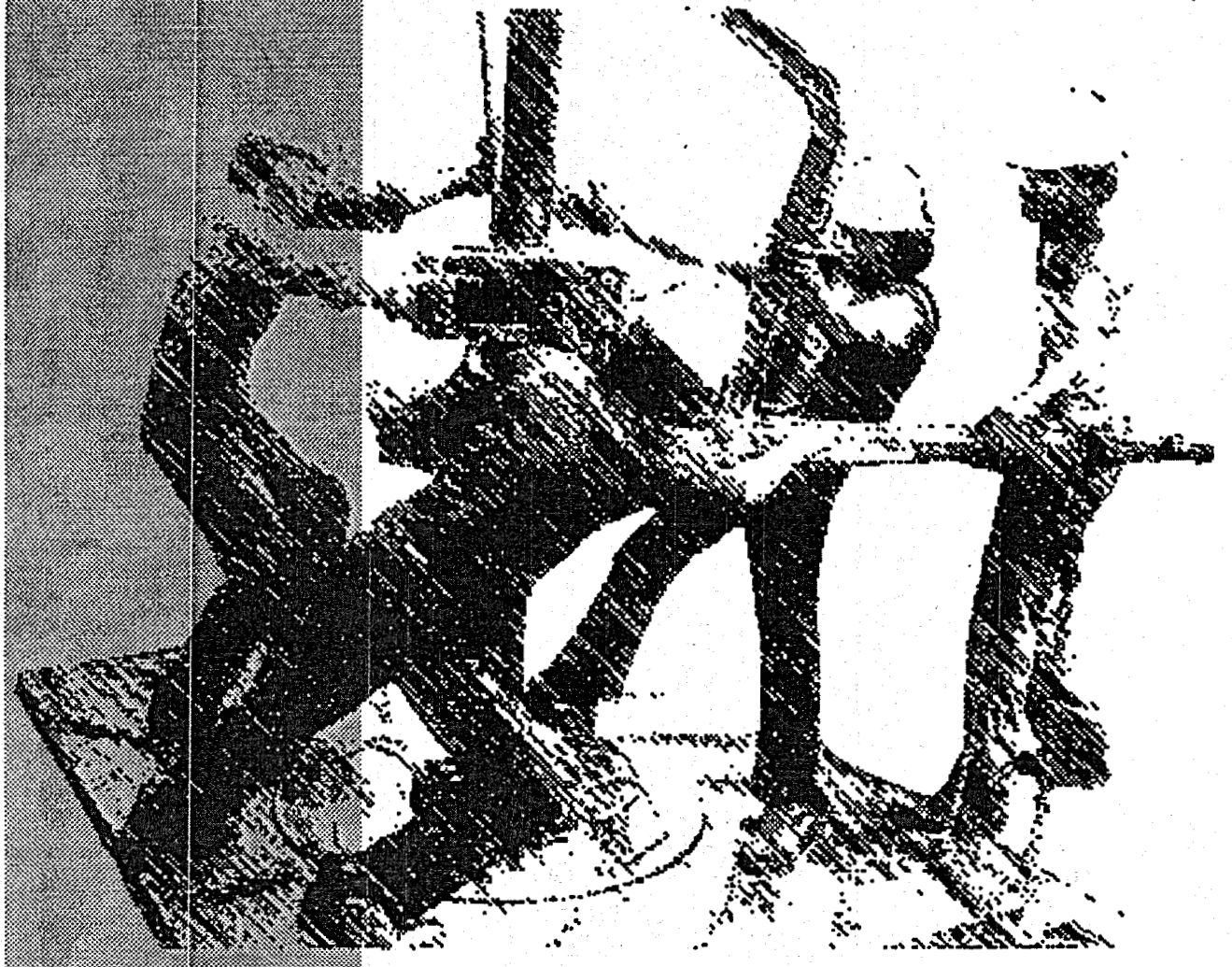
GEOTHERMAL ENERGY R&D PROGRAM



ANNUAL PROGRESS REPORT FOR FISCAL YEAR 1992

Geothermal Division
U.S. Department of Energy

DISCLAIMER

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JULY, 1993

prepared for:

GEOTHERMAL DIVISION
U.S. Department of Energy

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EXECUTIVE SUMMARY

Research in Geothermal Energy, on a national scale, began in 1971 under the supervision and funding of the Department of Energy's (DOE) predecessors. In the development of technology for using the nation's vast geothermal resources, DOE's Geothermal Division oversees a network of national laboratories, industrial contractors, universities, and their subcontractors.

The research program serves two broad purposes: to assist industry in solving near-term problems in a competitive energy market -- DOE undertakes this research on a cost-shared basis with industry; and, to undertake long-term research with potentially large commercial payoffs in the future.

RESEARCH PROGRAM PURPOSES

Since the inception of the Geothermal Program, the Federal Government and private industry have worked closely together -- in promising new research directions, as well as in overcoming difficult technical barriers -- to establish an extensive geothermal knowledge base. Over the past two decades, industry, in turn, has succeeded in creating an infrastructure that translates research results into marketplace applications. The DOE/industry partnership guides the DOE research program towards more cost-competitive power generation from geothermal resources. This partnership assesses the value of long-term research options as well. Private-sector inputs to DOE's planning process are critical to a logical, balanced strategy for the geothermal research program. This joint strategy serves to increase geothermal energy's role in the U.S. electric utility sector.

NEW RESEARCH PRIORITIES

The Geothermal Energy R&D program also reflects shifting priorities within the Federal Government. In last year's annual progress report, the research program focussed on geothermal resources: Hydrothermal, Geopressured-Geothermal, and Hot Dry Rock. This year's report represents a transition from a program based on resources to one focussed on the functional components of every geothermal project: exploration, drilling, reservoir technology and energy conversion. This change reflects a policy direction involving closer cooperation with industry on near-term problems of mutual concern.

The functional components of the current research program are classified under the following three geothermal resource categories: HYDROTHERMAL, GEOPRESSURED-GEOTHERMAL, and HOT DRY ROCK. Each category enjoys its own unique potential but has its own unique hurdles to overcome. Each category also has a different range of applications and different timelines for expected progress.

Hydrothermal Research involves liquid-dominated (hot-water) and vapor-dominated (steam) reservoirs with temperatures for electric power production ranging from 150° to 360°C (300° to 680°F). Lower temperature hydrothermal resources (< 105°C) are attractive primarily for Direct Heat Applications or non-electric uses of geothermal energy, including Geothermal Heat Pumps. Low-temperature applications involve the use of geothermal heat for the full range of space conditioning and industrial applications.

Hot Dry Rock Research is based on the recovery of thermal energy from a man-made, fractured-rock reservoir to bring the heat of dry (water-deficient) rock to the surface. Water, under pressure, is pumped

down one well, circulates through this man-made reservoir, and is recovered through a production well. Research concentrates principally on the Long Term Flow Test, which will provide baseline data for commercialization of the technology.

Geopressured-Geothermal Research aims at improving the technology required to recover thermal energy and natural gas from the existing geopressured reservoirs. The main focus during the fiscal year has been on well operations which includes field experiments, such as well testing, to determine the power potential and to demonstrate the feasibility of long-term operation.

RESEARCH FOCUS

The Work Breakdown Structure (WBS) for FY 1992 reflects DOE's commitment to both continuing research, identified as *Core Research,* and short-term, cooperative research with industry, identified as *Industrial Coupled* or *Applications Research*, organized by the four components of a geothermal project.

EXPLORATION TECHNOLOGY: Most of the 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 task focuses on developing instruments and techniques to discover hidden hydrothermal systems and to explore the deep portions of known systems.

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 drilling and completion technology for geothermal wells 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 task focuses on developing improved, economic drilling and completion technology for geothermal wells.

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 task combines laboratory and analytical investigations with equipment development and field testing to establish practical tools for resource development and management.

CONVERSION TECHNOLOGY: Three technologies in current use are: 1) Dry steam conversion, such as that used at The Geysers in California since 1960; 2) Flash steam plants, favored for liquid-dominated or two-phase resources and when the resource temperature is over 150°C (360°F); and 3) Binary cycles, favored for low-to-moderate resource temperatures in the range of 100° to 150°C. Dry steam and flash steam plants are mature technologies generating cost competitive electricity. Binary cycle power plant technology is less mature, only recently coming into general use as an economic conversion alternative. The conversion technology task focuses on reducing costs and improving binary conversion cycle efficiency -- to permit greater use of the more abundant moderate-temperature geothermal resource.

R&D ACCOMPLISHMENTS FOR FY 1992

- Researchers completed self-potential field surveys over several hidden and exposed geothermal systems, in cooperation with industry and state resource teams in Nevada, Utah, and New Mexico.

- A research team identified several slim-hole drilling sites where reservoir parameters measured in slim holes could be compared with those from production-size wells.

- Investigators determined that existing wellbore and reservoir codes can be combined or slightly modified to produce a useful tool for analyzing reservoir parameters from wellbore (slim-hole) flow data.

- A preliminary model of the Coso geothermal system evolved from detailed evaluation of fluid inclusion data, new modelling of the early fluids discharged from the wells, and newly acquired thermal data.

- Researchers developed a rolling float meter, which is capable of much greater accuracy in measuring outflow rates of drilling muds and also is much more sensitive in detecting lost circulation and fluid influx. Rolling float meter units have been transferred to a number of drilling service companies for field testing and evaluation.

- Two fluorescent tracers, Rhodamine WT and Tinopol CBX, were successfully tested and appear to be suitable as tracers in liquid-dominated geothermal systems at temperatures up to approximately 220°C.

- Researchers added a methane-carbon dioxide-water system to the USCD brine chemistry model to enable prediction of conditions in wellbores and production equipment, under which methane and carbon dioxide gas will form.

- Researchers discovered that by simply reordering the pipes in the drillstring according to pipe length, the effective signal transmission distance for acoustic data telemetry can be doubled or possibly tripled. A model was developed to perform surface simulations of the fundamental attenuation mechanism in the drillpipe.

- Resource assessment for low temperature geothermal resources has begun, and a resource inventory is in progress. Preliminary review of resources located near communities has been completed for Utah, New Mexico, Oregon and Colorado.

- Researchers developed a conceptual model of The Geysers thermal system from investigating hydrothermal alterations and fluid inclusions in samples from two dozen wells. This model was used to study the evolution of the geothermal system. Results indicate that formation of the corrosive steam in the deeper reservoir is related to lower permeabilities and higher salinities of the liquid that existed in the pore space prior to boiling.

- Researchers identified three main influences on gas and isotope compositions in a southeast Geysers field study: (1) original (pre-exploitation) gradients from the lateral movement of steam which resulted in the production of high-gas steam near field margins; (2) injection of steam condensate which vaporizes and mixes with reservoir steam to dilute gases; and, (3) a decrease in the availability of liquid in the reservoir which has decreased pressures and flow rates, and increased gas content.

- Researchers applied digital image processing to estimate potential liquid reserves from adsorption of water on reservoir rocks at The Geysers.

- An analysis of historical field injection data of The Geysers field suggests a positive response by the reservoir to re-injection on a large scale. This result mainly applies to the areas where exploitation has reduced reservoir pressures to low values and in the areas of greatest permeability. The data also indicate that reservoir structure and geometry strongly influence injectate movement.

- The long-term well testing of the Geopressured-Geothermal Design Wells was completed. The wells are scheduled to be plugged and abandoned.

- Preparation for the Long-Term Flow Testing (LTFT) of the hot dry rock reservoir at Fenton Hill was completed and testing has begun.

How This Report is Organized

For each of the research subtasks, the narrative provides:

Background -- putting the R&D into technical and historical context,

Objectives - stating measurable goals,

Expected Outcomes -- listing the products that will move the industry forward,

Approach -- summarizing the research methodology,

Research Status and Findings -- giving actual program accomplishments,

Industry Interest and Technology Transfer -- listing specific organizations and their stated interest in the research,

Implications for Future Development -- projecting the impact of research on the costs and viability of geothermal technology, and

Publications and Presentations.

Program Management and Budget

As Figure 1 depicts, the Geothermal Division reports to the Assistant Secretary for Energy Efficiency and Renewable Energy (formerly Conservation and Renewable Energy) through the Office of Renewable Energy Conversion. The Division Director implements energy research policy and allocates resources for program activities. The Division Director also provides guidance for the operations offices and national laboratories, and approves their annual plans in accordance with national energy policy.

Figure 2 gives the management organization of the Geothermal Division. Table 1 presents the Geothermal Energy R&D budget for FY89 through FY93 by resource type.

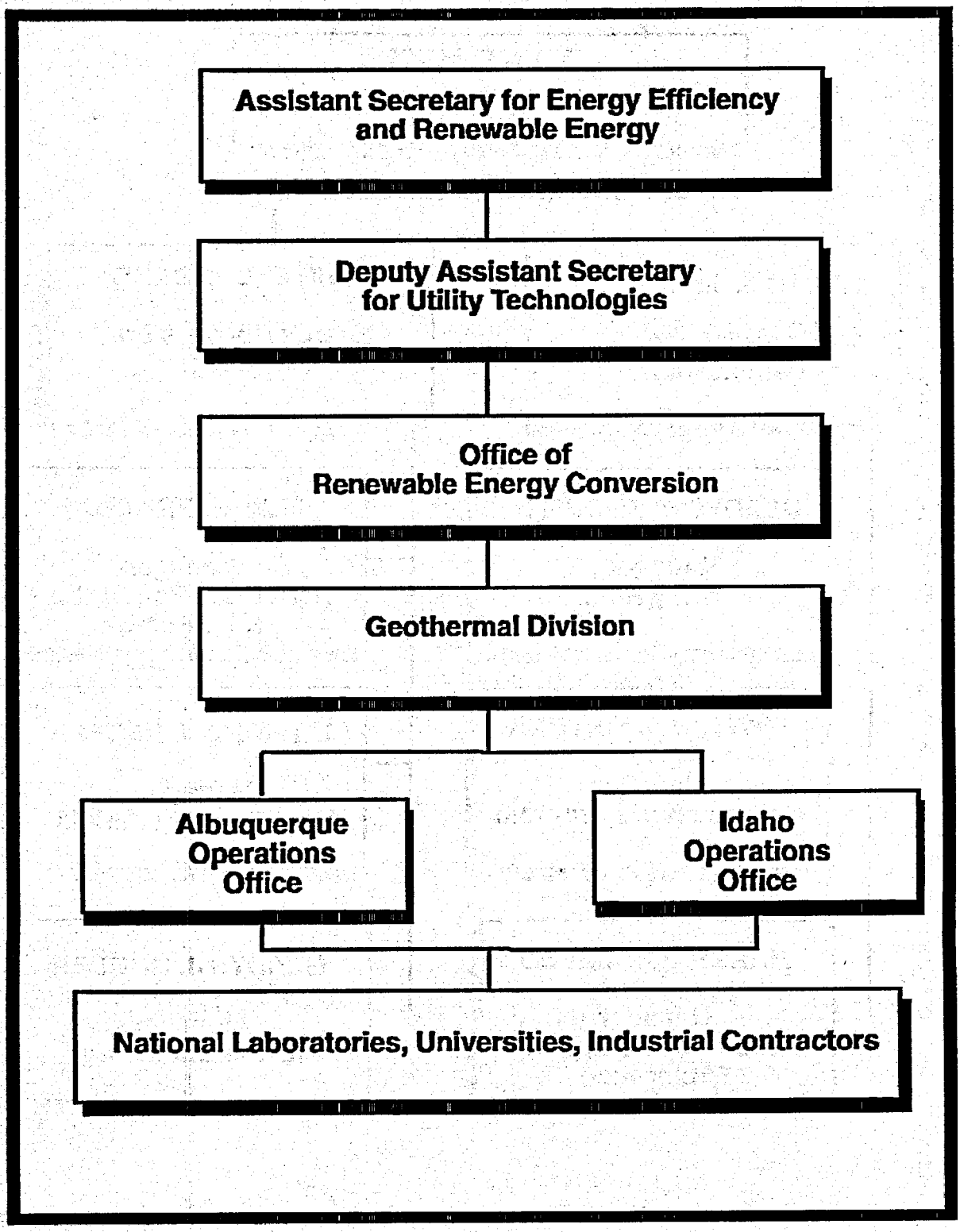

Figure 1
Geothermal Research and Development Program Participants

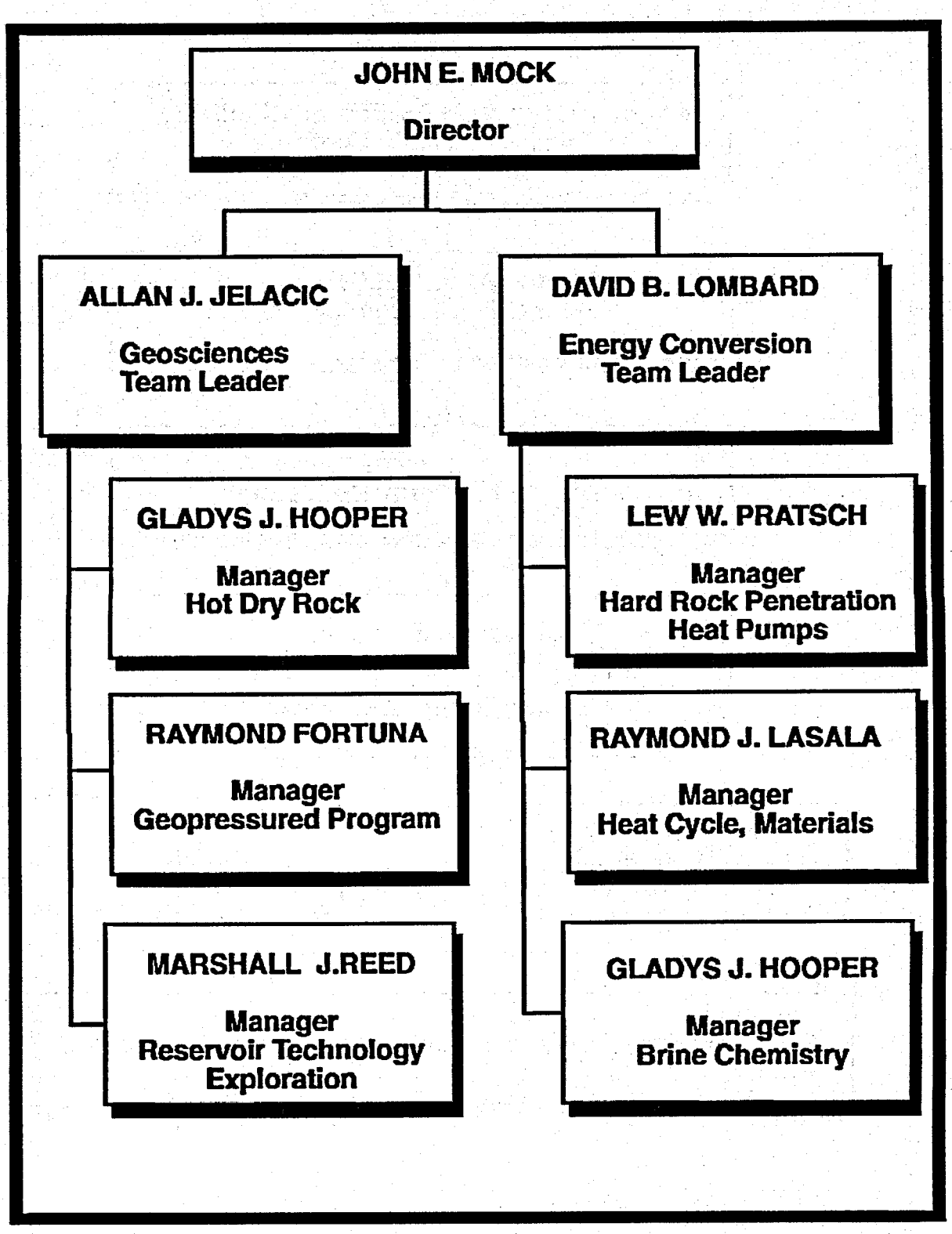

Figure 2
Management Structure of the Geothermal Research and Development Program

TABLE 1

GEOTHERMAL RESEARCH & DEVELOPMENT BUDGET ($1,000s)

	Actual				Est.
	FY89	FY90	FY91	FY92	FY93
HYDROTHERMAL:					
Drilling Technology	2,250	2,205	2,435	2,555	4,749
Reservoir Technology	2,450	2,074	4,393	5,400	4,891
Conversion Technology	1,935	1,527	2,055	4,120	4,315
Long Valley Operations	1,635	1,663	1,150	622	650
TOTAL	**8,270**	**7,469**	**10,033**	**12,697**	**14,605**
GEOPRESSURED-GEOTHERMAL:					
Well Operations	6,698	2,898	3,746	2,950	0
Geosciences & Engineering Support	1,504	1,826	980	1,005	0
Energy Conversion	1,678	644	593	0	0
Management Support	500	487	565	961	0
TOTAL	**10,380**	**5,855**	**5,884**	**4,916**	**0**
HOT DRY ROCK:					
Fenton Hill Operations	2,520	2,570	2,500	3,068	1,668
Scientific & Engineering Support	980	856	1,140	800	800
Reserve & Misc.	0	0	327	432	432
TOTAL	**3,500**	**3,426**	**3,967**	**4,300**	**2,900**
OTHER:					
Capital Equipment	795	444	402	821	900
Program Direction	826	814	889	1,000	1,000
Hawaii	-	-	4,440	0	282
Low-Temperature Res. Assist.	-	-	2,485	1,034	300
GTF Clean-up	-	-	150	191	74
Support Activities	-	-	1,526	1,919	2,739
TOTAL	**1,621**	**1,258**	**9,912**	**4,965**	**5,295**
TOTAL GEOTHERMAL R&D	**23,771**	**18,077**	**29,796**	**26,878**	**22,800**

GEOPHYSICAL METHODS RESEARCH

BACKGROUND

To expand its resource base, the geothermal industry needs to improve the methods and reduce the costs associated with exploration and field development. More effective techniques to evaluate reservoir potential serve to reduce geothermal development front-end costs. These costs frequently reflect the developers' equity investment, and they limit the extent and speed of development. Exploratory drilling is currently a primary exploration technique and accounts for much of the pre-development costs. Improved geophysical methods for locating and characterizing reservoirs will lower these costs. A more accurate understanding of the reservoir, in turn, facilitates better plant design. And, finally, lowered exploration costs stimulate exploration on a regional level.

