utility meters recorded kilowatt-hours of consumption at 15-minute intervals, accessed by data loggers. The loop was monitored continuously to obtain the minimum daily loop temperatures.

RESEARCH RESULTS

In recent years, there has been a substantial increase in the efficiency of geothermal heat pump equipment. Based on the performance of a typical machine reported in the American Refrigeration Institute (ARI) directory for 1987 and 1994, the average increase in energy efficiency ratio (EER) ranged from 26 to 56 percent, and in coefficient of performance (COP) from 35 to 50 percent. (Figure 1)

In order to verify the performance of geothermal heat pumps, information from 256 case studies has been collected on residential, commercial, and school systems from primarily utilities throughout the United States. These were compiled into a database. 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 compared with competing energy systems. There were 184 residential, 26 school, and 46 commercial systems in the 256 case studies (Lienau, 1995).

Case Studies

Of the 184 residential systems, only 128 GHP and 46 conventional systems were monitored. These conventional systems were compared to GHP systems for energy saving patterns, power reduction for eclectic resistance (heating only), operating costs, etc. The average annual energy savings of GHP systems ranged from 31% to 71% and dollar savings ranged from 18% to 54%. For a breakdown of each conventional system see Table 1. The residential GHP system peak demand reduction compared to single-zone electric resistance heating for 13 case studies ranged from 5.3 kW to 10.4 kW with a mean of 7.2 kW. (Figure 2)

The potential for savings of GHP systems in schools are documented in 26 case studies, with 23 of the 26 monitored. The benefits reported using GHP systems in schools are the addition of mechanical cooling, improved control, and simplicity of maintenance and repair. In southern climates, the benefits include: elimination of cooling towers, outdoor equipment, mechanical rooms and ductwork.

Commercial systems were monitored in 84% of the 46 case studies, with only 20% compared to conventional systems. They ranged in capacity from 30 to 4700 tons. These systems employed ground-coupled well fields of up to 370 boreholes for a 850-ton system, to 3 wells for a 4700-ton groundwater system. The average annual energy savings of geothermal heat pump systems ranged from 40% to 72% and dollar savings ranged from 31% to 56%.

The savings attributable to the use of GHP systems in commercial buildings vary over a wide range (Figure 3). This is due mainly to such parameters as climate, GHP system type, soil conditions, equipment efficiency, sizing and other issues which influence GHP applications. Unique to commercial buildings are building use, internal heat gains, and more complex rate

structures. Clearly given all the potential influences upon commercial building energy use, prediction of savings to be achieved with a GHP system becomes a very site-specific endeavor.

The economics of GHP systems are represented by the simple payback reported in the case studies. There were 27 residential, 5 school, and 17 commercial systems that reported simple paybacks. A favorable payback is considered to be 5 years. The range for residential simple paybacks was 1.4 to 24.1 with a mean of 6.8 years. Simple paybacks for schools were reported in only 5 out of 26 case studies. Therefore, this is not a good statistical representation of economics for using GHPs in schools. Commercial building case studies reported simple paybacks for 17 out of 46 GHP systems. The range was 1.3 to 4.7 with a mean of 2.8. All but four of the simple paybacks represent buildings located in northern climates.

Utility Programs

The geothermal heat pump is one of the many technologies electric utilities are considering or implementing for demand-side management (DSM), especially aimed at improving the efficiency with which customers use electricity. The results of DSM programs aimed at energy efficiency provide two benefits: they save 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/television 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 manufacturers, suppliers, dealers and loop installers; and customers resistance to heat pump technology.

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, discount energy rates, lease/purchase programs and in a few cases ground loop installations.

Montana House

The monitored home in Helena, from beginning operation on April 12, 1991 until March 23, 1995, has drawn 44,670 kWh of electrical energy. Of these, 887 kWh were used by a resistance strip heater to augment the heat pump output and the remaining 43,783 kWh served the heat pump providing household heat and supplemental heat for the hot water heater. The strip heater use was mostly frivolous, done in experimentation with various thermostat settings. Over the 3.95 years of operation, energy consumption averaged 11,310 kWh per year, about 20% greater than that predicted by the installers' computer design program. Likewise, the predicted annual heating and cooling cost of \$598 was exceeded by 16% in the actual average of \$692. The cause

for the discrepancy is unknown, and may be unique to this particular installation or may require a different application of general design criteria (Van Voast, 1995).