In view of the above, researchers at the University of Utah Research Institute (UURI) are conducting research to improve existing geophysical methods.

Objectives

- To further develop, improve, and test selected geophysical techniques for exploring geothermal resources and to direct drilling and to monitor production in discontinuous reservoirs.
- To reduce geothermal exploration and development costs, mainly associated with drilling and to minimize the environmental impact in exploring for and producing resources.

Expected Outcome

- Sensitive exploration methodologies and algorithms, which will result in more cost-effective exploration and increased geothermal reserves.
- Intermediate results may include establishing priority drill targets for moderate and low-temperature resources at Newcastle, Woods Ranch and Thermo (Utah), and at Rincon and Radium Springs (New Mexico).

APPROACH

UURI researchers will concentrate on the development of electrical geophysical techniques since they have broad applicability to mapping geothermal resources on both regional and detailed scales. Researchers will continue to test existing methods, to improve techniques and equipment for gathering field data, and to improve interpretation algorithms and computer programs. Integrated geoscience interpretations will provide additional insight into these methods. At present, research is focused on the magnetotelluric (MT), self potential (SP), and cross-borehole electrical methods. Improvements in signal/noise ratios, cost-effective data gathering, and numerical and geological interpretations are expected.

The work plan contains four phases:

Phase I	Self potential and magnetotelluric field surveys in various geothermal environments.
Phase II	Instrumentation and field methodology improvement.
Phase III	Algorithm and interpretation development.
Phase IV	Reporting and technology transfer.

RESEARCH STATUS AND FINDINGS

UURI researchers reported progress on the three major geophysical exploratory methods:

The Self-Potential Method:

SP field studies are well underway (50-60% complete), but quantitative geologic interpretation lags behind the field effort. Some innovation in field survey techniques adaptable to regional-scale exploration is possible.

In cooperation with industry and state resource teams, UURI researchers completed field surveys over several hidden and exposed geothermal systems, including: Carson Lake, Nevada, (Oxbow Power Corp. prospect); Abraham and Meadow-Hattan Hot Springs, UT; and Tortugas Mountain-Las Cruces East Mesa, NM. Researchers also characterized SP anomalies for these resources and identified significant geologic noise sources (sound dunes at Carson Lake and caliche-capped hills at Tortugas Mountain). Researchers then began data interpretation, and published and presented results of earlier FY90-91 SP studies in Utah and New Mexico.

The Magnetotelluric Method:

A major upgrade for the MT field recording system nears completion, but minor improvements are still ongoing. Researchers need field surveys to define new recording efficiencies and to further demonstrate

the viability of the method for deep electrical exploration in priority geothermal areas. Although algorithm development has progressed well, funding may not be adequate to develop more complex model interpretations.

Researchers continued to upgrade MT instrumentation and noise-reduction algorithms. Specifically, researchers completed an integral-equations algorithm for modeling magnetotelluric responses of 3-D bodies in layered media. Finally, researchers interpreted results from the Controlled Source Audio MT survey at Valles Caldera, NM and compared these with scalar natural electrical signals from the earth. UURI published reports and presented interpretation results.

The Cross-borehole Method:

UURI researchers completed a preliminary algorithm and used the results to design a multi-array cross-borehole system. UURI has also acquired a logging truck and has modified the associated electronics to conduct borehole electrical surveys using specialized electrodes, both for sending and receiving current. A field test of the system remains to be done.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
New Mexico State University	Possible power and greenhouse development at Rincon, NM; resource delineations
Masson S.W. Inc.	Greenhouse development at Radium Springs
Unknown lease applicant	Geothermal lease applicants, Thermo H.S., UT
Utah Geological Survey	Geothermal resource assessment
Oxbow Power Corp.	Siting drill targets at Carson Lake prospect
The Geophysics Group and Transpacific Geothermal	Methodology and SP technique development

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

Reducing drilling costs and better evaluation of reservoir potential 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. UURI researchers estimate an additional power-on-line of 500 MWe and an additional 300 acres of greenhouse development could be achieved by the year 2000 within the Basin and Range and Southern Rio Grande Rift if significant cost reduction and risk could be achieved.

PUBLICATIONS AND PRESENTATIONS

Blackett, R.E. and Ross, H.P., 1992, "Recent Exploration and Development of Geothermal Energy Resources in the Escalante Desert Region, Southwestern Utah," Utah Geological Association, Transactions, 21, 261-279.

Ross, H.P. and Witcher, J.C., 1992, "Self-potential Expression of Hydrothermal Resources in the Southern Rio Grande Rift, New Mexico," Geothermal Resources Council Transactions, 16, 247-253.

Wannamaker, P.E., 1992, Tensor Controlled-Source Audiomagnetotellurics-Methodology and Comparison with Scalar and Natural Field Results," EOS, Transactions of the American Geophysical Union, p. 305.

Wannamaker, P.E., 1992, PW3D - Integral Equations Algorithm for Modeling Magnetotelluric Responses of Three-dimensional Bodies in Layered Earths, University of Utah Research Institute Report, ESL-92003-TR, DOE/ID12929-02.

BOREHOLE SEISMOMETER AND GRAVITY IN THE LONG VALLEY EXPLORATORY WELL

BACKGROUND

The more than two kilometer deep Long Valley Exploratory Well (LVEW) provides an excellent opportunity to study the Long Valley Caldera, a major silicic volcanic system that is being exploited for geothermal energy. The possibility that this area is underlain by an active magma chamber is of considerable interest to the geothermal community. Researchers at the Lawrence Livermore National Laboratory (LLNL) are trying to identify the proposed magma chamber using images based on natural seismicity and on gravity surveys. Both methods are limited by complications caused by the complex near-surface environment consisting of nearly 2 km of volcanic materials that lie above basement. Borehole gravity can be used to remove the effects of these near-surface features from surface gravity interpretations, and a borehole seismometer can detect and characterize high-frequency seismic signals that are muted by the time they reach the surface.

Objectives

- **To study the nature and spatial and temporal distribution of micro-seismic sources recorded beneath the center of the Long Valley Caldera.**
- **To use the collected data set to assess the value of down-hole seismometry at other geothermal systems.**

Expected Outcome

- **Seismograms from a high-temperature, high-frequency, 3-component seismic sensor installed at 2 km depth in the Long Valley Exploratory Well for a period of 6-12 months will provide a profile of density and porosity as a function of depth in the Long Valley Caldera. The resultant profiles will be integrated into the scientific studies of the LVEW to get a better understanding of the thermal and mechanical state of the Caldera.**

APPROACH

The LLNL research team's approach has been to focus on the borehole seismometer design and construction, where the team could design reliable equipment that produced the highest probability of

getting good data under the conditions in the wellbore, and that posed little or no risk to the well. The team consulted with the University of Southern California (USC) and the Air Force, two other groups with downhole seismometer experience, and surveyed all existing seismic sensor packages. The team found that no package provided the ideal combination of dependable response at 102° Centigrade and broad frequency response. Researchers considered using an experimental system being developed by a small company, but decided that the innovative high-temperature sensors would probably not be ready in time to build the instrument. Instead, another company modified its rugged accelerometers to function at the appropriate temperature. Although loss of some low-frequency information is expected, these sensors will record the high-frequency signals above 200 Hz.

RESEARCH STATUS AND FINDINGS

LLNL designed, procured and constructed the borehole sensor package and winch system, and awaits the availability of the borehole for installation in FY93. Borehole gravity measurements will also be made in FY93 by the USGS.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organizations	Extent of Interest
Geothermal Operators	Geologists from industry participated in planning of experiments and are receiving the results.
USGS	Want to use LLNL seismometer to supplement data from surface in Long Valley.
Universities (NSF/OBES)	Information will contribute to scientific goals of LVEW project.

IMPLICATIONS FOR GEOTHERMAL FUTURE DEVELOPMENT

Borehole gravity may improve existing interpretations of gravity anomalies in Long Valley and help guide exploration and development to the west of the LVEW site. Seismic measurements may provide some characterization of small faults and high-temperature earthquake-free zones, but this data will not be of use to the developers before 1995. In the short term, the results of this study may contribute to production related decisions by operators in the Long Valley area. In the long term, it could lead to the identification of major new geothermal systems associated with the magma body.

ENHANCED SELF-POTENTIAL (SP) METHODS

BACKGROUND

Improved measurement and interpretation methods, and exploration strategies can reduce the cost of discovering and operating geothermal fields. Researchers at Lawrence Livermore National Laboratory (LLNL) are conducting studies on enhanced self-potential techniques to provide these improvements.

Electrical self potential (SP) surveys provide the only geophysical method that directly measures the effects of heat and mass transport, which are crucial for the detection and observation of geothermal fields. Most SP surveys are relatively crude, with widely spaced lines, and relatively simple interpretation approaches. While this makes SP attractive as a relatively inexpensive exploration tool, researchers believe that much more information can be gained by applying advanced approaches to collecting and interpreting the data. Enhanced SP methods will provide more information about the patterns of heat and mass flow within a geothermal system. This will, in the short term allow operators to better understand the changes resulting from production and injection; in the long term, provide better tools to locate geothermal systems in unexplored areas in the Western U.S.

Objectives

- **To develop techniques to overcome problems in data collection and interpretation for the self potential (SP) method in geothermal systems.**

Expected Outcome

- **A spreadsheet to estimate SP cross-coupling coefficients from rock descriptions.**
- **An improved SP modelling code that can handle realistically complex geological models.**
- **An evaluation of an innovative approach to SP data collection.**

APPROACH

The approach has two parts: 1) enhancing the existing data interpretation codes used by industry by including a compilation of all existing laboratory data on cross-coupling coefficients in rocks and by modeling more complex 2-D structures; and, 2) conducting field experiments to test the value of spatial and areal filtering methods on SP data. By combining the results of these two efforts, researchers anticipate the development of an improved exploration and monitoring technology to be used by industry.

The work plan breaks out into three phases:

Phase I Compile an extensive collection of laboratory measurements of electrical cross-coupling coefficients, based on literature searches and interviews with SP researchers. These data will be provided in a spreadsheet that can be used by industry geophysicists.

Phase II Identify an area in which to test the spatial and areal processing of SP data. In the last month of FY92, researchers collected a two kilometer line of detailed SP data. Much of the data was collected with a multi-channel recording system that allowed time domain processing of the data to remove the effects of telluric and other noise sources.

Phase III In early FY 1993, researchers will return to the area and collect a detailed grid of data over the largest anomaly detected. These data and interpretation methods will determine if enhanced SP surveys provide more information than routine approaches.

RESEARCH STATUS AND FINDINGS

To date, it has been determined that for the noise levels at the site chosen, the complexity of recording data for time-averaging outweighs the benefits. Researchers will continue to investigate the value of spatial averaging at this site. The data compilations and modelling studies are not expected to produce results soon.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
USGS	Sharing data on groundwater flow in area studied, and where USGS thinks it may locate hot aquifers.
Geophysical Consultants	Will apply methods to geothermal problems.
LBL	Coordinating modeling efforts.

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

The results of this research will be useful for exploration and monitoring in geothermal areas. Further, it could be used to identify effects of production and injection on geothermal systems. Improved exploration tools will provide new candidates for geothermal production in the event that oil prices or environmental costs rise.

GEOTHERMAL HEAT FLOW STUDIES

BACKGROUND

Heat flow and temperatures at depth are important factors in assessing the potential for exploring and developing geothermal resources. Such data are particularly important to geothermal exploration groups which need improved accuracy in predicting subsurface temperatures in the 0 to 4 km depth range. The correction of thermal conductivity and heat flow values based on knowledge of subsurface flow of water is being studied at the Southern Methodist University. Estimates of basement heat production based on lithology are also being evaluated to infer heat flow in areas of sparse direct measurements.

Objectives

- **To produce a heat flow data set in both contour and grid form for the U.S. at a resolution of less than 10 km.**

Expected Outcome

- **Maps and data of heat flow and subsurface temperatures for the U.S. that can be used for geothermal exploration.**

APPROACH

Thermal conductivity values for the sedimentary section above basement were collected for the central and Eastern conterminous United States. These conductivity values will be matched with their respective stratigraphic columns and existing heat flow data to calculate the distribution of temperature at depth. Highly accurate heat flow measurements will be stored as digital, map-based data to provide reliable information over large areas of the United States.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All U.S. geothermal firms conducting geothermal exploration have an interest in this research. The results of these studies, including the data base, will be presented and made available at appropriate technical meetings.

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

A heat flow data set in contoured and gridded form will be produced for the conterminous United States at a resolution finer than 10 km. This can serve as a site-specific data base of temperatures for depths from 0 to 4 km and can be used by the U.S. geothermal exploration industry to delineate exploration targets and to better understand the temperature measurements made during drilling operations.

PUBLICATIONS AND PRESENTATIONS

Blackwell, D. B., et al, 1992, "Heat Flow Patterns of the United States: A Key Component of Geothermal Resource Evaluation," Geothermal Resources Council Transactions, v. 16., p. 119-124.

SLIM HOLE DRILLING FOR GEOTHERMAL EXPLORATION

BACKGROUND

Although the vast majority of the drilling technology used in the geothermal industry is derived from the oil and gas industry, geothermal requirements are qualitatively different. Geothermal drilling encounters hard, abrasive, and fractured rocks, high temperatures, and under-pressured formations which frequently contain corrosive fluids. All these factors impose a more rigorous environment than normally found in oil and gas drilling. The service and drilling tool industries have little incentive to address these problems, since the number of geothermal wells drilled in a year is about 0.1 percent of the corresponding number for oil and gas. This lack of commercial R&D is the primary rationale for DOE's support of drilling technology development.

A recent systems analysis of geothermal development costs identified drilling costs associated with exploration and reservoir assessment to be as high as 35 to 50 percent of the total project cost. The geothermal industry (utilities and geothermal operators) needs to reduce exploration and reservoir assessment costs in order to be competitive in meeting the expanding requirements for environmentally benign, alternative energy sources. Slim hole drilling has been shown to reduce oil and gas exploration costs by 25 to 75 percent; however, the more hostile conditions for geothermal resources present technology challenges which must be solved before the cost impact there can be thoroughly evaluated. Once demonstrated, slim hole drilling technology will have application to geothermal exploration and reservoir assessment in both the U. S. and international markets.

Drilling production-size holes for geothermal exploration adds a large expense at the beginning of the project, thus requiring a long period of debt service before those costs can be recaptured from the sale of power. The actual amount of savings is heavily dependent on economic factors of interest rate and power demand. These values make it reasonable to assume that saving more than 25 percent of the exploration cost, or approximately $20M for a 100 MW power plant, is possible. The principal reason for the lower cost of drilling slim-holes is the smaller size of crews and wellbore equipment. Rigs can be helicoptered to drilling sites eliminating the need for constructing roads to remote locations.

The corresponding reduction in drill-site size, road preparation, mobilization, and human traffic is also critical in minimizing environmental impact. If geothermal development follows its expected expansion into the Pacific Northwest, a relatively benign environmental presence will be critical to public acceptance and progress. Smaller equipment is also especially appropriate for geothermal exploration in Third World countries, or wherever financial, infrastructure and institutional support are minimal.

In view of the potential benefits associated with slim hole drilling, researchers at Sandia National Laboratories are conducting studies to identify geothermal reservoirs and evaluate reservoir properties with data collected in slim holes.

Objectives

- **To demonstrate that a geothermal reservoir can be identified and evaluated with data collected from slim holes.**
- **To correlate fluid flow and injection tests between slim holes and production size wells.**
- **To develop and validate a coupled wellbore-reservoir flow simulator for reservoir evaluation using slim hole data.**
- **To transfer slim hole exploration drilling and reservoir assessment to industry so that slim hole drilling becomes an accepted method for geothermal exploration.**

Expected Outcome

- **Techniques for drilling and completing slim holes.**
- **Recommended test procedures, including data requirements, for the slim holes.**
- **Improved downhole instrumentation to collect needed data.**
- **Data interpretation techniques, possibly in the form of a PC-compatible flow simulator available at a nominal expense to independent developers. This software would allow basic reservoir evaluation from slim hole data and, once accepted as an industry standard, would be considered sufficient to attract development financing.**
- **Publication of the analysis and procedures which led to the above products.**

APPROACH

A coordinated working group has been established and includes Sandia, Lawrence Berkeley Lab, University of Utah Research Institute, US Geological Survey, and independent consultants. Other Sandia organizations, such as the Fluid Flow and Transport, Computational Fluid Dynamics, and Thermal and Fluid Engineering Departments, are also providing significant support.

The research team surveyed the geothermal industry to identify and prioritize research needs. Industry indicated a strong interest in slim hole exploration for geothermal resources; however, the technique has been used in only a few special cases and has an insufficient track record to secure power plant financing. The survey convinced the research team to begin a program to validate slim-hole drilling as an exploration tool.

The research team collected, evaluated, and consolidated existing wellbore-flow computer codes to be used to analyze field measurements in the geothermal field at Steamboat Hills, Nevada. Sandia signed an agreement with Far West Capital, the company which owns and operates a 24MW power plant there, to test existing core holes for comparison with existing production wells. The team then performed flow and injection tests with simultaneous pressure-temperature-spinner logs in three core holes at Steamboat Hills.

RESEARCH STATUS AND FINDINGS:

- An industry survey identified several sites where reservoir parameters could be compared between slim holes and production-size wells.
- Flow and injection tests on coreholes at Steamboat Hills with pressure-temperature-spinner logs yielded data which could be modeled with wellbore simulator codes. The modelling is necessary to extend specific results at a well-characterized reservoir like Steamboat Hills to a more general predictive capability.
- Existing wellbore and reservoir codes can be combined or slightly modified to produce a useful tool for analysis of reservoir parameters from wellbore flow data.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organizations	Extent of Interest
Far West Capital (FWC)	FWC has signed an agreement that permits Sandia to conduct experiments, take new data, share existing well data, and, if desired, drill new core holes on their lease. FWC has cost-shared the experiments to date, and will continue to do so.
Others	All U.S. geothermal firms conducting geothermal exploration have an interest in this research.

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

Even preliminary results from this research could have immediate impact on exploration or development. The shortest-term application would be the use of slim-hole data to secure financing from lending institutions. If a reservoir can be adequately defined by drilling smaller, relatively inexpensive slim-holes for exploration, the production well drilling can be delayed until the power plant is under construction, saving years of interest payments.

Current initiatives, such as the Bonneville Power Administration agreement, serve as a stimulus to geothermal development in previously poorly-characterized areas, which are ideal settings for slim-hole exploration techniques. The overall level of activity in the industry will depend heavily on such global issues as energy prices and the national economy. If these issues favor geothermal development, the team should have a substantial portion of the projected final product completed by 1995.

PUBLICATIONS AND PRESENTATIONS

Presentation at DOE Program Review, DOE Headquarters, October 1991.

Presentation at DOE Geothermal Program Review X, San Francisco, March 1992.

GEOCHEMICAL METHODS

BACKGROUND

Geochemical investigations aim toward a better understanding of the chemistry and fluid flow patterns within geothermal reservoirs. This information is needed at all stages in the development of a geothermal system, from early exploration to full exploitation. At the initial stage of a project, exploration geologists use generalized hydro-geochemical models to interpret geochemical, geophysical and geologic observations to site thermal gradient wells. Later, detailed hydro-geochemical models help the developer by providing information on the natural state of the reservoir, which is needed as input for reservoir modeling. At the time this study was initiated, suitably detailed models of geothermal systems had not yet been developed.

Researchers of the University of Utah Research Institute (UURI) are directly addressing priorities established by the geothermal industry. The direction of current studies on liquid-dominated systems reflects the results of a 1989 industry survey which reiterated the need for a better understanding of reservoir processes, properties, conditions, and boundaries in different geologic environments.

High-to moderate-temperature, liquid-dominated geothermal systems may be broadly categorized as granitic, volcanic, or sediment hosted. Although geothermal systems share a number of common characteristics, recent studies conducted at UURI and at other institutions demonstrate that there are significant differences in the hydro-geochemical characteristics of geothermal systems in, for example, granitic and volcanic environments.

Objectives

- **To develop better hydro-geochemical models of geothermal systems by incorporating physical and chemical similarities and differences in different environments, including vapor-dominated systems.**

Expected Outcome

- **Basic hydro-geochemical data needed for the development of conceptual models in different geologic environments. These models form the basis for the siting of exploration drill holes.**

APPROACH

In this project, researchers first demonstrated that fluid inclusions in reservoir rocks record the required chemical data. They then compared salinities and temperatures determined from the inclusions in paragenetically late minerals to temperatures measured in the well bore and to the salinities of the production fluids. This comparison helped to establish the relationship between the fluid inclusion data and the present conditions.

The second stage of the project involved the application of fluid inclusions as a means of determining the CO_2 contents of the reservoir. Researchers adopted several approaches to insure the validity of the work. Fluid inclusion measurements conducted at UURI were cross-checked using independently calibrated equipment at other institutions. UURI researchers sought direct evidence for CO_2 in the fluid inclusions, establishing this evidence by crushing individual samples. Computer models were developed to predict the characteristics of the inclusions under changing temperatures, compositions and gas contents. These predictions were compared with the measurements made on the inclusions.

In the third stage of the project, researchers are combining the fluid inclusion data with fluid analyses to develop detailed hydro-geochemical models of the systems being studied.

These studies have demonstrated that fluid inclusions can provide accurate information on temperatures and fluid compositions in regions of thermal systems that cannot be sampled directly. Fluid inclusions also reflect the processes occurring in the reservoir. Geologists can evaluate the extent and importance of different processes using techniques similar to those used for the interpretation of geothermal fluids chemical analyses. This evaluation proceeds by establishing the relationships between the salinities and temperatures of the fluid inclusions, and then by interpreting the relationships in terms of boiling, mixing, gas loss, and conductive cooling. Plots of the fluid inclusion temperatures vs. depth, and well bore temperature and salinity vs. depth provide data on thermal and composite compositional gradients within the reservoir.

Because fluid inclusions may form throughout the life of a thermal system, researchers are conducting petrographic studies to determine the relative ages of the trapped fluids and to assess changes as a function of time. The petrographic investigations utilize standard thin-section, X-ray diffraction, scanning electron microscope, and electron microprobe techniques.

RESEARCH STATUS AND FINDINGS

Several significant findings emerged. In addition to the results discussed below, the techniques developed in this project helped to develop the first detailed evolutionary model of The Geysers geothermal system.

The most significant result was the completion of detailed hydrogeochemical models of two volcanic-hosted geothermal systems. These systems, located at Zunil, Guatemala, and Los Azufres, Mexico, are characterized by two compositionally distinct fluids: a shallow CO_2-charged steam-heated water reservoir and a deeper NaCl reservoir.

Fluid inclusion data demonstrate that the CO_2-rich waters form umbrella-shaped caps that thicken outward away from the upwelling centers of these systems. Fluid inclusions within these caps contain 4 to 6

percent CO_2 by weight. The CO_2 contents of the inclusions require that they be formed at pressures several tens of bars above hydrostatic. Elevated pressures and gas contents may have developed through compression and condensation of CO_2-enriched steam by tectonic stress.

Musgrave and Moore (1992) applied the results of this work to an interpretation of data from the Tecuamburro geothermal field in Guatemala. Isotopic sampling of local ground waters in the region around Zunil has shown that the deep reservoir fluid and the shallow steam-heated waters are recharged from different areas. Although such recharging may be a common feature of many geothermal systems, it is generally not possible to distinguish the recharge areas of these fluids. These data will help in understanding how volcanic systems are recharged.

A preliminary model of the Coso geothermal system has been developed by incorporating a detailed evaluation of fluid inclusion data, new modelling of the early fluids discharged from the wells, and newly developed thermal data. The results indicate that the system was emplaced within a groundwater regime that is no longer present. Mixing between these groundwaters and the reservoir fluids has produced clays which act as a seal over the top and bottom of the thermal plume. The data also demonstrates that two-phase conditions exist in the upwelling center.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER:

Organizations	Extent of Interest
Domestic geothermal companies: e.g., California Energy Co., Calpine Inc., Far West, Ormat, Mother Earth Resources, Russian River Geothermal Corp., UNOCAL	Cost-shared studies
Comision Federal de Electricidad (*Mexican National Utility*)	Cost-shared studies
Instituto Nacional de Electricificion (*Guatemalan National Utility*)	Cost-shared studies
United Nations	Review of U.N. Funded Programs

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

The results of this study are already being applied to the interpretation of existing geochemical data by geothermal developers (e.g., California Energy Company at Coso, California, and at geothermal prospects in other states) and in the exploration of new geothermal systems in Guatemala by government agencies.

The applications of this work are likely to increase, particularly within the U.S., as exploration activities move to systems with no surface manifestation. Improved models will decrease the number of dry holes drilled during a geothermal project. This research will also help the developer by providing information on the natural state of the reservoir and how the reservoir changes as a result of production. Various

aspects of this project bear directly on programs currently underway at the Idaho National Engineering Laboratory, Stanford University and Lawrence Berkeley Laboratory, where reservoir modelling studies are in progress. This investigation provides natural-state data and "ground truth" for the modelling studies.

PUBLICATIONS AND PRESENTATIONS

Adams, M. C., Moore, J. N., White, L. D., Mink, L. L., Leiva, O., Ramirez, S., and Caicedo, A. A., 1992, "Fluid Recharge of the Zunil, Guatemala Geothermal System," *Transactions*, Geothermal Resources Council, v. 16, pgs. 113-118.

Musgrave, J. A., and Moore, J. N., 1992, "Chemical and Thermal History of Fluids from the Tecuamburro Geothermal Field in Results of Geothermal Gradient Core Hole TCB-1 Tecuamburro Volcano and Geothermal Site," Guatemala, Central America (S. Goff, Ed.) Los Alamos Special Publication, LA-12185-MS, pgs. 62-78.

Moore, J. N., Adams, M. C., and Lemieux, M. M., 1992, "The Formation and Distribution of CO_2-enriched Fluid Inclusions from Epithermal Environments," Geochimica et Cosmochimica Acta, v. 56, pgs. 121-135.

LOST CIRCULATION CONTROL

BACKGROUND

Hydrothermal fluid production zones are usually underpressured, compared to oil and gas wells, and often occur randomly along the wellbore. The most costly problem routinely encountered in geothermal drilling is lost circulation, i.e., drilling fluid used for cooling the bit and flushing rock chips out of the borehole is lost to the rock formation rather than circulated back to the surface. Besides fluid replacement costs, the loss of fluid also results in expensive loss of continuity and integrity of the cement used to bond the wellbore casing to the rock formation. The fluid loss also results in a discontinuous supply of cuttings. Care must be taken to prevent mud from plugging production zones and from being lost in intermediate-depth fractures. Lost circulation accounts for 10 to 20 percent of the total cost of drilling a typical geothermal well.

Objectives

- **To develop downhole and surface tools, materials, and techniques that can be used to reduce the cost of detecting, diagnosing, and treating lost circulation zones encountered in geothermal drilling.**

Expected Outcome

If found to be feasible and development is successful, the following products will result from this research:

- **Rolling float meter to provide an early warning of a fluid loss situation;**
- **Drillable straddle packer for increasing the effectiveness of conventional cements treatments;**
- **Borehole televiewer (BHTV) fracture characterization software and hardware for locating and characterizing lost-circulation zone fractures;**
- **Drilling fluid flow testing procedures for determining lost-circulation zone characteristics;**
- **Porous packer for wireline deployment of polyurethane foam sealant downhole;**
- **Formulations for fast-setting, temperature activated cementitious muds for sealing loss zones;**

Expected Outcome (continued)

- **Downhole injector system for delivering and injecting separate streams of cementitious mud components downhole; and,**
- **Rig-site expert system for assistance with detecting, characterizing, and treating lost circulation.**

APPROACH

Eight technology areas for lost circulation research covering detection, diagnosis, and treatment of lost circulation zones have been identified. The research, being conducted at Sandia National Laboratories, calls for investigating each technology area to identify those measures with the greatest potential impact on lost circulation costs. Technologies with significant potential impact are then further developed. Sandia researchers then undertake feasibility studies, conceptual design, laboratory scoping studies, detailed design, laboratory testing, and field testing for each tool or technique investigated.

The work plan breaks out into six phases:

Phase I Investigation of each of the eight technology areas. This phase evaluated: (1) the feasibility of developing a specific tool or technique; and, (2) associated the potential lost circulation cost savings. Researchers prioritized technology areas based on the potential cost savings, development feasibility, and potential acceptance by industry.

Phase II Detailed design of downhole or surface hardware or procedures. The design process itself is an important component of the feasibility evaluation.

Phase III Design and construction of any laboratory facilities that may be needed for testing purposes.

Phase IV Testing of downhole or surface hardware, investigators evaluate and refine hardware designs in the laboratory.

Phase V Field testing, where designs and procedures are exercised and evaluated in the field.

Phase VI Technology transfer, where a tool or technique is made available to industry through publication of results and assistance in implementing the technology in the field.

RESEARCH STATUS AND FINDINGS

Rolling Float Meter Development

The rolling float meter is a device that employs a bearing-mounted float that rides and spins on the surface of the drilling fluid in the mud return line leading from a wellbore to the mud pit. The float is mounted on a pivot arm that allows the float to respond to varying levels of fluid in the partially filled return line. The level of the fluid, which is a measure of the flow rate, is measured with a pendulum potentiometer that detects the angle of the pivot arm. Bernoulli forces, generated by the fluid accelerating beneath the spinning float, act to adhere the float to the fluid surface, preventing it from bouncing free of the turbulent surface.

The rolling float meter was developed and laboratory tested in FY90-91 and field tested in late FY91. In early FY92, the results of the six-week field test indicated that the rolling float meter is capable of much greater accuracy in measuring outflow rates than current commercial transducers, and is also much more sensitive in detecting lost circulation and fluid influx.

The rolling float meter experienced two field test failures:

(1) warping of the plastic float used in the field prototype when return mud temperatures exceeded 140°F.

Sandia fabricated floats of high-density polyurethane foam by developing an injection molding technique to produce exact replicates of the original plastic float used in the laboratory and field tests. Researchers then designed and built a Float Durability Tester that allowed a foam float to be rotated in a barrel of heated and stirred drilling mud for long periods, up to several weeks. Initial problems of cracking when mud temperatures approached 180°F were solved by altering the heat-treatment conducted on the foam during the curing process. The final process produced floats capable of withstanding at least 28 days of testing at 180-195°F with no significant abrasion, cracking, or water absorption.

(2) periodic sticking of one of the float's roller bearings.

Simple, lightweight mud splash guards were designed to prevent mud from splashing on the bearing assemblies. No significant degradation of the bearing assemblies occurred with the mud splash guards in place, even after 28 days of high-temperature testing.

Detailed design drawings of the meter were released. Seven rolling float meter units were fabricated and lent to seven different service companies for independent field testing and evaluation. In addition, one of the companies built five additional units for a comprehensive field testing program. All twelve units are expected to be field tested extensively in FY93.

Drillable Straddle Packer Development

The drillable straddle packer is a packer assembly for isolating and directing the flow of cement into a selected loss-zone interval, while maximizing the volume of cement delivered to the loss zone and

minimizing the volume of cement remaining in the wellbore.

The goal of the project is to develop a low-cost packer assembly that is drillable and is left in the bottom of the wellbore at the completion of the drilling operation. To accomplish this, a new type of packer is being developed using two high-strength, flexible, impermeable fabric bags capable of withstanding a 40-psi internal pressure differential -- one above and one below the loss zone. Inflation of the bags is accomplished by the pressure differential created by the flow of cement through the packer ejection ports located in the vicinity of the loss zone.

During FY92, a bag was developed using woven fiberglass-reinforced silicone rubber fabric in conjunction with a unique bag design that minimizes stresses in the fabric bag. The fabrics employed are only 0.015 to 0.045 inch thick but have exceptional strengths, ranging from 190 to 400 lb per lineal inch. Although highly flexible, the fabrics do not undergo significant stretch under a load. The fabric is sewn into a tube, then the ends are pleated and clamped between two PVC-plastic flange plates on each end of the bag assembly. An O-ring fits between the two mating flange plates with an optimal amount of interference for maximum clamping force on the fabric.

Prototype packer assemblies were tested in the Packer Test Facility during FY92. The facility employs a 14-ft-high length of 16-inch casing to simulate a wellbore, including fluid inlets and outlets that simulate production and loss zones, respectively. Tests were conducted with a single fabric bag situated midway between an upper production zone and a lower loss zone. During a test, a flow of 10-15 gpm begins from the upper production zone into the wellbore and out the loss zone. The flow rate then increases through the packer assembly and into the loss zone to inflate the bag.

Near-term plans for the drillable straddle packer include: 1) testing of a laboratory prototype packer assembly designed to evaluate the packer shroud and flow-through mechanism; and, 2) a full-scale demonstration of a packer assembly using cement in a surface or near-surface wellbore with a simulated loss zone. If successful, this development effort will then concentrate on field testing a packer assembly under actual field conditions.

Borehole Televiewer Fracture Characterization Study

The borehole televiewer (BHTV) fracture characterization study will yield techniques for using a BHTV to accurately measure the fracture apertures in lost circulation zones. Although the BHTV has been in use for many years to locate fractures and determine their spacing, dip and strike, quantitative fracture measurement is not readily accomplished because of the effects of signal amplifier settings on the apparent size of features, as seen with the televiewer. In FY90, researchers developed a technique for determining the optimal amplifier settings for filtering out unwanted signal perturbations and displaying only significant fractures that may be associated with a loss zone. This work, based upon laboratory experiments in fractured rock samples, resulted in a technique that appears to enable fracture thicknesses to be measured to within 15% accuracy, if the fractures are at least 0.15 inches in thickness. Fractures as thin as 0.03 inches can be detected but not accurately measured.

During FY92, researchers field tested the technique twice in the Long Valley Exploratory Well. The bottom 720 feet of the well was wireline-cored and subsequently logged with the BHTV. In the first test, a 150-ft. section of the corehole was logged twice, once with a conventional amplifier setting that

resulted in significant gray-scale sensitivity, and once with an optimal amplifier setting determined according to the previously developed technique. The conventional amplifier setting results in a log that identifies many more features than that of a log obtained with the optimal gain setting. Many of the additional features on the first log are actually due to variations in borehole wall reflectivity rather than open fractures. From a fracture identification standpoint, a log obtained at an optimal gain setting is more useful than one obtained with greater gray-scale sensitivity. By eliminating extraneous, non-fracture features, development of automated fracture identification and measurement software will be more easily accomplished.

Significant progress in FY92 included the design and construction of a travel-time board with greatly improved resolution. This board will allow acoustic-wave travel time data to serve as an additional fracture diagnostic tool. Software and hardware improvements in the real-time data display included replacing the oscilloscope camera system with a gray-scale printer and appropriate software. A BHTV magnetometer calibration test stand was also designed and built to allow accurate calibration of the BHTV's magnetometer in the field.

Near-term plans for the BHTV study include more laboratory tests with fractured rock samples to further determine the effects of rock type, borehole fluid properties, and televiewer eccentricity on the optimal gain selection technique, and also developing algorithms for automated fracture characterization.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organizations	Extent of Interest
Marlin-Decker Totco	Rolling Float Meter testing
Exlog, Inc.	
Schlumberger-Anadril	
Halliburton Services	
Electro-Flow Controls, Ltd.	
International Logging Epoch	
Tecton Geologic & UNOCAL Geothermal	Rolling Float Meter testing, Drillable Straddle Packer evaluation
Unocal	Borehole Televiewer testing

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

A 30 to 50 percent reduction in lost circulation costs would result in a 1 to 5 percent reduction in the cost of geothermal power. All tools and techniques under development in the lost circulation program have short-term industrial applications in geothermal drilling. Additionally, some of the technology has near-term application in petroleum drilling. For example, the rolling float meter has considerable petroleum - industry interest because of its potential for detecting gas kicks often encountered in oil and gas wells.

PUBLICATIONS AND PRESENTATIONS

"An Evaluation of Flowmeters for the Detection of Kicks and Lost Circulation During Drilling," Paper IADC/SPE 23935, 1992 IADC/SPE Drilling Conference, New Orleans, LA, February 18-21, 1992.

"Lost Circulation Technology Development Status," Geothermal Program Review X, U. S. Dept. of Energy, San Francisco, CA, March 24-26, 1992.

"Development and Evaluation of a Meter for Measuring Return Line Fluid Flow Rates During Drilling," Sandia Report SAND91-2607, Sandia National Laboratories, Albuquerque, New Mexico, June 1992.

"Development and Use of a Return Line Flowmeter for Lost Circulation Diagnosis in Geothermal Drilling," Geothermal Resources Council Transactions, Vol. 16, October 1992.