FUTURE PLANS

The geothermal heat pump industry is currently in a state of transition from primarily residential applications to a broader based residential-commercial form. The success of this transition to larger projects hinges on information availability: design information for engineers, performance information for utilities, and economic information for owners.

An effective means of address this information need would be a digital database containing design, energy and cost information on a wide variety of existing GHP systems. The database which could be accessed via the Internet would permit users to quickly compare their applications to existing systems. This would afford the opportunity to quickly and efficiently evaluate feasibility, compare costs, refine mechanical design, and identify key contact individuals associated with similar systems.

Based on the results of "Geothermal Heat Pump Case Studies", the Geothermal Heat Pump Consortium, Inc., has requested the GHC propose to maintain the database, and update or enhance its availability for the public.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The following are industries and institutions that have expressed an interest in the results of this project:

Organization(s)	Type and Extent of Interest
Electric Utilities Rural Electric Cooperatives	Performance and economic information.
Engineering Firms Contractors	Design information, economics and contacts.
Geothermal Heat Pump Consortium, Inc.	Maintenance and update of the database and Internet access.

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Table 1. Residential Dollar and Energy Savings

Conventional System	Mean Annual Savings (%)			
	Number ^a	Energy	Number ^a	Dollars
Electric Resistance Heat/AC	21	57%	18	54%
Air-Source Heat Pump	33	31%	21	31%
Natural Gas Furnace/AC	17	67%	21	18%
Oil Furnace AC	6	71%	9	33%
Other (propane, unspecified)	7	46%	7	39%

a. Case studies

Figure 1. EER and COP efficiency improvements from 1987 to 1994.

Figure 2. Peak reduction for residential.

Figure 3. Commercial annual energy savings.

GEOHERMAL HEAT PUMPS

William Sullivan and Gale Martinez
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KEY WORD

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

PROJECT BACKGROUND AND STATUS

Sandia National Laboratories (SNL) initiated a modest geothermal heat pump (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 and acquiring data at a few GHP installations. 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 technology 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 GHPs' outstanding potential to reduce energy and emissions associated with space conditioning and water heating. 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 40,000 units today to 400,000 in the year 2000.

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 of ground heat exchanges 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.

A comprehensive measurement program for installed GHP systems (funded by SERDP) yielded several demonstration projects which have been monitored for a year or more.

Technical Objectives

- Define and implement a comprehensive R&D program in cooperation with the GHP industry to reduce the installed cost of drilled ground source heat exchangers by 25%.
- Prepare a set of case histories for GHP installations, including quantitative evaluation of system performance, cost, and design quality. Document 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 initial cost of drilled ground heat exchangers. Key program elements include improved bit systems, incremental improvements in drilling equipment, and enhanced grouting/loop installation methods.
- Establish a clear set of performance measurements of installed hardware that will allow industry to more accurately set design specifications for existing technology, and to identify areas needing improvement.

APPROACH

The program consists of four basic elements:

1. Performance of existing GHP hardware will be monitored with automated data acquisition equipment and documented so that the energy savings expected from GHPs can be confirmed and areas for improvement identified.
2. 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 test facilities at other organizations involved in GHP research. Suggestions for further research for drilling techniques and equipment will be made and implemented.
3. A vertical loop handbook and training manual will be written to enable water or oil/gas drillers to enter the GHP marketplace.
4. 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

- Sandia managed a major portion of the SERDP program to encourage geothermal heat pump use on military bases. As part of this project, more than 25 proposed or ongoing GHP projects at DoD facilities were identified and given technical or direct financial support. Major measurement programs to evaluate performance of GHP's were initiated at Ft. Polk, LA; Ft. Hood, TX; Patuxent River, MD; and Selfridge, MI. The data from these projects has proven invaluable for marketing GHP's and assessing the effectiveness of these systems. These results have been presented at several DoD and GHP conferences throughout the year. The SERDP activity has additionally provided technical consulting or direct grants to the following facilities: Dyess AFB, TX;; Ft. Irwin, CA; Camp Merrill, GA; Ft. Leavenworth, KS; Ft. Riley, KS; Naval Security Facility, VA; and Bolling AFB, VA.
- Sandia established a jointly funded project with the Electric Power Research Institute (EPRI), Atlantic Electric, and Stockton College, NJ, 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. In FY 95, an experimental 18 bore, 15 ton heat exchanger was installed at Sandia's Photovoltaic Systems Scientific Laboratory (PSSL), DOE's first GHP building. This loop field was jointly designed by South Dakota State University and Sandia Laboratories to evaluate the relative effectiveness of six different grouting methods. A long-term evaluation is planned to assess the stability and heat transfer of the grouts.
- 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. A draft drilling handbook was also completed in FY 95.
- Sandia 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 Virginia State Energy Office.

FUTURE PLANS

We will focus our program next year more toward the development of improved drilling methods. The specific program is still being finalized, but it will deal with component improvements (e.g. drill bits, mud handling, downhole hammers, clay management schemes), development and testing of enhanced rigs, and improvements in well completions (high performance grouts, more effective

downhole heat exchangers, and loop insertion tools). The PSSL GHP installation will be monitored next year to provide head-to-head comparison of vertical loops installed with six different completion methods.

Connection of our R&D effort with the growing loop drilling industry is vital to maintaining focus and relevance. Sandia National Laboratories plans to sponsor frequent forums to solicit industry reviews of ongoing and future R&D projects. When possible, R&D projects will be partnerships between industry and Sandia.

We plan to maintain our measurement program for sites developed previously 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 96.

Organization(s)	Type and Extent of Interest
Geothermal Heat Pump Consortium (GHPC)	Serve on R&D advisory panel, identify key GHP R&D initiatives
Atlantic Electric/EPRI	Joint program at Stockton State
Detroit Edison	Joint measurement program at Selfridge ANG Base
TU Electric	Joint measurement program at Fort Hood
WTU Electric	Joint measurement program at Dyess Air Force Base
South Dakota State University	Design of PSSL loop experiment completion
Cold Regions Research and Engineering Lab (DoD)	Conduct measurement programs at DoD sites

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GEOTHERMAL HEAT PUMPS: Technology Transfer Publications

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KEY WORDS

geothermal brochures, geothermal case studies, geothermal heat pumps, ground source heat pumps, HVAC, heating, cooling

PROJECT BACKGROUND AND STATUS

Geothermal heat pumps (GHPs) used in the residential and commercial heating cooling and water heating market have demonstrated that this technology can save significant amounts of energy and save customers money. A series of brochures, case studies and fact sheets have been developed and distributed to assist in increasing the awareness of GHPs. These publications have been funded by DOE, DoD and IGSHPA. DOE and DoD jointly fund the development and production of these publications. IGSHPA pays for printing and any additional development costs for the documents shown below.

The following is the status of these publications:

Publication	Percentage of Work Completed	Date of Completion
Brochures		
School Brochure	100% completed	1-15-95
Commercial Brochure	100% completed	5-5-95
Residential Brochure	100% completed	11-9-95
Utilities Brochure	50% completed	Early 1996
A&E Brochure	50% completed	Early 1996
Case Studies		
Gait House Case study	100% completed	9-1-95
Park Chase Case study	99% completed	Early 1996
Paragon Case study	95% completed	Early 1996
Phillip Russell House Case study	50% completed	Early 1996

Publication	Percentage of Work Completed	Date of Completion
Fact Sheets		
Financing Fact sheet	100% completed	11-8-95
Loop Design Fact sheet	30% completed	Early 1996
Plastic Pipe Selection Fact sheet	0% completed	Early 1996

PROJECT OBJECTIVES

Project objectives are to produce brochures to introduce the GHP concept to specific audiences, to produce case studies to assist in convincing individuals the viability of GHPs in their industry, and to produce fact sheets which give answers to technical considerations. All these are for the purpose of increasing the number of building customers, installers, developers, engineers and architects who have first hand knowledge of the technology and its potential benefits.

Technical Objectives

- Provide the readers access to information about specific topics in the field of geothermal heat pumps.
- Provide a set of successful case studies that will stimulate readers to further investigation and a greater level of confidence in the technology. Provide concise information about specific technical considerations.

Expected Outcomes

- Increased number of users and suppliers involved in the technology.

APPROACH

The approach was to offer a series of brochures, case studies and fact sheets that would cover GHP applications for residential, commercial, and institutional buildings.

Information for each of the publications was obtained from all viable sources. The pertinent topics were written and then edited by both IGSHPA staff and external sources in pursuit of accuracy, clarity and meeting the objective of the publications.

RESEARCH RESULTS

To date, brochures sold or distributed to utilities and at national teleconferences include approximately 15,000 school, 12,000 residential, 8,000 commercial brochures, 7,000 financing fact sheets, and 5,000 Gait House case studies.