INSTRUMENTATION AND MEMORY LOGGING TOOLS

BACKGROUND

Downhole logging and surface geophysical measurements have become a backbone for hydrocarbon reservoir analysis. Since the first recorded borehole measurements in 1927, advances in hardware and interpretative methods have produced an impressive series of successes. Some experts envision that within five years, an industry-wide consensus will emerge regarding a multi-disciplinary approach to reservoir definition. This approach will range from the petrophysics of individual pores at a scale of 10^{-4} meters (0.004 inches) to surface geophysical investigations with investigative lengths of 100 meters (328 feet).

While some surface geophysical studies are used by the geothermal industry, these studies are limited. There is also a general lack of downhole measurements even though they are required to interpret surface studies, to extrapolate core data away from a hole, and to correct production difficulties.

Often-cited obstacles to downhole measurements are the incompatibility of tools used in low-temperature formations with the geothermal environment, and also the cost of developing and maintaining a suitable tool suite, which exceeds the anticipated revenues from logging services. A market can only be supported if measurements produce a meaningful output.

Interpretative techniques developed for hydrocarbon reservoirs are not typically applicable in geothermal formations, resulting in a general inability to relate log data to meaningful information. The Memory Logging-Tool Program, at Sandia National Laboratories, will help rectify this shortcoming in the geothermal industry.

Objectives

- **To develop quality tools using self-contained, data-storing computers (memory tools) so that measurements can be made simply in extreme environments without the use of an electric wireline.**
- **To insure that the cost of tools and logging services is not prohibitive to the geothermal industry.**
- **To develop appropriate inversion algorithms that relate tool responses to geothermal production parameters.**
- **To transfer tools and software to service companies and to the geothermal industry.**

Expected Outcome

A logging industry supportive of the needs of the geothermal industry through the development of the following tools:

- **A low-cost temperature-pressure tool suitable for use in slim, diamond-cored holes. The first few copies of the tool will be loaned to geothermal operators so that they may see the gains made when logs are run often. Even such simple logs will aid in reservoir evaluation and in establishing engineering solutions for such difficulties as lost circulation control.**
- **A spectral gamma device for the identification of Potassium, Uranium and Thorium. These elements are carried by hydrothermal solutions, and can be used to identify fractures when they are precipitated on the wall rock. The tool can also be used to identify scaling in cased wells.**
- **A high-temperature fluid sampler. This effort involves scientists from the National Science Foundation (NSF) Ocean Drilling Program, and will utilize industry wells for the testing of the new sampler device. A technology transfer is unfolding between an international scientific program and U.S. geothermal operators.**

APPROACH

This new generation of "memory" tools will be programmed to make some computerized decisions. This programming should be simple so that it can be done by average field personnel.

Memory tools are relatively new, and prototype tools are costly. For example, the first slim-hole (2 inches diameter), high-temperature (700 degrees Fahrenheit) temperature-measuring tool costs $58,000. This cost is too high for many anticipated applications. To be cost-effective, these tools should cost less than $10,000.

An evolutionary step is to develop a modular tool with a universal computer/battery section that may be attached to one or more sensor packages. While this vision is in the future, it is feasible, and will result in further cost reductions.

The intent of the Memory Logging Tool Program is to work with industry in the development of inversion algorithms, which are often proprietary. Inversion algorithms relate a myriad of characteristics, from tools response, formation temperature, gamma ray count rate, etc., to formation parameters of interest. Sandia envisions collaboration with the U.S. Continental Scientific Drilling Program and the NSF Ocean Drilling Program.

The work plan breaks out into four phases:

Phase I Consisted of assessing the state-of-the-art regarding downhole measurements in a geothermal environment. This work arose in the DOE/OBES Thermal Regimes studies done as part of the Continental Scientific Drilling Program. Phase 1 was completed in 1991.

Phase II Direct interactions are underway with UNOCAL Geothermal operators, involving temperature measurement in industrial holes. The resulting data are given to the operators for their comments and criticism. Comments are generally favorable. The operators have noted that, within a few hours, memory-temperature tools can yield about two orders of magnitude more data than operators had amassed in several months of work using rudimentary instruments.

Phase III Interactions are underway with the suppliers of tool components. Specifically, SNL approached Onset Computer Company to explore their interest in upgrading their Model 5 computer for downhole work. Likewise, researchers assigned National K Works to design a low-cost Dewar/pressure vessel for the memory tools. Both approaches have been successful, and resulted in cost reductions.

Phase IV This phase will deal with the use of a memory tool suite in industry holes, with the intent of developing appropriate algorithms for the reduction of tool data.

RESEARCH STATUS AND FINDINGS

Computers for Memory Logging Devices

Traditionally, computers for logging devices have been simple data-logging systems which are unable to make a "decision" downhole. Smart computers are available, but cost is an issue. The Onset Computer Company has a line of suitable smart computers, but they were not tested at high temperatures. A facility for temperature testing the Onset Model 5F computer was designed and used to prove this computer's capabilities in repeated temperature cycles up to 1500°C. This successful testing means that the computing problem has been solved. The approximate cost of the Onset Model 5F is $500.

Calibration of Memory-Logging Devices

Memory loggers must be self-contained. This means that all measurements of voltage, frequency, or phase must be made remotely, and appropriate standards must be carried on-board the tool. References traceable to U.S. National Standards must exist in extreme environments.

Secondary Sandia standards, traceable to the National Institute of Science and Technology, were established in the Memory-Logging-Device laboratory. These standards serve to qualify the analog-to-digital converters and the clock on the Onset Model 5F computer, as the computer is being temperature-cycled.

Dewar/Pressure Vessels

The Dewar/pressure vessel is the one most costly item in a modern high temperature logging system. A Request for Proposals was published to find a company to help develop a low-cost Dewar/pressure vessel. The award was made to National K Works, and work is in progress to develop a new protective vessel. The cost of the new system will be about $7,000.

The Dewar/pressure vessel is designed to be no longer than a pair of skis. The concept here is that all components of a logging system (electronics, spare parts, pressure vessel, etc.) be transportable by ordinary commercial air carriers as luggage. This vision is considerably different from the present services that require mobilization of special trucks and crews. It is hoped that the cost savings will provide the impetus to establish logging as a common feature of geothermal operations.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
UNOCAL	All areas of research
CalEnergy	

IMPLICATIONS FOR GEOTHERMAL FUTURE DEVELOPMENT

U.S. geothermal operators will be able to utilize a suite of tools with the capability of: (1) temperature-pressure measurements, (2) potassium, uranium, and thorium determinations, and (3) fluid sampling. Some of these tools will be still in the developmental phase, especially in the area of tool interpretation. Interactions with industry will be needed to further the evaluation process.

PUBLICATIONS AND PRESENTATIONS

Lysne, P. "Downhole Memory-Logging Tools," *Proceedings, Geothermal Review Number X,* San Francisco, 24-26 March, 1992.

Lysne, P. "Memory Logging Tools," a program supported by the US Department of Energy/Geothermal Division at Sandia National Laboratories. Documentation provided the DOE Peer-Review Panel, April 1991.

CHARACTERIZATION OF FRACTURE- & VEIN-CONTROLLED POROSITY & PERMEABILITY IN ACTIVE GEOTHERMAL SYSTEMS

BACKGROUND

Fractures and their partially mineralized counterparts, vuggy hydrothermal veins, provide the bulk of porosity and permeability in many active geothermal systems. Yet, in most such systems, the three-dimensional geometries and pore-creating (or -occluding) hydrothermal features are poorly constrained.

A variety of complex interactions between mechanical rock rupture and circulating thermal waters of diverse compositions can lead, in some instances, to creation of through-going, cavernous conduits, flanked by porous rocks effective for thermal-fluid storage. In other cases, these fluid/fracture interactions foster tight sealing of pores and blockage of potential fluid-flow channels. Moreover, the textures of certain pore-lining secondary phases affect the phenomenon of adsorption, a process that may control a large percentage of reserves at The Geysers.

The thrusts of this research project, conducted at the University of Utah Research Institute (UURI), are to gain an improved understanding of these phenomena in order to model and develop known geothermal resources more effectively, and to reduce the risk in searching for presently hidden new reserves.

The project employs a variety of geologic techniques from mesoscopic to microscopic scales to: (1) map three-dimensional fracture configurations, sizes, and orientations; (2) characterize mineralogy and internal textures; and, (3) decipher the tectonic and hydrothermal evolution with a focus on creation or enhancement vs. destruction of critical secondary porosity and permeability.

Objectives

- **To improve understanding of fractures, veins and breccia cements as reservoir controls in active geothermal systems. Through better knowledge of the three-dimensional configuration, evolution, and secondary-mineral zoning in active systems, this project will enable more confident and cost-effective targeting of additional resources.**

Expected Outcome

- **New tools for effective targeting of productive geothermal-reservoir rock, while allowing more confident reservoir modeling through more realistic constraints for fracture/breccia/vein-controlled porosity and permeability.**

APPROACH

A fundamental focus of this project has been careful characterization of cores from various portions of active, high-temperature geothermal systems, with emphasis on those recently made available from The Geysers steam field. Cores, although expensive to collect, provide superior, solid samples of the selected systems -- most geothermal-well samples are small diameter drill cuttings, production of which destroys the larger-scale features under investigation. Similarly, standard well-logging tools have, up to now, performed poorly under the hot, corrosive conditions encountered at reservoir depths. Cores, therefore, preserve the only direct evidence of the nature of subsurface fracturing, veining, brecciation, and attendant porosity and permeability.

As an allied task, researchers have begun to investigate the use of various new borehole imaging techniques for determination of *in situ* stress orientation, as well as determination of fracture attitudes, apertures, and degree of mineralization. These techniques, including Schlumberger's Formation Microscanner and Formation Microimager, are potentially very powerful tools, but few operators have applied them to date in geothermal environments. Another promising research approach has been utilization of imaging techniques to study the geometries and internal textures of fractures and miscellaneous pores in geothermal cores.

The first steps in this research project involved getting cores and cuttings for study from geothermal field operators, then cataloguing and archiving these samples to ensure their availability on a timely basis for other interested researchers. This task also involves curation and dispersal of core samples to these geoscientists. Next, the cores are logged in detail, with emphasis on: (1) lithology; (2) mechanical rock rupture, hydrothermal alteration and mineralization; (3) the nature, and temporal relationships of veins, fractures, and breccias; and, (4) the distributions, sizes, and apparent volumes of pores (all open spaces). Vertical zoning of alteration and vein mineralogy, above and below the cored intervals, are also determined (using drill cuttings) to establish the relative position of these features in cores with respect to the geothermal system as a whole. Multiple thin sections from the cores and cuttings are petrographically examined. To investigate the above-listed features at a microscopic scale, researchers injected samples with a fluorescent epoxy so that voids can be readily recognized and quantified, utilizing standard point-counting techniques. Selected samples are examined using the scanning electron microscope. This is the best approach for investigating the internal structures of pores as well as the textures and potential adsorptive capacities of pore-filling or -blocking phases. Researchers have begun to implement automatic analysis of composite SEM images using software designed initially for processing remote-sensing imagery. The results of these efforts are being synthesized with other available corresponding geothermal-reservoir data to yield fresh insight into mechanisms of fracture and vein/breccia porosity evolution.

RESEARCH STATUS AND FINDINGS

Much of the porosity and permeability in cores from The Geysers steam field owes its existence to relatively early dissolution of pre-Geysers metamorphic vein calcite and aragonite by high-temperature hydrothermal fluids. The field is floored by a large, Plio-Pleistocene granitic/rhyolitic intrusion (also the system's likely heat engine). Core studies conducted to date by UURI researchers strongly suggest that early, aggressive, high-temperature aqueous solutions circulating above and driven by this pluton were responsible for dissolving this metamorphic vein calcium carbonate from tens of cubic kilometers of

overlying, Mesozoic metasedimentary rock, creating vital secondary porosity and permeability in otherwise intrinsically impermeable lithologies.

Furthermore, this hydrothermal system deposited intricate networks of various secondary minerals in the interiors of the newly created voids, providing effective substrates on which much of the modern steam field's liquid water reserves may now be stored. This process had been theoretically predicted, but an effective mechanism for its operation had not been documented prior to this research.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The technology developed through this project for fracture- and vein-controlled porosity and permeability characterization should be equally applicable in certain oil fields or in various underground waste-storage repositories.

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

Geothermal exploration and development geoscientists, as well as reservoir engineers, should be able to implement the results of this research in exploitation of known resources, prediction of reservoir longevity, and exploration for lateral or deep reservoir extensions. The findings should also help reduce the risk in prospecting for new geothermal fields.

Utilizing remote-sensing imagery methods for automatic porosity characterization and quantification has yielded promising results. Further testing of this technique on samples from additional high-temperature geothermal systems should be conducted.

PUBLICATIONS AND PRESENTATIONS

Hulen, J.B., Nielson, D.L., and Martin, W., 1992, "Early Calcite Dissolution as a Major Control on Porosity Development in The Geysers Steam Field," California: Geothermal Resources Council *Transactions*, 16, pgs. 167-174.

Nielson, D.L., and Hulen, J.B., 1992, "The Nature of Permeability in The Geysers Geothermal System," USA: International Geological Congress, Kyoto, Japan, Proceedings Vol. 3, p. 848 (abstract and presentation).

RESERVOIR ANALYSIS

BACKGROUND

This research task examines various types of geothermal systems to evaluate conceptual and numerical models of geothermal and geopressured-geothermal reservoirs. The integration of all available geoscience data (reservoir engineering, geology, geophysics, geochemical) and the construction and testing of conceptual models allows detailed investigation of reservoir production mechanisms. This research then provides the industry with tested tools to evaluate and, ultimately, to optimally manage the reservoir. On a smaller scale, the parametric investigation of numerical models insures that the reservoir physics is properly represented.

Objectives

- **To develop geological, conceptual, and numerical models of known geothermal and geopressured-geothermal fields.**
- **To evaluate the models' validity.**
- **To increase confidence in numerical models as a reservoir management tool.**

Expected Outcome

- **Numerical models enjoying full confidence as reservoir evaluation and management tools to maximize energy recovery, to predict long-term reservoir performance, and to decrease the life cycle cost of geothermal energy.**

APPROACH

Idaho National Engineering Laboratory (INEL) participates in joint DOE/Industry studies of The Geysers, and Roosevelt Hot Springs geothermal fields, and also participated in the studies of the Hulin, Pleasant Bayou, and Gladys McCall geopressured-geothermal fields. INEL researchers review existing field data, develop conceptual models of these systems, and appraise the effectiveness of different techniques in locating, characterizing and evaluating reservoir behavior. Detailed parametric studies to further understand specific features of reservoir performance are also conducted.

Data on select fields was gathered and incorporated in data banks for future analysis and evaluation. This preliminary work was performed in close cooperation with the field operators. The project also calls for literature review and numerical model development in conjunction with the vendors.

RESEARCH STATUS AND FINDINGS

A previously undetected pressure-dependent fault strongly influences reservoir pressure response at the Pleasant Bayou geopressured-geothermal field. This supplemental reservoir drive mechanism was unsuspected prior to the integration of all geoscience data and the development of a conceptual and numerical model of this reservoir. The occurrence of this type of fault behavior has important implications for the production of energy from this type of resource. This study is one of the few in the literature integrating and documenting the actual occurrence of a pressure dependent fault.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All industrial organizations involved in the exploration and development of geothermal resources in the United States should be interested in technology transfer. The most active companies are: California Energy Co., Oxbow Geothermal Co., TransPacific Geothermal Co., Southern California Edison Co., and Sierra Pacific Power Co.

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

A better understanding of the geological environments favors the discovery of geothermal systems and the identification of the most effective exploration methods to locate them. Such an understanding will result in a significant cost reduction in geothermal exploration. Lower costs will allow a systematic exploration effort in the Basin and Range Province and the possible identification of additional geothermal resources in the region.

PUBLICATIONS AND PRESENTATIONS

Shook, G.M. "TETRAD Reservoir Simulation," *Proceedings, Geothermal Program Review X*, March 24-26, 1992.

Shook, G.M. "Reservoir Modeling and Prediction at Pleasant Bayou Geopressured-Geothermal Reservoir," *Proceedings, Geothermal Program Review X*, March 24-26, 1992.

Shook, G. M., "Integrated Approach to Reservoir Engineering at Pleasant Bayou Geopressured-Geothermal Reservoir," EG&G Report # EP-10557, December 1992.

Shook, G. M., "Integrated Approach to Reservoir Engineering Detects Pressure-Dependent Fault and Fluid Recharge," submitted to *Scientific Drilling*, December 1992, in review.

Vinsome, P.K.W., and G.M. Shook, "Multipurpose Simulation," accepted for publication, *J. Petroleum Science and Engineering*, 1992.

WELL TEST & TRACER TEST INTERPRETATION

BACKGROUND

Measurements made in wells and during tracer tests provide the principal means of determining geothermal reservoir parameters. Understanding reservoir properties permits the development of better resource recovery strategies. In particular, parameters required for simulation need to be inferred by these measurements. Tracer analysis reveals the structure of the reservoir flow paths, thereby allowing for an appropriate injection strategy, which may add several years of useful life to a field.

Objectives

- **To reduce uncertainty in geothermal reservoir engineering design by improving reservoir analysis techniques. Specifically, researchers are examining the methodologies of well test analysis and tracer testing.**

Expected Outcome

- **A series of reservoir engineering techniques that operating geothermal companies can use for reservoir analysis leading to better management practices for the production of geothermal reservoirs.**

APPROACH

Researchers at Stanford University are investigating several well test configurations, including flow into fractures and flow in a reservoir with a two-phase or gas zone overlying a liquid zone. In addition, researchers are looking at simultaneous analysis of pressure transient and tracer test information and are developing mathematical models, most of which require solution using computer-based techniques.

RESEARCH STATUS AND FINDINGS

Researchers have completed the work on gravity drainage and fractured reservoirs. They have also completed a preliminary phase of the work, combining well tests and tracer tests, in which they investigated the methodology of fitting multiple data sets. The preliminary work considered only single well test data, although simultaneous matching of data from multiple wells was applied.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
UNOCAL	Cost sharing
Calpine	
PG&E	

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

The results of the research will be of interest to all of the operating companies, public utilities, and state agencies involved in the development of the nation's geothermal resources. These results will be particularly important from the point of view of the design of geothermal injection projects.

PUBLICATIONS AND PRESENTATIONS

Michael Riley, "Finite Conductivity Fractures in Elliptical Coordinates"

Elena Macario, "Optimizing Reinjection Strategy Using Chloride Data"

Xianfa Deng, "Analyzing Multiwell Pressure Data of a Reservoir with Variable Properties"

Francois Graff, "Microcomputer Simulation of the Transient Flow of Real Gas"

STUDY OF GEOTHERMAL RESERVOIR CHARACTERISTICS AND PROCESSES

BACKGROUND

For several years, because of the temporary marginal economic value of geothermal steam due to low oil and natural gas prices, the U.S. industry has not had the financial resources to carry out the necessary research to develop the general methodology needed to optimize the recovery of the thermal energy stored in geothermal systems. In light of this situation, DOE continues to support core research in reservoir technology.

A better understanding of the dynamics of geothermal systems would permit U.S. industry to design optimal reservoir management practices.

Objectives

- To better understand hydrothermal reservoir characteristics and processes, and to identify the critical phenomena in geothermal systems located in different geological and hydro-geological environments.

Expected Outcome

- Gain a better understanding of the processes occurring in geothermal reservoirs in response to production and injection of fluids. This will allow industry to develop reservoir management plans to extend the commercial lifetime of geothermal fields, as well as to augment the amount of energy that can be extracted economically from these fields.

APPROACH

Researchers at Lawrence Berkeley Laboratory (LBL) are analyzing field data from geothermal systems located in different geologic and hydro-geologic environments, and are developing or improving reservoir engineering techniques to identify and characterize the physical and chemical processes in geothermal reservoirs.