FUTURE PLANS

The remaining publications will be finished. Future plans include creating Web pages on the internet that address the same market areas, utilizing the materials in the brochures, case studies and fact sheets.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Response has been excellent on the brochure series. They are being bought and distributed in large numbers. Utility companies particularly order large amounts.

An indication of the interest level is demonstrated in that numerous industry company's request permission to reuse information, drawings, and photographs from the brochure and fact sheet series.

REFERENCES

Copies of the brochures, case studies and fact sheets are available from the International Ground Source Heat Pump Association.

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GEOHERMAL HEAT PUMPS: Developing New Design, Simulation Methodologies, and Tools for Geothermal Pump Systems

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KEY WORDS

heat pumps, geothermal heat pumps, ground-source heat pump systems, ground-coupled heat pump systems, ground-loop heat exchangers, boreholes, BLAST (Building Loads Analysis and System Thermodynamics)

PROJECT BACKGROUND AND STATUS

While ground-source heat pump systems initially became popular for residential buildings, they are increasingly being used in the commercial building sector. Use in these applications requires the ground loop heat exchanger design to account for the same thing as a residential design: ground thermal properties, undisturbed ground temperature, expected peak capacity, etc. However, several additional factors become very important when designing a commercial-building ground-loop heat exchanger that may usually be safely ignored in a residential design: annual load profile, usually described in terms of monthly cooling and heating loads; and borehole configuration and the resulting interaction between boreholes.

Although a number of approximations may be made when designing commercial-building ground-loop heat exchangers, designers must be careful not to fall into one of two extremes: 1) using approximations that under-estimate the required size, so that the system fails after construction; or 2) using approximations that significantly over-estimate the required size, so that the system cannot be cost-competitive.

While a number of design tools have been available, they have often been difficult to use and/or not very accurate. Research at OSU has been aimed at improving the ease-of-use of available design software and increasing its accuracy. The work described in this report is an extension of those efforts. The tasks described in this report were jointly funded by the Department of Energy and the Department of Defense through the Strategic Environmental Research and Development Program.

PROJECT OBJECTIVES

The general objective of this project is to expedite the selection and design of ground-loop heat exchangers for commercial-building ground source heat pump systems. In order to accomplish this, improvements in the currently available design tools and methods are necessary. The specific objectives are listed below.

Technical Objectives

- Integration of an existing ground loop heat exchanger model with the water loop heat pump system model of BLAST.
- Investigate optimization techniques that can help users of such programs automatically select the 'best' ground loop heat exchanger design.

Expected Outcomes

- A version of BLAST which incorporates a ground loop heat exchanger model coupled to the water loop heat pump system model.
- New methods for selecting and optimizing ground loop heat exchanger designs for individual buildings.

APPROACH

The existing water loop heat pump system model is used for conventional systems which incorporate a number of water source heat pumps on a water loop, and a boiler and cooling tower or fluid cooler which serve as the ultimate heat source/sink. In the ground loop system, the ground loop heat exchanger replaces both the boiler and the cooling tower.

This will allow a more accurate solution, as the two models can be coupled more closely, and perhaps more importantly, will be more convenient for the designer to use. Both improvements will allow comparisons to be made between ground-source heat pump systems and conventional systems with greater convenience and accuracy.

The integration of the ground loop heat exchanger model with the water loop fan system model of BLAST was accomplished by creating a new 'control strategy' for the water loop temperature that allows the loop temperature to float based on the ground loop performance. The solution procedure iterates until the monthly fluid temperatures predicted by the ground loop heat exchanger model and the water loop fan system model converge. BLAST has also been modified to allow multiple year system simulations, so that if a user would like to simulate the 20th year of operation, BLAST will perform 20 years of system simulation, taking into account the history of the ground loop.

The selection and optimization of ground loop heat exchanger designs has been divided into two phases: automated selection of borehole configurations that will work for a specific site and determination of optimal borehole length for each configuration. The 'best' ground loop heat exchanger design is the one with the lowest life cycle cost.

The selection phase takes as input the monthly heating and cooling loads, the peak heating and cooling loads, the ground thermal properties, heat exchange fluid properties, heat pump performance data, maximum/minimum entering fluid temperatures, and the maximum length, width, and depth of the borehole field. Using the peak heating and cooling loads, a set of three candidate configurations is chosen. Each of the three candidate configurations are sized, and then an average total ground loop heat exchanger length is determined. Using this length as an estimate of the required length, all 146 vertical configurations are checked as to whether or not they meet the size constraints, if they have a total ground loop heat exchanger length as estimated above. This provides a short list of potential configurations, which then may be individually sized and/or optimized to find the best configuration.

The optimization problem is initially limited to minimizing the life cycle cost using the user-defined borehole depth as the independent variable. The input parameters for this optimization routine include rates for drilling, piping, heat pumps and circulating pumps, as well as electricity rates. Using these additional parameters, the life cycle cost can be determined for a single borehole configuration. The life cycle cost is then treated as the objective function, and a golden section search (one-dimensional, unimodal) is utilized to find the optimal borehole depth.

RESEARCH RESULTS

Several important research results have been obtained:

- The integration of the ground loop heat exchanger model with the water loop fan system model of BLAST was successful. It offers several advantages in terms of convenience and accuracy for comparison of ground source heat pump systems with conventional systems.
- The approximations that are currently made, to allow the ground loop heat exchanger to be designed sequentially after the building simulation has been performed, appear to be adequate for design purposes.
- The automated selection procedure appears to be very useful and convenient when designing a ground loop heat exchanger.
- An unanticipated result was that the optimal borehole length appears to always be the minimum borehole length that will meet the temperature constraints. While rendering the optimization procedure unnecessary, this does point to the importance of accurate sizing procedures. Even with very high electricity rates and very low drilling costs, nothing is to be gained by making the ground loop heat exchanger longer than necessary.

FUTURE PLANS

Future plans include a number of further refinements to the design tools both in convenience and in accuracy. The improvements in accuracy will primarily be aimed at allowing better comparisons to be made and allowing additional system features to be investigated.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

A wide variety of industry interest has been expressed, primarily in the improved tools for design of ground loop heat exchangers. The design tools have been cited in the new ASHRAE Commercial/institutional Ground-Source Heat Pump Engineering Manual. The ground loop heat exchanger simulation methodology has been transferred to the BLAST program through the BLAST Support Office at the University of Illinois at Urbana-Champaign.

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GEOHERMAL HEAT PUMPS: Technology Transfer Teleconferences

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KEY WORDS

geothermal heat pumps, teleconferencing, ground source heat pumps, HVAC, heating, cooling

PROJECT BACKGROUND AND STATUS

Geothermal heat pumps (GHPs) used in the residential and commercial heating cooling and water heating market save significant amounts of energy and save customers money. A series of seven teleconferences have been aired since July 1992 on topics pertaining to geothermal heat pump applications. These past teleconferences have been co-sponsored with DOE, EPA, EPRI, IGSHPA, NRECA and other industry and government organizations. According to questions and comments from viewers these have been effective in disseminating geothermal heat pump information to diversely located groups.

PROJECT OBJECTIVES

Project objectives are to continue the teleconference series thus increasing the number of building customers, installers, developers, engineers and architects who have first hand knowledge of the technology and its potential benefits. A further objective was to bring together in a common meeting those parties that are involved in commercializing the technology.

Technical Objectives

- Provide the audience access to experts in the geothermal heat pump field
- Provide a set of successful case studies that will stimulate the audience to further investigation
- Provide an open forum for discussions of the technical merit of the technology

Expected Outcomes

- Increased number of electric utilities, contractors, building owners, etc. involved in GHP technology

APPROACH

The approach was to offer a series of teleconferences covering a large market area that would include residential, commercial and institutional buildings. Three teleconferences were held in 1995 and a brief synopsis of each follows:

June 15, 1995 -- Geothermal Heat Pumps: The State of the Art

This teleconference consisted of the latest developments in GHP technology and applications, presentations, and case studies of GHP applications in the residential, commercial, institutional, and agricultural sectors, as well as news about the Geothermal Heat Pump Consortium and new products and techniques were cast.

September 14, 1995 -- Geothermal Heat Pumps in Commercial Buildings

This teleconference focussed on case studies of GHP applications in: hotels, motels, retirement homes, apartments, and condominiums. It was aimed at an audience of electric utilities, state regulators, architects/engineers, commercial builders and developers, and geothermal heat pump installers/drillers.

November 16, 1995 -- Geothermal Heat Pumps for Residential Customers

Applications and success stories, aimed at an audience of dealer/contractors, installers, electric utility residential customer service representatives, realtors/developers, and others involved in HVAC system selection for single family residential buildings.