Researchers are carrying out theoretical and laboratory studies of phenomena associated with multiphase (steam, liquid and non-condensible) flow in porous and fractured rock masses, and are developing mathematical techniques to improve the modeling of heat and mass transport in liquid- and vapor-dominated reservoirs.

Data on U.S. and foreign geothermal fields is gathered and analyzed. Results of analyses and predictions are then discussed with researchers from industry, universities and federal and state organizations.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
INDUSTRIAL PARTNERS: California Energy Co. Oxbow Geothermal Co. Trans-Pacific Geothermal Co. UNOCAL Geothermal Division Central California Power Agency Northern California Power Agency Calpine Corporation *FOREIGN ORGANIZATIONS:* Comision Federal de Electricidad (*Mexico*) Ente Nazionale Energia Electrica (*Italy*) Orkustofnun (*Iceland*) Instituto Costarricense Electricidad (*Costa Rica*)	Contributions (in kind): Geologic, geophysical, geochemical, production and reservoir engineering data, and personnel to review and discuss research results. Value of these contributions: Several million dollars.

RESEARCH STATUS AND FINDINGS

LBL researchers attained a better understanding of the effects of injection into geothermal reservoirs by evaluating the importance of capillarity and vapor adsorption in vapor-dominated geothermal systems. Further, researchers developed a semi-analytical solution of heat and mass transfer between rock matrix and surrounding fractures.

It is difficult to estimate how much more research has to be done on reservoir characteristics and processes. As the development of geothermal systems throughout the world continues, new problems arise which need to be solved. This type of core research began with the support of DOE's Geothermal Division, without which U.S. industry will have to rely more and more on foreign companies and organizations to solve operational problems that arise during the evaluation and exploitation of geothermal energy.

IMPLICATIONS FOR FUTURE GEOTHERMAL DEVELOPMENT

The successful completion of this research will allow industry to develop reservoir management plans to extend the commercial lifetime of geothermal fields, as well as to augment the amount of energy that can be extracted economically from these fields.

PUBLICATIONS AND PRESENTATIONS

Lai, C.H. and Bodvarsson, G.S., 1992. "Numerical Studies of Cold Water Injection into Vapor-Dominated Geothermal Systems," Paper submitted to SPE Reservoir Engineering.

Pruess, K. and O'Sullivan, M., 1992. "Effects of Capillarity and Vapor Adsorption in the Depletion of Vapor-Dominated Geothermal Reservoirs," Proceedings, Seventeenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., January 29-31 (in press).

Truesdell, A.H., Manon, A., Quijano, L., Coplen, T., and Lippmann, M.J., 1992. "Boiling and Condensation Processes in the Cerro Prieto beta Reservoir under Exploitation," Proceedings, Seventeenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., January 29-31 (in press).

Zimmerman, R.W., Chen, G. and Bodvarsson, G.S., 1992. "A Dual-Porosity Reservoir Model with an Improved Coupling Term," Proceedings, Seventeenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., January 29-31 (in press).

TRACER DEVELOPMENT

BACKGROUND

In most geothermal fields, the spent cooled brines must be injected back into the reservoir. The purposes of injection are to avoid surface and ground water pollution and to maintain reservoir pressure. The locations of the injection wells within the three-dimensional network of fractures that form the reservoir are critical to the successful exploitation of the field. Properly located wells lead to higher power production from enhanced pressures, less reservoir scaling from boiling around the production wells, and reduced thermal breakthrough. Improperly sited wells either give no benefits or result in rapid thermal breakthrough. Unfortunately, prior to field start-up, only the ground aspects of the hydrologic connections are known, not the pathways and velocities that the injection fluid will take through the reservoir. The latter data can only be obtained by using evidence of mass transfer, i.e., chemical data. Introduction of a tracer into the injection-production loop is the most efficient and quantitative method of obtaining data that describe the subsurface flow of injected fluid.

Power production is limited by the amount of water in the reservoir because the heat is primarily stored in the rock. Injecting produced geothermal water back into the reservoir after its heat has been removed increases the efficiency of heat extraction by recycling the working fluid, in effect, removing the limiting factor of water mass in the system. The development of geothermal tracers will allow industry to more effectively site injection wells, increasing the amount of water recycled to the reservoir. At the same time, the use of tracers will help the operators avoid locating injection wells where the recycled fluid would flow rapidly to the production wells. Such a short-circuit would reduce the power output of the plant by lowering the temperature or enthalpy of the produced fluids.

At the inception of the tracer development program in 1982, very few tracers were in use by the geothermal industry. The poorly quantified stability of the geothermal tracers that were known in 1982 produced a lack of confidence in the results of tracer tests, which considerably lowered the utility of tracer tests as a reservoir tool. Surveys of the geothermal industry by the DOE revealed 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 is currently being conducted at the University of Utah Research Institute (UURI).

Objectives

- **To identify and test compounds for use as geothermal tracers with the following characteristics: a) nontoxic; b) thermally stable or easily quantifiable rates of decay under geothermal conditions; c) minimal rock-tracer interaction; d) detectable at low conditions; e) and, are relatively inexpensive. As many of these compounds as possible must be identified because of the need for using them to tag individual injection wells uniquely.**

Expected Outcome

- **A wide variety of tracers suitable for the variable phases, conditions, and temperatures found in geothermal systems.**

APPROACH

UURI researchers are evaluating the utility of various compounds as tracers and have identified the immediate need of organic tracers for the geothermal industry.

The work plan breaks out into five phases:

Phase I Researchers tested the geothermal tracers currently used by industry. The tests consisted of injecting the tracers into a geothermal reservoir, letting the injectate sit in the reservoir for a few days, and then withdrawing the injected fluid back from the same well. These field tests identified several compounds which were suitable as tracers and others which were not. Because the results indicated that only one or two compounds were suitable, researchers proceeded to Phase II - the development and laboratory testing of new tracers.

Phase II Researchers tested the most commonly used groundwater tracers for stability in a geothermal environment. The tracers were tested in a laboratory-simulated environment rather than in field tests because a large number of compounds had to be processed. Although very few groundwater tracers proved to be stable at high temperatures, the results of Phase II led to generalizations on which types of compounds might be most stable in a geothermal environment.

Phase III Researchers identified tracer compounds and laboratory-tested them.

Phase IV Researchers field-tested the best of the compounds.

Phase V Researchers are identifying and laboratory- and field-testing the fluorescent tracers. Fluorescent tracers are more expensive and subject to more rapid thermal decay than the tracers initially developed, but they are favored by industry because they can be easily analyzed in the field.

RESEARCH STATUS AND FINDINGS

Researchers published work on 39 non-fluorescent organic tracers in the journal *Geothermics* this year. Of the compounds tested, 24 can be used in geothermal systems with temperatures up to 200°C, 15 can be used up to 250°C, and 7 are stable to at least 300°C.

Two of the fluorescent tracers that were tested this year appear to be suitable as liquid-phase tracers in geothermal systems at temperatures up to approximately 220°C. The tracers are Rhodamine WT, a red dye, and Tinopol CBX, a blue dye. Both of these compounds can be analyzed in the field with a filter fluorometer, an inexpensive but accurate instrument.

UURI has now identified and tested several tracers that are stable in geothermal systems. Researchers have used some of these in actual field tests, and learned how to get additional information about the reservoir from the tracer behavior, such as the effective temperature along the injection-production flowpath. The remainder of the project will consist of identifying and testing fluorescent tracers, and deciphering what other information can be gleaned from tracer behavior during injection tests, such as reservoir steam fractions and the relative speeds of steam and water in the reservoir.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organizations	Extent of Interest
Domestic & int'l geothermal industry: UNOCAL Geothermal, California Energy Co., Ormat, Oxbow Geothermal, Far West Capital, etc.	Inquiries on tracer usage and choices, cost-shared tracer tests, short courses.
DOE: Waste Isolation	Need data on tracers that can be used for analyzing the hydrology of waste repositories.
Geothermal Resources Council	Short courses on tracers for geothermal industry.
United Nations	Short courses on tracers for developing countries.
International Atomic Energy Agency	Tracer tests in developing countries.
DSIR (*New Zealand national science division*)	Inquiries on tracer usage and choices.
England Hot Dry Rock Program	Inquiries on tracer usage and choices.
ENEL (*Italian national electrical utility*)	Inquiries and paid lectures on tracer usage and choices.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The tracers developed are already being used by industry. By 1995, the geothermal industry will already be using the fluorescent tracers that are currently being evaluated.

PUBLICATIONS AND PRESENTATIONS

Adams, M. C., Moore, J. N., Fabry, L. and Ahn, A. H., 1992, "Thermal Stabilities of Aromatic Acids as Geothermal Tracers," *Geothermics*, v. 21, p. 323-339.

"Tracing and Monitoring Reinjection Fluids," 1992, United Nations Workshop on Reinjection of Geothermal Fluids in Volcanic Environments, Costa Rica.

GEOCHEMISTRY OF GEOTHERMAL SYSTEMS

BACKGROUND

To minimize operational difficulties during geothermal production, operators must have knowledge of the chemistry of the system and the potential chemical reactions caused by temperature, pressure and composition changes caused by production. Successful completion of this research project, being conducted at the University of California at San Diego (UCSD), will allow geothermal operators to construct geochemical models of geothermal systems, so they can operate geothermal systems with minimum corrosion and mineral precipitation problems.

Objectives

- **To collect fundamental chemical data needed for predicting chemical changes in reservoirs and plant facilities involved in the extraction of geothermal energy.**

Expected Outcome

- **A computer code capable of modeling complete geothermal systems that will allow geothermal operators to construct geochemical models in order to minimize corrosion and mineral precipitation.**

APPROACH

The basic approach is to develop chemical models that predict the equilibrium relations of the brine - equipment-rock system during production. These models are entered into a computer based code that can predict system behavior at the elevated temperatures, pressures, and total dissolved solids content of geothermal systems. A model is needed that will encompass the important chemical species within a geothermal system.

UCSD researchers review geochemical literature and carefully validate the data so that accurate equilibrium systems can be established based on experimental data. Using the Pitzer theory, researchers are developing binary and ternary models from the data and, from these systems, are determining the chemical behavior of geothermal systems. The computer code is updated on an annual basis and is made available to interested geothermal developers through a training session conducted by UCSD researchers.

RESEARCH STATUS AND FINDINGS

UCSD researchers published several papers describing the methane-carbon-dioxide-water system. Researchers added this system to the geochemical models to simulate conditions in wellbores and production equipment under which methane and carbon dioxide gas will form. Researchers also held a tutorial for the industry and distributed copies of the present code for use with UNIX, DOS and MacIntosh environments.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All geothermal developers within the U.S. have shown interest in this research project. Most geothermal operators have attended the training sessions and use interim versions of the code to predict formation of scale and separation of carbon dioxide from the brine into a gas phase. The Canadian Potash Industry is also involved in cost-sharing the project.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Future development includes improvement of geochemical models for geothermal systems and a consequent improvement in industry's ability to operate geothermal fields with a minimum of chemical problems.

PUBLICATIONS AND PRESENTATIONS

Tutorial presented to the industry.

Presentation made at the DOE San Francisco Geothermal Program Review.

Duan, Z., Moller N. and Weare J.H. (1992) "An equation of State for the CH_4-CO_2-H_2O System: I. Pure Systems from 0 to 1000°C and 0 to 8000 bar," *Geochim. Cosmochim. Acta*, Vol. 56, pgs. 2605-2617.

Duan, Z., Moller N. and Weare J.H. (1992) "An Equation of State for the CH_4-CO_2-H_2O System: II. Mixtures from 50 to 1000°C and 0 to 1000 bar," *Geochim. Cosmochim. Acta*, Vol. 56, pgs. 2619-2631.

Duan, Z., Moller N. and Weare J.H. (1992) "The Prediction of Methane Solubility in Natural Waters to High Ionic Strength from 0 - 250°C and from 0 to 1600 bar," *Geochim. Cosmochim. Acta*, Vol. 56, pgs. 1451-1460.

Duan, Z., Moller N. and Weare J.H. (1992) "Molecular Dynamic Simulation of PVT Properties of Geological Fluids and a General Equation of State for Nonpolar and Weakly Polar Gases up to 2,000°K and 20,000 bars," *Geochim. Cosmochim. Acta*, Vol. 56,
pgs. 38-39.

GEOCHEMISTRY OF GEOTHERMAL SYSTEMS

BACKGROUND

Fundamental chemical data are needed for predicting chemical and permeability changes in reservoirs and plant facilities involved in the extraction of geothermal energy. This research project, conducted at Oak Ridge National Laboratory (ORNL), will make data available to construct geochemical models of geothermal systems to enable engineers to operate systems with a minimum of corrosion and mineral precipitation.

Objectives

- **To collect thermodynamic data needed for accurate modeling of geothermal systems.**

Expected Outcome

- **Geochemical models that can be used for predicting changes in chemistry and that help geothermal operators minimize corrosion and mineral precipitation problems.**

APPROACH

Utilizing the unique facilities and expertise at ORNL, researchers are studying selected chemical equilibria. Of particular importance are the liquid-vapor distribution of HCl, aluminum speciation, liquid-vapor isotopic distributions, and bisulfate ionization. A series of solute volatility experiments were completed for the HCl + NaCl system.

RESEARCH STATUS AND FINDINGS:

ORNL researchers completed a manuscript for submission to *Geochimica Cosmochimica Acta* on the potentiometric studies of the first hydrolysis constant of Al^{3+} in NaCl brines to 5 molal and 200°C. The results were presented at the 7th International Symposium on Water-Rock Interaction. The results of studies of the effects of dissolved salts on the partitioning of stable hydrogen and oxygen isotopes between water liquid and vapor in saline waters were also presented at the Water-Rock Interaction Symposium.

The ORNL isopiestic study of aqueous sulfuric acid and aqueous sodium bisulfate has culminated in the publication of two papers in 1992.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Interest in this research has been indicated by all geothermal developers within the U.S.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The improvement of geochemical models for geothermal systems should result in industry's ability to better handle and operate geothermal fields with a minimum of chemical problems.

PUBLICATIONS AND PRESENTATIONS

Holmes, H. F. and R. E. Mesmer, "Isopiestic Studies of H_2SO_4(aq) at Elevated Temperatures. Thermodynamic Properties," *Journal of Chemical Thermodynamics*, Vol. 24., pgs. 317-328 (1992).

Holmes, H. F. and R. E. Mesmer, "Isopiestic Studies of $NaHSO_4$(aq) at Elevated Temperatures. Thermodynamic Properties," *Journal of Chemical Thermodynamics*, in press.

Palmer, D. A. and D. J. Wesolowski, "Aluminum Speciation and Equilibria in Aqueous Solutions. Part II. The Solubility of Gibbsite in Acidic Sodium Chloride Solutions from 30 to 70°C," *Geochimica et Cosmochimica Acta*, Vol. 66, pgs. 1065-1091 (1992).

Simonson, J. M. and D. A. Palmer, "Liquid-Vapor Partitioning of HCL(aq) to 623 K," *Geochimica et Cosmochimica Acta* (in press) 1992.

Wesolowski, D. J., "Aluminum Speciation and Equilibria in aqueous Solutions. Part I. The Solubility of Gibbsite in the System Na-K-$Al(OH)_4$-OH-Cl from 0 to 100°C," *Geochimica et Cosmochimica Acta*, Vol. 56, p. 1065-1091 (1992).

SUPERCRITICAL CYCLE INVESTIGATIONS

BACKGROUND

When the Heber Binary Plant was under construction, the Idaho National Engineering Laboratory (INEL) began to consider a second generation binary geothermal plant. INEL developed a number of advanced concepts to improve binary plant performance as measured by increases in the net geofluid effectiveness and the net electrical energy produced per unit mass of geofluid (whr/lbm). At the same time, INEL determined the impact of these improvements on the cost of producing electricity and also estimated market penetration potential.

At that time also, at the Raft River Geothermal Site, a simple prototype (60 kWe) power plant, complete with a turbine-generator, was assembled to study the operation of a binary plant. This system was subsequently redesigned with new heat exchangers, a condenser, a pump and a refurbished turbine to permit investigation of the advanced concepts. This system became known as the Heat Cycle Research Facility (HCRF). This small plant was run at the Geothermal Test Facility in the Imperial Valley of Southern California and finally at a site adjacent to the McCabe Binary Plant (presently owned by Mission Energy). Tests at this plant verified that the gains discovered in the early analysis were indeed possible, and that tools were available to design the components for such an advanced plant. These tests also verified that the heat exchanger design computer programs of Heat Transfer Research, Inc. could be used with some modification to design the condensers and heaters.

Objectives

- **To increase binary plant effectiveness and reduce the life-cycle cost of producing electricity from liquid-dominated, moderate- to high-temperature hydrothermal resources.**

Expected Outcome

- **An increase in geofluid effectiveness (net watt-hour of electrical energy produced per unit mass of geofluid) of around 20 percent and a corresponding reduction in the cost of producing electricity of 13 percent.**

APPROACH

Initial investigations of possible performance increases identified a series of promising concepts together with predicted incremental decreases in cost of producing electricity. Researchers tested the components

required to effect the greatest impact on cost of electricity in the HCRF. Researchers compared test results with existing design methods and made appropriate changes.

RESEARCH STATUS AND FINDINGS

A number of significant research results emerged:

- A Rankine cycle with supercritical, counterflow heating and integral, counterflow condensing gives the best performance and lowest cost of producing electricity.
- Proper choice of a working fluid and operating pressures is extremely important. For a given resource temperature, a mixture of hydrocarbons (or halocarbons) with a large fraction of a light component and a much smaller fraction of a significantly heavier component is optimum, e.g., 94 percent isobutane and 6 percent n-heptane by mass.
- If the minimum geofluid outlet temperature is restricted to avoid silica precipitation, recuperative heat transfer, which uses the turbine exhaust to preheat the working fluid, results in a more cost-effective system. (A simple shell-and-tube exchanger which cools and perhaps partially condenses the turbine exhaust to heat the liquid from the condenser is sufficient. No gain was noted in using turbine bleed to create the recuperation.)
- For some systems with a retrograde working fluid (butane and heavier), a cycle with a turbine expansion which goes through the two-phase region gives better results than one which operates on the superheated vapor region. (This is true if the turbine expansion is metastable and no condensation actually results.)

All work is completed on these tasks except for reporting the final results, which will consist of three reports to be issued by the end of the 1992 calendar year. The first report will bring together all of the work done on the project with the exception of the supersaturated turbine expansion. This will include the early analytical work and the experimental work from past references along with the experimental studies of the system with the condenser at a 60° inclination from the horizontal. This report will cover the material to a "reference" depth. A separate in-depth report on the results of the supersaturated turbine expansion experimentation is being completed at this time. A third report, more of a "guidebook" or "Users Manual", will outline the significant lessons learned from the program and will discuss how the results of the program effort can be used to produce the most cost-effective binary power plants.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All geothermal developers involved in power generation in the U.S. and abroad have interests in this project.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Application of the first three improvements results in a 20 percent increase in the net geofluid effectiveness over a conventional binary plant (such as the Heber Binary plant). This performance improvement results in a decrease in the cost-of-electricity of about 13 percent. The supersaturated turbine expansion gives an additional 8 percent performance improvement over the best plant without this improvement and an additional 6 percent decrease in the cost of electricity. This improvement in performance will open access to more cost-competitive power generation from low-temperature geothermal resources.

PUBLICATIONS AND PRESENTATIONS

Demuth, O. J., "Analysis of Mixed Hydrocarbon Binary Thermodynamic Cycles for Moderate Temperature Geothermal Resources", EGG-GTH-5753, February 1981.