Activities to produce these teleconference included production, coordination with hundreds of sites, studio panels for overview, phone in questions and answers, uplinking and delivery. A brochure was developed to advertise the conference and the selected technology. In addition, a 15 to 30 minute video highlighting each teleconference was produced.

Policy Research Associates, Inc. was responsible for production assistance along with the Educational Television Services Department of Oklahoma State University

RESEARCH RESULTS

Approximately 5,000 persons viewed each of the three teleconferences. Based on their written comments, the teleconferences were highly successful with suggestions on topics to be covered and technology to be presented.

FUTURE PLANS

Integrate more technical information into the teleconference series. Design examples and design methods could be presented which would take a project from conception to operation.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Each teleconference had approximately 5,000 viewers and based on their written comments, the industry was able to actively participate in the discussions and/or observe successful projects.

REFERENCES

Copies of the teleconference video tapes are available from the International Ground Source Heat Pump Association. Written comments collected from the teleconference downsites are available from Policy Research Associates, Inc.

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GEOTHERMAL HEAT PUMPS: Technology Transfer Training

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KEY WORDS

engineering training, geothermal heat pumps, ground source heat pumps, HVAC, heating, cooling

PROJECT BACKGROUND AND STATUS

Ground source heat pumps are one of the nation's fastest growing businesses in terms of increased sales of equipment as reported by geothermal heat pump manufactures. One reason for the fast growth of geothermal heat pumps (GHPs) used in the residential and commercial heating cooling and water heating market are demonstrations that this technology can save significant amounts of energy and save customers money. Engineers and architects are needed to be trained in the ground source technology to provide the desired growth in the industry. This project was focused upon assisting and training those in the federal sector to increase implementing this technology. Technical support was provided for several federal projects, primarily DoD's SERDP (Strategic Environmental Research and Development Program) funded by DOE. A training manual for architects and engineers was developed, material was prepared for presentation, and a training seminar was presented in the Washington DC area in September 1995.

Over the course of the SERDP Program eight DoD bases received SERDP funds after considering 20 bases. The eight bases involved installations of about 4,500 GHPs with an investment of about \$20 million. Much of the effort was coordinated with Sandia National Laboratory and Oak Ridge National Laboratory who were involved with design assistance, GHP acquisition and installation, and monitoring.

PROJECT OBJECTIVES

Project objectives are to provide technical assistance for selected federal geothermal heat pump design projects to increase the installation of GHP systems and to develop and deliver an architects and engineers training program to enhance the implementation of GHP systems in the federal sector.

Technical Objectives

Technical Assistance

- Provide the federal sector access to experts in the geothermal heat pump field

Technical Objectives (continued)**Technical Training**

Present "the state of the art" overview of:

- Geothermal technology,
- Space heating and cooling and water heating technology,
- The design of residential, commercial and industrial applications,
- Geothermal equipment (heat pumps, circulators, underground piping, etc.),
- Design procedures and methods, software, design tools,
- Installation methods and procedures, the associated equipment, types of heat exchangers, completion (grouting/backfill) choices, and
- Inspections, commissioning, performance monitoring, contracting, & fed. customers.

Expected Outcomes

- Increased number of federal projects involving GHP technology through the leadership of class participants and recipients of technical assistance on projects.

APPROACH

With respect to technical assistance, the approach was to be available to assist in the design of any federal GHP project upon request by the project officer. The approach for the training portion of the project was to develop material pertaining to design and specifications of GHP systems and assimilate pertinent material already developed for inclusion into a design manual. A team of experienced persons was organized to develop material for the manual and for presentation during the training seminar. Individuals in the federal sector having or potentially having responsibility for GHP projects were contacted and invited to attend the seminar.

Technical Assistance

Examples of projects which were given assistance and a brief synopsis of each follows: Army bases in Texas and Michigan receive assistance through coordination with Bill Sullivan, Sandia National Laboratory, providing basic information to do a review of building loads and heat exchanger lengths for GHP projects on the respective bases. Vance AFB, Enid OK, was also visited by a team to evaluate and select potential projects. The selection was a day care center

on base to do a design study in incorporating GHP for heating and cooling the building. A design was accomplished for this facility. Another example is the evaluation of the potential for using GHP's on a large maintenance building on Tinker AFB.