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CONDENSATION BEHAVIOR OF SUPERSATURATED TURBINE EXPANSIONS

BACKGROUND

Binary cycles, used in the conversion of geothermal energy to electrical energy, commonly utilize hydrocarbon working fluids. The cycles have generally been structured to prevent turbine expansions in the two-phase region to avoid moisture condensation, which decreases turbine efficiency and erodes the turbine blades. In binary cycles, it is assumed that the working fluid will always be in thermodynamic equilibrium and that liquid will form during the expansion according to thermodynamic equilibrium constraints. Working fluids include isobutane or heavier alkanes, or mixtures which have one of these as a major component.

If for a binary cycle the turbine inlet temperature is decreased, then the turbine expansion goes through the two-phase (wet) region. Such a case would avoid superheating of the turbine exhaust -- indicating that the irreversibility in the heat rejection process is probably smaller than in the cycle which avoids the two-phase region. For a binary cycle which expands through the two-phase region, the geofluid cools to a temperature lower than in the cycle which avoids the two-phase region, indicating a greater conversion efficiency because of a lower amount of residual available energy in the geofluid leaving the plant. In addition, the average temperature difference between the geofluid and working fluid is lower in the cycle which expands through the two-phase region -- indicating a higher conversion efficiency resulting from a lower irreversibility in the heat addition process.

This research, conducted at the Idaho National Engineering Laboratory (INEL), indicated that this expansion through the two-phase region probably would not allow the predicted moisture to condense, but would remain a single-phase vapor in a supersaturated (metastable) state. This phenomenon is observed in steam turbines and has been exploited since the 1930s.

Objectives

- **To increase binary plant effectiveness and reduce the life-cycle cost of producing electricity from liquid-dominated, moderate- to high-temperature hydrothermal resources.**

Expected Outcome

- **Gain an increase in geofluid effectiveness (net watt-hour of electrical energy produced per unit mass of geofluid) of around 8 percent and a corresponding reduction in the cost of producing electricity of 4 to 8 percent.**

APPROACH

Analytical studies indicated that supersaturated turbine expansions (through the two-phase region) could result in increases in geofluid effectiveness (net watt-hr of electrical energy produced per unit mass of geofluid). If these expansions take place with the working fluid in a supersaturated (metastable) state, reductions in turbine efficiency and any potential erosion can be avoided -- resulting in performance gains and reductions in electricity costs. This research investigates the limits of this supersaturated region in a two-dimensional nozzle which approximates the expansion in a turbine.

Initial analysis identified possible performance increases for certain resources where a turbine expansion which went from a supercritical turbine inlet state to a single-phase outlet state, while expanding through the two-phase region (assuming that no liquid formed during the expansion). Further analysis indicated an incremental decrease in the cost of producing electricity in a plant employing this type of turbine expansion compared to a baseline plant (representing the current state-of-the-art, where typical turbine expansion avoids the two-phase region).

INEL researchers are conducting expansion nozzle tests with flow visualization using laser beam scattering in the flow path to detect droplet formation. Testing is conducted at a small-scale plant, the Heat Cycle Research Facility (HCRF). Researchers will use test results to validate analytical predictions of droplet formation. If droplets do not form or remain very small during the expansions, concerns about any potential damage to the turbines should be alleviated. Actual turbine testing could follow.

RESEARCH STATUS AND FINDINGS

Researchers have installed and checked the expansion nozzle and droplet detection system at the HCRF. Confirmation of the necessary conditions to produce supersaturated (metastable) expansions and mapping of the region in which the expansion remains metastable are currently underway. All field experiments will be completed in the spring of 1993.

A report of the results of the nozzle testing will be drafted in the Summer of 1993. This information will appear in the guidebook discussed in the section, "Supercritical Cycle Investigations." If results are favorable, a cooperative effort may be pursued with an industrial partner to run a turbine in this flow regime.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All geothermal developers involved in power generation in the U.S. and abroad have interests in this project.

IMPLICATIONS FOR FUTURE DEVELOPMENT

An increase in geofluid effectiveness (net watt-hour of electrical energy produced per unit mass of geofluid) of around 8 percent and a corresponding reduction in the cost of producing electricity of 4 to 8 percent will result in better performance of binary geothermal power plants. This improvement in performance will open access to more cost-competitive power generation from low-temperature geothermal resources.

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WELL CEMENTS

BACKGROUND

The quality of the cementing phase of a geothermal well completion often established the life expectancy of the well. Poor cements can result in blowouts and casing corrosion or collapse. The conventional use of normal weight (14 lb/gal) cement slurries can contribute to the formation of lost circulation zones during completion operations. Therefore, lightweight (10 lb/gal) slurries that cure to form hydrothermally durable materials are badly needed.

During the period 1978-85, Brookhaven National Laboratory (BNL), under DOE 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 CO_2 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 which were evaluated, that had densities less than 13.6 lb/gal, failed to meet the test criteria -- identifying a research goal that, to date, has still not been fully attained. 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 CO_2-containing brines and the calcium silicate hydrate compounds present in conventional well cements. Rapid reductions in strength, increased permeability, and corrosion on the outside surfaces of the well casing occur. Solving this materials problem is the goal of the current cement research activity.

Objectives

- **To develop and field test non-Portland cement-based materials meeting the following criteria: 1) life expectancy, 20 years, 2) carbonation rate, <5% after 1 yr in brine at 300°C containing 500 ppm CO_2; 3) slurry density, 10 lb/gal; 4) pumpability, 4 hr at 150°C; 5) compressive strength, >1000 psi at 24 hr age; 6) bond strength to steel, >10 psi; 7) H_2O permeability, <0.1 m Darcy; 8) bulk density, <62.4 lb/ft^3; and 9) cost, <$10/bag.**

Expected Outcome

- **Advanced, high-temperature, CO_2-resistant, lightweight cement meeting all of the API criteria for geothermal well completions. Well life extensions to 20 years will be attainable with the availability of cements resistant to high (>500 ppm) CO_2-containing brines at temperatures >100°C.**

APPROACH

Since all conventional calcium silicate hydrate-based cements are subject to reactions with CO_2, other reaction paths leading to superior cements are being identified and elucidated. These are the subjects of the fundamental research phase of the BNL program. Researchers are currently placing emphasis on the synthesis of calcium and aluminum phosphate cements formed by acid-base reactions. Reactive lightweight fillers are then selected.

The research team then studies interactions that occur between them and the cementing matrix under hydrothermal conditions. Property characterizations of the cementing formulations in a slurry state and upon curing are then performed. The next step is to select retarding admixtures needed to insure pumpability. Larger-scale flow tests and downhole evaluations are conducted. These latter phases are cost-shared cooperative efforts with geothermal well completion firms and well owners.

The work plan breaks out into five phases:

Phase I	Fundamental work to synthesize calcium and aluminum phosphate cements and to elucidate the interactions that occur between them and a number of aluminosilicate-based microsphere fillers. State-of-the-art surface science analytical techniques are used in all parts of this phase.
Phase II	Development of cement-filler mixtures and curing conditions to yield the desired properties.
Phase III	Determinations of the mechanical, physical and chemical resistance characteristics of promising formulations before and after autoclave exposures to CO_2-containing hydrothermal fluids.
Phase IV	Determination of the technical feasibility of using the cement slurries in well completions with conventional placement technology. 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. A well service company contributes industrial assistance in the selection of retarders.

Phase V Verification of the ability to mix and place the cements on a large-scale, and determination of the long-term durability of samples cured in and exposed to downhole geothermal environments. This is a cost-shared activity with a well service company and a well owner.

RESEARCH STATUS AND FINDINGS

Researchers successfully completed small-scale laboratory studies to determine the compatibility of several inorganic and organic microsphere-type fillers with phosphate modified calcium aluminate cements. Because of the promising results which identified a reaction path for producing a lightweight, CO_2-resistant well cement, researchers formulated plans to transfer the technology to industry by means of a Geothermal Drilling Organization (GDO)-sponsored program conducted by BNL, Halliburton Services (a well service company), and UNOCAL (a major producer of geothermal energy). This effort will determine the technical and economic practicability of mixing and placing large-scale quantities of the cement into geothermal wells, and will characterize the properties of the cements after long-term downhole exposures at four geothermal sites. This GDO activity was scheduled to start late in the fiscal year, but was delayed by fiscal constraints.

In the laboratory studies, Phases 1-3, researchers prepared lightweight slurries by incorporating microspheres into calcium phosphate pastes. These microspheres were composed of the following:

(1) borosilicate-based glass;
(2) aluminosilicate;
(3) napheline syenite; and,
(4) a $CaCO_3$-sized acrylonitrile copolymer.

The latter was derived from calcium aluminate cement as a base reactant and an $NH_4H_2PO_4$-based fertilizer as the acid reactant. The density of a neat calcium phosphate cement slurry is 1.98 g/cc. The addition of the microspheres reduced the density to the range 1.1 to 1.5 g/cc. The density goal of the program is $\sim$1.2 g/cc (10 lb/gal). These lightweight slurries were then cured in a hydrothermal environment at 200°C or 300°C. The following factors were found to govern the strength development and long-term stability of the cements: 1) phase composition and transformation of the matrix and the interfacial reaction products formed by reactions between the microspheres and the cement; 2) changes in the microstructure developed within the matrix and at the matrix-microsphere interface; and, 3) the susceptibility of the microspheres to thermal and hydrothermal decomposition. Aluminosilicate-based hollow microspheres with a density of 0.67 g/cc and particle sizes ranging from 75 to 200 μm produced the most suitable product. The slurry density of this product was $\sim$1.3 g/cc, and, upon hydrothermal curing at 200°C, the product had a compressive strength $>$6.89 Mpa. The resistance of the cementing matrix to attack by CO_2 at elevated temperature (300°C) had been demonstrated previously.

Researchers have begun tests to select retarding admixtures for these formulations to insure pumpability.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Halliburton Services	Potential supplier of the cement formulations and placement services to the geothermal industry.
Red Hill Geothermal	Well owner. Specifier of cement for their wells.
UNOCAL	

IMPLICATIONS FOR FUTURE DEVELOPMENT

Success in this project will facilitate high quality and reliable well completions in all geothermal reservoirs on a worldwide basis as well as in oil and gas wells.

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THERMALLY CONDUCTIVE POLYMER CEMENTS

BACKGROUND

A serious problem in the development of geothermal energy is the lack of cost-effective durable construction materials for handling hot brine, steam, cooling water and binary fluids. Scaling and corrosion are encountered in all geothermal plants and, to various degrees, they adversely affect plant availability, lifetime and power output. These problems are more acute when high temperature and chemically aggressive fluids are encountered. Ultimately, the lack of cost-effective materials of construction could seriously constrain the development of the nation's geothermal resources. 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 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 major 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. This could be used as a liner on low cost mild steel tubing. Another possibility is cost effective utilization of bottoming cycles in flash processes as a means of increasing energy conversion efficiency.

The technical feasibility for the use of high temperature composite materials for corrosion protection was demonstrated by Brookhaven National Laboratory (BNL) in the early 1980s. Since then, composite materials have been used successfully by the geothermal industry. Researchers observed that significant increases in the thermal conductivity of the polymer-matrix composites could be achieved by the incorporation of high conductivity materials and fillers. Conductivities approaching those of type-410 stainless steel were obtained. Also, the addition of high-temperature anti-oxidants into the composite significantly reduced the rate of scale deposition and adhesion to the surface. Therefore, researchers began to develop a low-cost low-fouling replacement material for the high alloy steels used in geothermal heat exchange applications.

The work is being performed as a cooperative effort with the National Renewable Energy Laboratory (NREL) and as a cost-shared activity with the geothermal industry.

Objectives

- **To fabricate, laboratory characterize, and field test a prototype single shell-and-tube heat exchanger with polymer-cement-lined tubing which meets the following criteria:**

  1) **heat transfer coefficient and surface roughness similar to those of AL-29-4C tubing;**

  2) **fouling factor <50% of AL-29-4C when used in brines typical of the Salton Sea;**

  3) **cost not more than twice that of mild steel.**

Expected Outcome

- **High-temperature thermally-conductive and corrosion-resistant liner materials which can be used in heat exchanger applications in energy conversion processes.**
- **Increased plant utilization factors due to reduced scale deposition.**
- **Decreased quantities of waste sludge for disposal from the use of binary processes with hypersaline brines.**

APPROACH

The work is a collaborative effort between BNL, NREL and private industry (Red Hill Geothermal). 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.

NREL conducts engineering analyses and heat transfer tests. This work includes measurements of heat transfer coefficients, cost estimates, and the management of field testing. Red Hill Geothermal will provide a field test site and ancillary equipment at a plant operating at the Salton Sea. Tests will be performed in an environment typical of that in a bottoming cycle application in a flash process.

The R&D is being performed in four phases:

Phase I The research team is using a mechanistic approach to learn about interactions between organic polymer binders containing anti-oxidants and reactive thermally-conductive fillers in composites. Researchers also determine how decomposition occurs upon exposure to the test environments.

Phase II The research team then determines the effects of compositional and processing variables on the resultant properties of the composite. Next, researchers define parameters necessary to centrifugally cast smooth, thin, uniform composite liners onto long lengths (20-ft) of small diameter (0.75 to 1.0-in.) tubing.

Phase III BNL fabricates test tubing, while NREL undertakes engineering-scale tests to measure fluid flow and heat exchange properties.

Phase IV Finally, the team undertakes field evaluations in bottoming cycle applications in one or more geothermal flash processes. Field evaluations proceed as cost-shared activities with the geothermal industry, followed by the design of full-scale heat exchangers and cost analysis.

RESEARCH STATUS AND FINDINGS

In FY 1992, researchers continued to evaluate low cost corrosion and scale resistant materials which can be used as protective liners for heat exchanger tubing. The emphasis of the work centered on *in-situ* field testing of four 20-ft lengths of tubing, lined with a thermally conductive polymer cement (PC).

In FY 1991, researchers lined four 20-ft lengths of 3/4-in. O.D. by 0.049-in wall thickness, seamless hydraulic steel tubing with a thermally conductive PC and sent them to the Del Ranch Geothermal Power Plant, operated by Red Hill Geothermal, for field testing. When this test was completed, the tubes were returned to BNL for analysis late in the fiscal year. With analysis completed in FY 1992, work commenced on methods for improving the fabrication process to yield smooth, uniformly thick liners. NREL became a collaborator in the activity, replacing INEL.

After 250 hours operation in hypersaline brine under heat exchange conditions at the Del Ranch plant at the Salton Sea, the interior cross-section of each tube indicated the following:

- Scale was present throughout the length of each section of tubing. The average thickness of the scale in each tube varied between 0.038 and 0.050-in.
- The thickness of the liner in each tube was very non-uniform and varied between an average of 0.006-in. to 0.024-in.
- No corrosion of the metal beneath the PC was detected.

Thermogravimetric analysis (TGA) of the liners after exposure indicated there was no deterioration of the liner system as a result of the field exposure tests. An infrared spectrophotometer (IR) analysis was done in an attempt to characterize the composition of the scale found in the tubes. The results, however, were inconclusive.

As a result of the field tests, emphasis is given to the subsequent laboratory work toward refining the centrifugal casting technique in order to produce a more uniform liner. Researchers are using tubing with a 1-inch O.D. Liners of relatively uniform thickness have been successfully cast in 2- and 3-ft lengths

of tubing, using a shop lathe. Researchers are also modifying the spinning assembly built for fabricating the 20-ft lengths of 3/4-in. I.D. tubing used in the field tests so that 10 and 20-ft lengths of 1-in. O.D. tubing can be lined. Emphasis is placed upon liner thicknesses ranging between 0.010-in. and 0.050-in. Calculations indicate that, in this range, the thermal conductivity of the PC has minimal effect on the overall heat transfer coefficient.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Red Hill Geothermal	Heat exchangers for bottoming cycles in flash processes.
UNOCAL	
Gas Research Institute	Condensing heat exchangers for use in high efficiency gas furnaces.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Heat exchanger tubes will be available for binary and flash geothermal electric generating plants, for district heating systems, and for solar process heat applications.

The availability of cost-effective materials for use in bottoming cycle heat exchangers could improve electric generation capacities in geothermal flash processes by 10%. Further, low temperature geothermal resources, which are currently uneconomical, will become feasible for development, thereby greatly expanding the exploitable geothermal reserves.

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ELASTOMER BONDING

BACKGROUND

If the goals for reducing the costs for geothermal wells are to be met, it is essential that a number of advanced high temperature elastomer-containing tools (such as drillpipe protectors, blow-out preventors, rotating head seals, and downhole drill motor stators) become available. The small size of the potential geothermal market currently precludes private sector R&D from producing these components. Earlier DOE-funded research, performed at L'Garde, Inc. and Brookhaven National Laboratory (BNL), developed a Y-267 EPDM elastomer which meets the design criteria for use in static sealing applications in hydrothermal environments at temperatures up to ~315°C. This technology was successfully transferred to industry. Modest changes in the formulation yielded products meeting the needs for dynamic sealing in the above mentioned tools.

In FY 1989, the Geothermal Drilling Organization (GDO) initiated contracts with industrial firms to fabricate and test drillpipe protectors and rotating head seals. Sandia National Laboratories (SNL) administered these contracts. The GDO also planned further work on blow-out preventors. While working on the drillpipe protectors, the contractor, Regal International, determined that a hydrolytically stable chemical coupling system was needed which would meet GDO specifications. This coupling system is needed to bond high temperature elastomers to metal reinforcement. The development of advanced blow-out preventors and Moineau stators for downhole pumps was expected to be impacted similarly, thereby adversely affecting DOE's ability to meet their goals for reducing well drilling costs.

As a result of this constraint, a program was initiated in mid-FY 1991 at BNL to develop high temperature (>200°C) hydrolytically-stable bonding systems.

Objectives

- **To identify and characterize one or more promising bonding systems.**
- **To establish cost-shared programs with tool manufacturers to fabricate and test prototype components. Further, to field test prototypes and, contingent upon the results, to fabricate full-scale units.**

Expected Outcome

- **Advanced hydrothermally-stable chemical coupling systems for use in bonding high temperature elastomers to mild steel and stainless steel reinforcing materials.**

APPROACH

This activity represents a collaborative effort among BNL, SNL, the GDO, and Regal International, a producer of elastomer products for the oil, gas and geothermal industries.

SNL and the GDO identified needed tools and design specifications for these tools. BNL is performing applied research to develop bonding systems, including studying the fundamental interactions at adhesive/substrate interfaces under hydrothermal conditions, and how various reactive groups within the polymer structure affect the interfaces. Such an understanding is essential for the molecular design and construction of advanced coating systems and adhesives.

Regal International will select promising systems produced at BNL and attempt to use them in the fabrication of prototype and full-scale drillpipe protectors, which will then be field-tested by GDO participants. This procedure will be repeated with commercial producers of other tools.

The work plan breaks out into four phases:

Phase I The research team studies interactions at polyaryl-type polymer/conversion coating/metal and polymer/metal interfaces. The team also determines decomposition mechanisms occurring upon exposure to severe environments.

Phase II The research team conducts laboratory characterization of promising bonding systems by measuring the mechanical properties of the systems before and after hydrothermal exposure. Test variables include metallic substrate composition, method of surface pretreatment, adhesive composition, and thickness. Mechanical properties such as bond and tensile strengths are measured in accordance with the appropriate ASTM standards.

Phase III The fabrication of the prototype and, contingent upon the results, full scale drillpipe protectors containing the advanced bonding system. This phase was performed at Regal International under GDO sponsorship. Current commercial fabrication methods must be applicable.

Phase IV After successful engineering-scale evaluations, GDO participants field test units.

Researchers adopted the following generic and specific end-use specifications:

Generic Goals

- Peel strength (180°), 40 psi on mild steel and stainless steel.
- Hydrothermal stability, 90 day in 300°C brine.