Technical Training

Speakers in the program included: Phil Albertson of Ditch Witch, James Bose, Fred Jones of OSU (Oklahoma State University), Steven Parker of Pacific Northwest Laboratories, Randolph Perry of OSU, Gary Phetteplace of US Army (CRREL), Philip Schoen of Earth Energy Technology and Supply, David Shizak of US Navy (Pax. River), A. Glenn Simpson of PEPCO Services, Inc., Marvin Smith, Jeffrey Spitler of OSU and Louis Torbett of Torbett Engineering.

Some salient features of the training activity and a brief synopses of each follows:

Design Methods and Software

Jeff Spitler prepared material for the manual and presented it, including load calculations and the programs available to predict the loads. Material presented covered examples to apply software packages to do building loads, heat pump selection, ground loop heat exchanger design, and determination of ground thermal properties including in-situ test procedures. A discussion of using rule of thumb methods and comparison with design calculation were made. Techniques of designing Slinky heat exchangers developed by Marvin Smith were included in the manual.

TEI-CADD AutoCAD Templates

Lou Torbett of Torbett Engineering developed material for the manual and gave a demonstration of the HVAC software module which is a supplement to the basic AutoCAD program. This module simplifies the interface between the operator/designer and the "machine", so that the simple repetitive CADD operations are automated to allow the operator/designer to concentrate on the design task. Various templates include electrical, heat pump equipment, plumbing and geothermal wellbore designs. Combined engineering and designer project time through the use of this system has been reduced from 50% to 75% once the users become familiar with it.

Ground Field Design & System Commissioning, and Specifications

Phil Schoen of Earth Energy Technology & Supply along with Lou Torbett developed and presented many combinations of wellbore template designs with header configurations. Phil also presented features of commissioning a system which would reduce potential problems and help expedite the process. A set of general specifications was assimilated by James Bose and Phil and they were integrated and included in the manual. Phil Schoen discussed special features of the specifications.

System Performance Monitoring

Gary Phetteplace of US Army Cold Region Research and Engineering Laboratory and Bill Sullivan of Sandia National Laboratories developed material for the manual on requirements and case studies regarding measuring and monitoring GHP systems in the federal sector. Gary presented the material at the training session.

Interfacing with the Federal Customer

Dave Shizak of the US Navy Public Works Engineering Department developed presentation material pertaining to experiences in promoting, obtaining approval and completing a GHP project for the Navy. He brought out some key features in working within the federal system.

Other material was included in the manual and presented at the training seminar, some which was developed previously and some specifically for this seminar. Demonstrations with pipe fusion equipment, pipe testing equipment, heat pump start-up, and purging were conducted by Jim Bose, Randy Perry, and Fred Jones. An ASHRAE manual was also provided to participants. All the IGSHPA manuals provided to train-the-trainers were also a part of the training packet.

A survey was made among several in DOE and DoD to determine the salient features that should be covered in the training sessions. The significant thrust is considerations in contracting GHP's from selling the concept to specifications and standards and from site selection to maintenance of the installed system.

RESEARCH RESULTS

Representatives from the Army, Navy, Marines, Air Force, Department of Defense, Department of Energy and others were participants in the training. One from Anderson AFB in Guam came and had direct application of the material presented. Over 25 people attended the training and manuals have been provided to several who could not attend and to those who have heard about the training and requested the material or attended the sessions and wanted the material for key people in their organizations.

FUTURE PLANS

Increase to six Pentium 90MM CPU computers and training engineers and designers on TEI-CADD systems in conjunction with other software design tools in cooperation with ASHRAE and GHPC. Increase the coverage in some of the design areas to include specific case studies for integrated systems, schools and commercial buildings. Design examples and design methods would be presented which would take these projects from conception to operation while utilizing design tree decisions and multiple software packages.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Industry interest is on the increase. More applications are being explored that will utilize resources not extensively tapped in the past. Examples such as convenience stores like the Phillips 66 stations where integration of the energy sources and sinks are made to reduce operating costs, and obtaining energy from abandoned mine waters to heat and cool with GHP's are being put into practice. These same concepts can be applied to the federal sector. Some of the participants in the training have projects which they are in the process of implementing, thus an indication of the interest. Training programs such as this project are an effective method of technology transfer.

REFERENCES

Copies of the architect and engineers training manual developed for this project are available from the International Ground Source Heat Pump Association at cost. It is referred to as the DOE/DoD 94 training manual.

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