End-Use Requirements (GDO Specifications)

- Drillpipe Protectors: No loss of bond after 48 hr in brine at 290°C and 5000 psi, or in steam at 260°C and 660 psi, while rotating at 100 rpm under a radial load of 3500 lb.
- Rotating Head Seals: No loss of bond after 24 hr in brine at 240°C and 425 psi, or in steam at 200°C and 130 psi.
- Blow-Out Prevention Seals: No loss of bond after 90 day exposure to brine at 250°C and 450 psi, or in steam at 200°C and 400 psi.

RESEARCH STATUS AND FINDINGS

Researchers evaluated polyaryl thermoplastic adhesives [polyetheretherketone (PEEK), polyphenylone sulfide (PPS), and polyphenylethersulfone (PES)] to see how they bond elastomers to metals in geothermal environments. Using peel tests, researchers also determined the strengths of the elastomer-to-metal joints made from various blends of adhesives. The key parameters in making the joints were temperature, time and curing atmosphere, in addition to the adhesive type. To determine the cause of adhesion failure to joints, researchers then conducted physical chemical analyses, including differential thermal analyses, thermal gravimetric analyses, infrared spectroscopy and electron spectroscopy for chemical analyses.

The tests showed that joints made of adhesive blends containing greater than 50% PES survived simulated geothermal conditions (200°C and water vapor pressure of 200 psi) for several weeks without significant decrease in peel strength. The chemical components of the adhesive appear to be highly stable under the conditions required to make the joints and in subsequent exposure to the simulated geothermal environment. These results are remarkable compared to previously tested adhesives, which, typically, disband completely within 24 hours in hydrothermal environments. Currently, the peel strengths have not yet reached the generic goal of 40 psi. However, in some cases, the actual peel strengths are not known because the elastomer tore before the interfacial bond failed. Use of higher pressures during the bonding process is expected to improve the peel strength values.

BNL began collaborative work with Regal International, which supplied metal coupons of compositions identical to those used as reinforcement in drillpipe protectors. BNL used these materials in bonding tests which were performed at Regal and BNL. Samples of the BNL-developed adhesives were then sent to Regal to determine their practicality with their commercial fabrication process.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Regal International	Producer of drillpipe protectors
Drilex	Producer of rotating head seals
UNOCAL	GDO member, advanced drilling tool user
Magma Power Co.	User of advanced drilling tools
No. California Power Agency	
Russian River Energy Co.	

IMPLICATIONS FOR FUTURE DEVELOPMENT

Good hydrothermally stable chemical coupling systems will extend the service temperature and life of drilling tools (drillpipe protectors, rotating head seals, blow-out preventors, and downhole drill motors). Drilling costs will be reduced by up to 10%, thereby expanding the size of the geothermal resource that can be exploited economically, and helping to reduce the life-cycle cost of electricity from liquid dominated reservoirs to 3-7 cents/kWh. Safety and environmental concerns during well drilling operations will also be reduced.

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LOST CIRCULATION MATERIALS

BACKGROUND

The cost of handling lost circulation problems during well drilling and completion operations constitutes 10 to 20% of the cost of a well. Therefore, a key objective is to reduce the frequency of lost circulation episodes and the cost of repair. Depending upon the size of the fissures encountered, chemical formulations could be used with or without particulate fibers to rapidly plug lost circulation zones. These formulations could also result in 47 to 78 percent reductions in repair costs compared to conventional two-plug cement treatments. The greatest savings will occur if the repair materials can be injected through the drillpipe without removing the drill bit. This will not only greatly reduce downtime, but also aid in the location of the fractured zones.

During the period 1985-1987, Brookhaven National Laboratory (BNL) developed and performed small scale laboratory tests on several advanced formulations that had potential for meeting the design criteria. Systems studied included mixtures of bentonite with class H or class J cements, and bentonite with magnesium oxide, ammonium phosphate, and borax. The latter formulation appeared most promising. In FY 1990, work resumed on optimizing the magnesium oxide-based lost circulation control formulation for use with several potential placement methods that were under development by Sandia National Laboratories (SNL). Other potential materials were also to be investigated.

Objectives

- **To reduce well drilling and completion costs through cement formulations which can be used to rapidly plug lost circulation zones.**

Expected Outcome

- **Advanced lost circulation control systems which can be used with or without bridging-type additives, depending upon the size of the fissures to be sealed. These systems will cure rapidly and predictably over a wide range of formation temperatures and will be compatible with a variety of placement techniques.**

APPROACH

This project is closely coordinated with well drilling and lost circulation control activities underway at Sandia National Laboratories. BNL participates at meetings of the SNL Industrial Review Panel, which

reviews the BNL program for relevance. SNL provided essential test equipment, such as a consistometer, slot tester, and a downhole test simulator to BNL. SNL will coordinate future large-scale laboratory and field tests.

Specific criteria for the formulations are as follows:

1) viscosity of individual reaction streams <70 Bc for 6 months at temperatures $<50°$ and for >24 hr at 50° to 300°C;

2) viscosity of mixed reactants <70 Bc for 4 hr at 300°;

3) compressive strength >500 psi at 2 hr age;

4) permeability to water $<10^{-2}$ Darcy;

5) volume increase upon curing;

6) durability in brine at 300°C >30 days;

7) all constituents environmentally benign;

8) compatibility with organic and inorganic particulates; and,

9) materials cost $<\$10$/bbl.

Laboratory work focuses on cementitious formulations compatible with bentonite-containing drilling fluids which will meet the mechanical and physical property criteria. Selection criteria include pumpability at various temperatures, degree of expansion upon curing, permeability, compatibility with fillers, and strength at early ages.

The research team optimizes the most promising formulations for use with one or more of the placement methods identified by SNL. BNL then performs small-scale flow tests under simulated downhole hydrothermal conditions. Next, BNL performs larger-scale pumpability and mud displacement tests cooperatively with SNL.

The work plan breaks out into four phases:

Phase I Cementitious formulations, which meet the materials specifications, are selected for evaluation in screening tests. These formulations must be potentially compatible with bentonite-contaminated rock formations and drilling fluids. The team emphasizes chemical interactions occurring between the cementing matrix and reactive fillers, and identification of the reaction phases.

Phase II Mechanical, physical and chemical durability characterization, the team emphasizes tests to determine pumpability at various temperatures, degree of expansion upon curing, and strength at early ages.

Phase III Optimization of the formulations for use with one or more of the six advanced placement techniques identified by SNL.

Phase IV Contingent upon these results, larger-scale laboratory and field tests in which the cements and fillers are placed under simulated downhole conditions.

RESEARCH STATUS AND FINDINGS

The most promising formulation identified to date for lost circulation control consists of mixtures of magnesium oxide, bentonite, ammonium polyphosphate and borax. Depending upon the placement temperature, pumpability can be controlled by varying the magnesium oxide and borax concentrations. At placement temperatures greater than 60°C, micro-encapsulation of the magnesium oxide in organic compounds such as waxes, epoxies, or polyethylene is generally needed to extend the pumping time for more than 2 hours. The formulation was optimized for use with three SNL identified placement technologies: 1) pumped through open drillpipe; 2) pumped through drillable straddle packer; and, 3) pumped through drillstring-deployed porous packer. Additional optimization is underway to allow formulation to be pumped directly through the drill bit.

The research team began additional exploratory experiments with three other cement systems: $CaO{\cdot}Al_2O_3$-bentonite-ammonium phosphate-borax, $CaO{\cdot}Al_2O_3$-$CaO{\cdot}(Al_2O_3)_2$-bentonite-ammonium phosphate-borax, and class H cement-bentonite. Researchers will select the most promising formulations from these systems for optimization of various placement methods and formation conditions. If successful, commercial suppliers and users of the advanced materials will then have a choice of one or more formulations which can be selected on the basis of existing field conditions and cost.

BNL has begun planning with SNL for larger scale flow and mud displacement tests to take place at SNL in mid-FY 1993. Placement utilizing a drillable straddle packer will be evaluated first.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Halliburton Services	Potential supplier for chemical system and field placement services.
UNOCAL	Well owners, potential users of technology.
Magma Power	
Russian River Energy Co.	
No. California Power Agency	

IMPLICATIONS FOR FUTURE DEVELOPMENT

The commercial availability of a low-cost circulation control system (which can be used alone or in conjunction with particulate bridging materials), and suitable placement methods could reduce the costs associated with lost circulation episodes by 30%. This would yield an overall 3 to 6 percent improvement in fluid production costs. These cost reductions will increase the size of the geothermal resource that can be exploited economically.

These lost circulation control systems could be also used in oil and gas wells. They could also be applied in the repair of civil engineering structures, as well as the isolation and stabilization of chemical and radioactive waste storage sites.

PUBLICATIONS AND PRESENTATIONS

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Kukacka, L. E., "Materials for Geothermal Production." *Proceedings of Geothermal Program Review X*, San Francisco, Mar 24-26, 1992, DOE CONF/920378, 97103.

ADVANCED BIOCHEMICAL PROCESSES FOR GEOTHERMAL BRINES

BACKGROUND

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. For example, 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 geothermal solid wastes in power plants. Currently, the disposal of these wastes can cost over $1 million per year for a 50-MW geothermal power plant. High disposal costs and the long-term liability associated with hazardous waste disposal provide the incentive for this study.

Objectives

- **To develop an economically and environmentally acceptable method for disposal of geothermal wastes and conversion of by-products to useful forms.**

Expected Outcome

- **New biotechnology for removing toxic materials from sludges from geothermal brines.**

APPROACH

Brookhaven National Laboratory's (BNL) strategy to develop detoxification biotechnology for geothermal waste focuses on biochemical methods to dissolve toxic elements found in geothermal residues. Since geothermal wastes contain both toxic and valuable metals, the approach isolates both types of compounds. BNL is developing chemical as well as biochemical recovery methods.

Technical feasibility has been demonstrated on biochemical processes for the conversion of geothermal wastes from hazardous to non-hazardous wastes. Laboratory-scale studies have shown that biotechnology for detoxification of geothermal wastes is versatile. This technology can apply to a variety of geothermal sludges (e.g., from The Geysers or the Salton Sea area) containing few or many metals, whose concentrations may exceed the threshold concentrations recommended by regulatory agencies. Metals, such as chromium, copper, manganese, and others, can be removed with 80 to 90% efficiencies. Continuing studies aimed at optimizing and scaling-up the emerging biotechnology processes have identified several key process variables for developing geothermal waste treatment techniques.

Methods are being developed for dissolution, separation and immobilization of geothermal wastes which are: (1) suitable for disposal; (2) usable in inert construction materials; (3) suitable for reinjection into the reservoir formation; or, (4) used for recovery of valuable metals. If the results from this R&D effort are

successful, the high disposal costs and the long-term liability associated with hazardous waste disposal will be reduced significantly. Assuming adequate funding, it is anticipated that at least a 25% or more reduction in disposal costs will be accomplished by FY 1995/96. This will enhance the rate at which U.S. hypersaline brine geothermal resources are developed.

The work plan breaks out into nine phases:

Phase I	Identification of process type, i.e., chemical or biochemical. Biochemical identified as best candidate.
Phase II	Determination of system and choice of microorganisms. Development of thermophilic microorganisms which operate at 50°-60°C and pH 1-2.
Phase III	Multi-element kinetic studies. Bench-model bioprocesses.
Phase IV	Comparison of bioreactors. Choice of bioreactors for scaling-up.
Phase V	First generation of scaled-up fluidized bed and agitated tank bioreactors, and first full process design. Economic and technical feasibility studies based on expertise gained in Phase I - V indicate cost-efficient, environmentally acceptable process.
Phase VI	Identification, optimization, and automation of process variables. (Current)
Phase VII	Parallel studies for metal recovery technology and production of clean water. (Current)
Phase VIII	Construction of 3-bioreactor 50-gallon system pilot-plant. (Current)
Phase IX	Removal of radionuclides. (Current)

RESEARCH STATUS AND FINDINGS

- Researchers have completed a preliminary economic evaluation using several different loadings (10, 20, 30, and 40%) and several hours residence times. The relative economic evaluation, which, in this phase of the project, takes two different bioreactor designs into consideration, has been extended to elevated temperatures. The results were used to develop a computer program for the Advanced Biochemical Processing.
- Although neither state-of-the-art design nor best materials has been taken into consideration, differences in the cost of various processes further stress the importance of loading, residence time, and the type of bioreactor. This study has also indicated the importance of process quality control and appropriate monitoring needs.
- First generation pilot-plant was constructed and is being tested.
- A secondary bioprocess for the removal of radionuclides has been identified.

- Under the experimental condition used, sludge loadings of up to 40% are practical, and at temperatures of >50°C, fast rates of 10 hrs or less are achievable at the pilot-scale level.
- Studies at elevated temperatures have also indicated that particular attention has to be paid to construction materials, compressors, pumps, and other equipment needed for an efficient detoxification process.
- Researchers initiated a study of metal recovery processes under varying environmental conditions. Preliminary results are very promising and indicate that 80% to 90% metals recovery is possible in the form of a small concentrate. The final aqueous phase meets drinking water standards.
- Educational programs were successful and are continuing as part of the ongoing R&D under the auspices of BNL and DOE's Geothermal Division educational programs.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
UNOCAL	In kind. Technical discussions.
PG&E	First draft of joint venture written and agreed on.
Magma Power	Discussing joint venture.
DOE/EM	First presentation encouraging. Further presentations and program discussions early in 1993.
NEA, Iceland	Possible International Program. Discussions may lead to a development of a joint venture.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The benefits that result from the development of this new biotechnology will be both environmental and economical. Not only will the detoxification be less expensive, but the end products will be useful. Recovered metals will have market value. The detoxified sludges can be used as landfill. The emerging biotechnology could find applications in other industries for detoxifying wastes or for recovering metals.

Field studies at the El Centro DOE site (GTF) are expected to take place in the immediate future.

PUBLICATIONS AND PRESENTATIONS

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BASIN AND RANGE GEOTHERMAL FIELD CASE STUDIES

BACKGROUND

All of the geothermal systems of the conterminous U.S., presenting obvious surface manifestations (e.g., hot springs, geysers, fumaroles), have been explored and evaluated. Some have been developed with the purpose of using the geothermal fluids for electricity generation or for direct applications.

The geothermal community shares a perception that vast amounts of geothermal energy resources have yet to be identified in this country. Because of the lack of manifestations, finding these resources would require a major exploration effort. At present the private geothermal sector does not have the financial resources for such a costly project.

DOE, in consultation with industry, decided that a first step in the search of these "hidden" geothermal systems would entail a review of field data from geothermal areas under exploitation in the Basin and Range Province (mainly in California, Nevada, Utah). Lawrence Berkeley Laboratory (LBL) is conducting analysis of field data that might indicate what geological environments are most favorable for hosting geothermal resources, as well as what exploration techniques could be most successful for locating them.

Objectives

- **To develop geological and conceptual models of known geothermal fields in the Basin and Range Province that could aid in planning and executing further exploration.**

Expected Outcome

- **Maps showing the most promising areas in the Basin and Range Province to explore for hidden geothermal resources, as well as the identification of the most effective exploration techniques.**

APPROACH

The approach entails participating in joint DOE/Industry studies of the Coso (CA) and Dixie Valley (NV) geothermal fields. Researchers will review existing field data, develop conceptual models of these systems and appraise the effectiveness of different techniques in locating, characterizing and evaluating liquid-dominated geothermal systems in the Basin and Range Province.

The quality and amount of geological, geophysical and geochemical data shared by industry on the Coso and Dixie Valley areas will allow the development of conceptual models of Basin and Range geothermal systems needed to carry out successful exploration efforts in the region.

RESEARCH STATUS AND FINDINGS

Data from the Coso and Dixie Valley geothermal fields has been gathered, but only very preliminary evaluations have been made. Careful analysis of the collected information is still needed. In addition, data from other Basin and Range geothermal fields might be needed to develop a set of conceptual models for the various type of systems encountered in this Province.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All industrial organizations involved in the exploration and development of geothermal resources in the Basin and Range Province have shown interest in this project. The most active companies in this region are: California Energy Co., Oxbow Geothermal Co., Trans-Pacific Geothermal Co., Southern California Edison Co., and Sierra Pacific Power Co.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Exploration costs, for the Basin and Range Province, can be significantly reduced if realistic conceptual models of "hidden" geothermal systems can be developed. These models can provide a better understanding of the geological environments favoring the presence of geothermal systems and can identify the most effective methods to locate them. The lower costs will allow industry to initiate a systematic regional exploration effort in the Basin and Range Province, which then can be followed by local studies of areas showing the most promising indications of geothermal resources at depth.

PUBLICATIONS AND PRESENTATIONS

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LONG VALLEY EXPLORATORY WELL

BACKGROUND

Much of future geothermal development, in general, will depend on the presence of large thermal reservoirs in young silicic calderas. It is believed that very large heat sources exist in areas such as the Long Valley caldera (USGS Circular 790 estimates 4800 quads there). So far, however, in spite of significant commercial exploration, power on-line in Long Valley remains limited because the groundwater circulation pattern is not well understood. On a broader scale, it is also uncertain whether these heat sources, with much of their thermal energy in molten rock, can be reliably detected with surface measurements. Since Long Valley is one of the most thoroughly studied calderas in existence, it provides an ideal location for validation of the current surface data interpretation. None of the objectives of this research can be accomplished by surface measurements; all require drilling into the deep structure of the caldera.

Objectives

- **To resolve questions about the deep fluid circulation patterns in the caldera, aiding hydrothermal development in the locale of the Long Valley caldera.**
- **To test the hypothesis of large amounts of thermal energy in young silicic calderas, which will affect the prospects for other kinds of geothermal development such as magma or hot dry rock.**
- **To provide a realistic environment for testing advanced drilling hardware.**
- **To afford a unique scientific access to the near-magmatic regime, permitting new studies of caldera formation and evolution.**

Expected Outcome

- **Investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor.**
- **Determination of the amount of collapse and subsequent resurgence of the central portion of Long Valley caldera.**
- **Direct investigation of the geophysical anomalies interpreted to be magma.**

Expected Outcome (continued)

- **Determination of the intrusion history of the central plutonic complex beneath the caldera, and establishment of the relationship of intrusive to eruptive events.**
- **Testing of advanced drilling hardware in a rigorous, realistic environment.**
- **Calibration of the geophysical techniques used to identify this location as a thermal target.**

APPROACH

Sandia National Laboratories (SNL) is coordinating the drilling and scientific activities on the Long Valley well to satisfy a wide spectrum of needs defined by government agencies, the scientific community, and the geothermal industry. The project has already received $1.5 million from the California Energy Commission. SNL will continue to pursue cost-sharing for the remainder of the project.

Although there are several lease-holders in the caldera, and many thermal-gradient and exploratory wells have been drilled, actual development has not been particularly active. The primary reason for this is the lack of understanding of the fluid circulation in the deep caldera structure. None of the exploratory wells drilled to date have been much deeper than 6000 feet, and SNL analysis indicates that even a very large and hot reservoir at greater depth can be masked by lateral fluid flow above it. Drilling far enough to give a better definition of the deep circulation patterns will be an indispensable aid to further hydrothermal development in this region of extremely high thermal potential.

This project proceeds through four phases:

Phase I	Drilled in 1989, the big hole reached 2,568 feet, and an additional 185 feet of continuous core was obtained.
Phase II	SNL deepened the large-diameter hole to 6,825 feet and extended a core hole to 7,578 feet in 1991.
Phase III-IV	The hole to be deepened to 14,000 feet in Phase III and 20,000 feet during Phase IV. SNL has been investigating the wellbore in the intervals between drilling operations, and will do so for several years after completion of drilling.

Current geothermal power production in the Long Valley caldera is approximately 27 megawatts. This is a very small number compared to the estimated 4,800 quads of thermal energy beneath the caldera. One way of visualizing this resource is to assume that the thermal energy in magma can be converted to electricity with 25% efficiency. In that case, the energy in one-half cubic mile of magma would drive a 2,000 megawatt power plant for thirty years. The volume of the chamber beneath Long Valley is estimated to be more than 100 cubic miles. Putting all this together, it is clear that tapping one-half percent of the thermal resource beneath Long Valley would increase on-line power 200-fold.

RESEARCH STATUS AND FINDINGS

FY 1992 saw the completion of Phase II drilling operations, with a core hole from 6,868 feet to 7,578 feet, (November 1991) and Phase II scientific measurements (August 1992).

The large-diameter (17-1/2") portion of the Phase II hole was drilled late in FY 1991, and reached a total depth of 7,130 feet. This depth was well into the Sierran Basement formation, which began at about 6,645 feet and was the target for a secure casing anchor. However, severe deviation below 7,000 feet required plugging the hole back to 6,826 feet and setting a 13-3/8 inch casing at that point. Planned coring for Phase II was a 100-meter hole below the casing point, but the plug-back to shallower depth led to an effort for a longer coring interval, so that more of the basement formation could be evaluated.

Coring equipment and personnel became available in November, and the Nabors-Loffland drill rig used for the big hole was partially remobilized to support core drilling. Using the same coring technique as in Phase I (the core rig placed on the floor of the rotary rig with core rods suspended inside a string of drill pipe), a 3.86-inch corehole (with 99+ percent core recovery) was drilled from 6,868 feet to 7,578 feet.

After completion of the corehole, Sandia researchers made periodic temperature logs and water level measurements until the beginning of Phase II in August 1992. Those activities focussed on: (1) determination of *in-situ* stress (hydrofracs, followed by televiewer and impression packers); (2) conventional wireline logs in the core hole; (3) hydrology experiments; and, (4) vertical seismic profiling.

The 3.86-inch corehole was entirely within the Mount Morrison roof pendant, primarily metapelites with some quartzite and marble. The temperature profiles indicate two thermally conductive zones within the Bishop Tuff – the upper zone at about 1900 feet to 2800 feet and the lower from 2,800 feet to 4,900 feet. The temperature profiles below 4,900 feet indicate a thermal regime dominated by vertical water flow in both the Bishop Tuff and the Mount Morrison roof pendant. In particular, the open corehole is isothermal at about 218°F, indicating substantial lateral or vertical water movement. Sandia researchers ran borehole televiewer surveys in the corehole before and after four sets of hydraulic fracturing tests between the depths of 7,218 feet and 7,415 feet. An impression-packer run after the hydrofracturing confirmed the televiewer data and indicated several borehole breakouts with consistent orientations and suggestions of changes in the image of the borehole wall near two of the hydrofractured intervals. Overall, the hydraulic fracturing pressures were at the very low end of the postulated breakdown and reopening pressures. From the pressure-time records, researchers deduced that hydraulically-induced fracturing occurred along preexisting fractures in at least three of the four measurements.

Researchers obtained several vertical seismic profiles with both compressional and shear-wave vibrator sources. The seismic sources were deployed close in and at distances of up to a few miles. Other measurements this year included extensive core analysis, permeability data, borehole gravity surveys, and a passive borehole seismometer deployed at a depth of 6,600 feet. Researchers are currently collecting copious high-quality data.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
California Energy Commission	Contributed $1.5M to this project, has urged continuation, and has indicated that it will support further drilling.
DOE/Office of Basic Energy Sciences	Contributed ~$280K during FY 1992 for scientific coring and wellbore experiments.
Ocean Drilling Program	Provided technical assistance and loan of equipment, and gave ~7,000 feet of drillpipe for the scientific coring.
Santa Fe Minerals	As the lease-holder for this location, spent ~$150K preparing the site to drill a 10,000-ft exploration well. With cancellation of drilling program, Santa Fe permitted Sandia use of the site. Santa Fe reserves right to test any producing horizons with commercial potential.

IMPLICATIONS FOR FUTURE DEVELOPMENT

If Phase III drilling is completed by 1995, there are two potential industrial applications:

- This will be, by far, the deepest hole drilled in Long Valley caldera. If the data from this well on lithology, temperature, and groundwater circulation are favorable, it could be a powerful stimulus for commercial geothermal development.
- The higher temperatures expected in Phase III drilling will give an opportunity for testing and eventual transfer of new technology such as high-temperature instrumentation and insulated drillpipe.

PUBLICATIONS AND PRESENTATIONS

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ACOUSTIC DATA TELEMETRY

BACKGROUND

Collection of navigation data at the drill bit and transmission to the surface rig is done in real time on virtually every off-shore drilling rig in the world. Logging data is often included in this transmission. This technology is called "Measurement-While-Drilling." 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 service is expensive (about $10,000/day) and, therefore, relatively inaccessible to the geothermal industry.

The transmission rates using mud pulse telemetry are also slow (<1 binary bit/second), which limits the service primarily to collecting drilling navigation data. Telemetry with acoustical carrier signals propagating through the steel drill pipe offers the promise of greatly increased data rates. 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.

Measurement-while-drilling (MWD) is a critical industry to the development of many energy resources including geothermal energy. The MWD industry is approaching one billion dollars in gross annual revenues. Today, the MWD service hinges on the ability to transmit data along the length of a subterranean well by a sequence of pressure pulses generated in the drilling fluid. 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. Sandia's acoustic telemetry program was started in 1987. 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.

Objectives

- **To develop a new data communications link for measurement-while-drilling (MWD) operations and to reduce economic uncertainties associated with the acoustic data telemetry system.**

Expected Outcome

- **A technology base to reduce the economic risks of the industrial partner, allowing industry to invest in the commercialization of acoustic telemetry.**

APPROACH

In Sandia's past work, researchers augmented the empirical approach of industry with a more systematic approach directed at the fundamentals of acoustic telemetry. Researchers assembled computer simulations, experimental data, and field test results which demonstrated the existence of acoustic transmission bands strongly correlated to theoretical predictions. Another past objective was to demonstrate that transducer arrays could be developed and used to directionally project and measure acoustic energy in the drill string. Several devices have been designed, built, patented, and licensed to an industrial partner, Baker Hughes/INTEQ.

Much of the work on transducer design, as well as the evaluation of array responses, is now in progress. Data from the scale model tests will be combined with full-scale surface simulations and field test data.

The principal investigator originally conceived this project because of his familiarity with wave propagation in solids with periodic structure. He quickly realized that physical concepts, computer algorithms, and experimental methods that he had developed for studying stress wave phenomena in missile heat shields could be directly applied to the telemetry problem.

Throughout this early work, exceptional correlations between this model and field test data have been demonstrated; however, while significant advances have been made, key elements of the problem are still unresolved. As an example, the mechanism of signal attenuation is not clearly understood -- either qualitatively or quantitatively. Characterization of this mechanism is central to the design of future field tests, estimation of signal transmission range, and evaluation of data telemetry rates. Ultimately, these questions are the key to successful commercialization of the technology.

Recent analysis of the attenuation mechanism has yielded significant insight into this aspect of the problem. It is evident that the majority of signal loss is due to coupling between axial, torsional, and bending motion in the drill string. The telemetry signal is an axial motion which in a curved drill string interacts with both rotational and transverse motions.

Future work will build upon the existing system code, the surface simulation facility, and the field test system. Transducers which can efficiently produce sound, but which are not an integral structural component of the drill string, will be designed and tested. Field test devices will emerge which can more economically collect information on attenuation and ambient noise. Finally, the surface simulation facility will serve as a testbed for full-scale echo cancellation and repeater arrays.

RESEARCH STATUS AND FINDINGS

In a recent experiment at the Long Valley Well near Mammoth Lakes, California, researchers uncovered a new aspect of the telemetry problem which has greatly increased expectations of success. Sandia researchers now believe that by simply reordering the pipes in the drillstring according to length, the effective transmission distance can be doubled or even possibly tripled. Thus, single-stage transmission may be possible over distances of 15,000 feet. Coupled with this discovery of the "pipe-length" effect, researchers also developed a model of the fundamental attenuation mechanism in drillpipe. This model leads the research team to believe that surface simulations of the telemetry system are particularly relevant to the actual drilling situations and are far less expensive than field tests.

The surface simulation facility has been assembled. Site development tasks included:

1) assembling several sizes and types of drill strings to a maximum length of 600 feet;

2) obtaining careful physical measurements of the pipe to characterize the intrinsic curvatures resulting from the hot-rolling manufacturing process; and,

3) obtaining acoustic measurements using a new real-time, data acquisition and signal-processing system.

A patent disclosure entitled, "Drillstring Conditioning for Improving Acoustic Telemetry," was filed. Sandia has requested a waiver.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Baker Hughes/INTEQ	Patent License

FUTURE IMPLICATIONS FOR DEVELOPMENT

The industry recognizes that the low data transmission rate of mud pulse telemetry is the restricting factor in advancing this technology. As with any communication system, limited transmission capability raises the cost and limits the use of the technology.

Both banking and industry sources have estimated that successful deployment of an MWD system with increased data capacity would double or triple the MWD industry's gross income over a few years. This is a potential payoff of $1 to 2 billion in short-term growth of annual revenues to an industry which is critical to the future reduction of geothermal drilling costs.

Near-term industrial applications for this research include improvement in geophysical imaging while drilling (TOMEX - Western Atlas), and analysis and control of vibratory drilling methods (Sonic Drill - Water Development).

PUBLICATIONS AND PRESENTATIONS

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GEYSERS GEOCHEMISTRY

BACKGROUND

Recent drilling has demonstrated that The Geysers reservoir is not as simple as the early conceptual models developed by White and others (1979) implied. The new data indicates that The Geysers reservoir consists of two regions, one with temperatures near 240°C, and a second with higher temperatures between 240°C and 360°C. Corrosive, HCl-bearing steam is associated with the high-temperature zone. The electrical output of the field is currently declining, which may necessitate the drilling of additional exploratory wells outside the known boundaries of the field.

Despite the large number of wells that have been drilled and the importance of The Geysers as an electricity resource, there is little knowledge about: (1) the thermal and chemical evolution of the present steam-dominated regime; (2) the origin of the two different thermal regimes within the reservoir; (3) the conditions that have led to the formation of highly corrosive HCl-bearing steam; or, (4) the direction and extent of any natural recharge. Answers to these questions are needed to mitigate the effects of the corrosive steam, to establish the pre-production state of the reservoir which is used as input to reservoir simulation codes, and site new wells.

The Geysers geochemistry research, conducted by the University of Utah Research Institute, directly addresses priorities established by the geothermal industry. This study of The Geysers was selected for DOE funding in 1990 by a committee composed of representatives from the four major companies operating this field.

Objectives

- **To develop a thermal and chemical model of The Geysers geothermal system that describes its evolution.**
- **To evaluate the geometry of the early liquid-dominated system developed in response to intrusion of the felsite beneath the field.**
- **To trace the conversion of this system to the present vapor-dominated regime.**
- **To determine the differences and similarities between the normal and the high - temperature reservoirs.**

Expected Outcome

- **Better predictions of the locations of the corrosive steam and the high-temperature portions of the reservoir, to help mitigate problems resulting from the occurrence of corrosive HCl-bearing steam.**
- **Data on the pre-production conditions within the steam reservoir needed for numerical simulations and reservoir engineering.**

APPROACH

The approach is to use chemical and thermal data obtained from fluid inclusions to establish the evolution of The Geysers geothermal system. Toward this goal, researchers have:

1) collected samples of all existing core and selected cuttings from the operators at The Geysers. Core samples are preferable for this project because they allow detailed investigation of vein relationships. In contrast, paragenetic data collected on chip samples is frequently ambiguous;

2) established the paragenetic relationships among minerals deposited by geothermal fluids;

3) conducted fluid inclusion studies on these well-characterized samples; and,

4) combined these data into a preliminary model of the geothermal system.

The work plan breaks out into two phases:

Phase I Researchers determined the relative ages of the geothermal minerals. Thin sections of the veins and adjacent country rock were prepared from the core samples and studied petrographically to establish the vein assemblages and the paragenetic relationships among the minerals. These petrographic studies were supplemented by X-ray diffraction and scanning electron microscope investigations to further characterize the mineral phases and their interrelationships.

Phase II Researchers conducted fluid inclusion heating and freezing measurements on these well characterized samples. The measurements were made on mineral grains in doubly polished thin sections, or on crystals that were hand picked from the core and cutting samples. A fluid inclusion stage that had been calibrated with synthetic fluid inclusions was used for the measurements.

Researchers plotted the fluid inclusion results analyzing the position of the samples within the reservoir, their distance from the granite contact, and their relative age. Researchers also prepared and interpreted cross plots of temperature vs. salinity using the techniques developed under the project "Geochemical Methods."

RESEARCH STATUS AND FINDINGS

UURI researchers established the following sequence of events at The Geysers:

1) intrusion of a felsite magma that initiated a convective hydrothermal system with temperatures near 500°C at the contact;

2) local groundwater incursion down into the felsite as temperatures cooled to 300°C;

3) renewed intrusion at the northern part of the field to produce the high-temperature reservoir; and,

4) initiation of the vapor-dominated regime at a temperature of 260°C.

The petrographic studies demonstrate that permeabilities within the present reservoir were enhanced during Stage 1 by the dissolution of pre-existing calcite, and reduced in the caprock by boiling induced mineralization during Stage 4.

The data indicate that the mineral assemblages in the normal and high-temperature reservoir are similar but that the evolutions of the two reservoirs were different. Of particular significance is the observation that the normal reservoir, where temperatures are close to 240°C, was flooded by locally derived, low-salinity waters prior to the development of the present vapor-dominated regime. However, the high-temperature reservoir was not flooded. Small amounts of salt would have been deposited in the fractures as the liquid-dominated system boiled off. In contrast, only highly saline fluid inclusions were found in the high-temperature reservoir rocks. This fluid would have produced significant amounts of salt as it boiled. Together, these observations indicate that the corrosive steam could be formed in the high-temperature reservoir by the reaction of vapor with salt contained in the fractures.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Domestic geothermal companies and utilities: California State Lands Commission, Calpine Inc., NCPA, Russian River Geothermal Corp., PG&E, Unocal	Cost-shared future studies.
ENEL (*Italian national electrical utility*)	Application of the conceptual model to Larderello.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Conceptual models based on the results of this study will help the operators site new wells at The Geysers and explore for other vapor-dominated systems. These numerical models are being developed at the Idaho National Engineering Laboratory, Stanford University and Lawrence Berkeley Laboratory, where reservoir modeling studies are in progress. The work will also benefit laboratory experiments that are currently underway at Oak Ridge National Laboratory. These experiments are designed to evaluate the chemical conditions that can lead to the formation of HCl-bearing steam. Work will place constraints on the range of conditions that are appropriate for these experiments. The results of this study are being applied to the interpretation of existing reservoir data by geothermal developers, and by reservoir engineers and chemists at the national laboratories.

PUBLICATIONS AND PRESENTATIONS

Moore, J. N., "Thermal and Chemical Evolution of The Geysers Geothermal System, California." Seventeenth Workshop on Geothermal Reservoir Engineering, Stanford University.

Moore, J. N., and Hulen, J. B., "The Geysers Steam Field: an Evolving Magmatic Hydrothermal System in Northern California," (abstract), Fourth Pan-American Conference on Research on Fluid Inclusions, 1992.

VAPOR PHASE TRACER DEVELOPMENT

BACKGROUND

In 1989, the DOE responded to urgent requests from industry by creating a Geysers cooperative research program. One industry request was to develop tracers that will work in the unique geothermal environment of The Geysers. The Geysers is unusual in that it produces steam with no liquid water; in other words, the field is vapor-dominated. The tracers used for conventional liquid-dominated geothermal fields will not work at The Geysers because they will not fractionate to the steam phase. The University of Utah Research Institute (UURI) is conducting this research task. UURI has done previous work on liquid-phase tracers.

Power production from geothermal systems is limited by the amount of water in the reservoir because the heat is primarily stored in the rock. Injecting the geothermal water back into the reservoir increases the efficiency of heat extraction by recycling the working fluid, in effect removing the limiting factor of water mass in the system. The development of geothermal tracers will allow industry to more effectively target their injection wells, increasing the amount of water recycled to the reservoir. UURI's target is to double the efficiency of injection through cooperative injection experiments with industry, where UURI furnishes tracer expertise.

Objectives

- **To identify and test compounds for use as geothermal tracers that are nontoxic, thermally stable (or have easily quantifiable rates of decay under geothermal conditions), have minimal rock-tracer interactions, detectable at very low concentrations, relatively inexpensive, and will fractionate to the vapor phase. As many of these compounds as possible should be identified because of the need for using them simultaneously in individual tracer tests that follow the fluid paths from multiple injection wells.**

Expected Outcome

- **A set of tracers suitable for use in the vapor-dominated Geysers geothermal field.**

APPROACH

The approach used evaluates the usefulness of various compounds as tracers. The geothermal industry has an immediate need for vapor-phase tracers. Consequently, the methodology has been as follows:

1. Search the literature for compounds that may be useful as geothermal tracers, such as groundwater tracers and compounds used for high-temperature applications. Using known thermodynamic data, evaluate the compounds found.

2. Perform field tests of candidate compounds for the purpose of rapidly sorting them.

3. Evaluate, in detail, the stability of selected compounds by performing laboratory tests.

4. Test laboratory results according to field conditions, and establish the usefulness of candidate compounds as tracers.

5. Refine laboratory methods based on the field results.

The primary procedure is to inject tracers used in field tests in pairs, so that their relative stabilities can be compared. This method allows testing of a single tracer in the laboratory and then using the field relationships to rapidly evaluate all of the tracers for which there is field data. Researchers used this method to accumulate data while they adapted the laboratory for vapor-phase tracer testing. Once the laboratory is up and running, in early 1993, researchers will produce detailed kinetic and solubility data on the tracers that have been used successfully in the field.

RESEARCH STATUS AND FINDINGS

During the fiscal year, researchers worked on planning another tracer test at The Geysers. The test will be done at Unit 18 in conjunction with a planned test that UNOCAL, PG&E, NCPA and Calpine will carry out. The purpose will be to examine the behavior of several tracers in the reservoir, and to evaluate the response of the southeast portion of The Geysers to injection. Several potential vapor-phase tracers have been prioritized in terms of cost, analytical sensitivity, and theoretical stability in preparation for the upcoming test. To date, researchers have performed one field test using two candidate tracer compounds at The Geysers. One of these compounds proved suitable for tracing injected water. Researchers need to find more tracers and develop quantitative data on their stabilities and solubilities.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Domestic & int'l geothermal industries and electrical utilities: Unocal, California energy Co., PG&E, Russian River, Calpine, NCPA, and CFE	Inquiries on tracer usage and choices, cost-shared tracer tests, short courses.
DOE Waste Isolation	Need tracer data to analyze the hydrology of waste repositories.
Geothermal Resources Council	Short courses on tracers for geothermal industry.
United Nations	Short courses on geothermal tracers for developing countries.
International Atomic Energy Agency	Tracer tests in developing countries.
ENEL (*Italian national electrical utility*)	Inquiries and paid lectures on tracer usage and choices; use at Larderello.

IMPLICATIONS FOR FUTURE DEVELOPMENT

This research will ultimately yield a variety of tracers (minimum of 6) suitable for conditions at The Geysers. Some of these tracers will fractionate into the liquid phase in the reservoir, so that they can be used to examine the rate and direction of boiling of the liquid injection plume in the reservoir. The tracers that were developed are already being used by industry. By 1995, the geothermal industry will be using the additional tracers that are now being developed.

PUBLICATIONS AND PRESENTATIONS

"Tracing and Monitoring Reinjection Fluids", United Nations Workshop on Reinjection of Geothermal Fluids in Volcanic Environments, Costa Rica, 1992.

GEOLOGY & MAGMATIC/HYDROTHERMAL HISTORY OF THE HYPABYSSAL FELSITE BENEATH THE GEYSERS STEAM FIELD

BACKGROUND

For several years, The Geysers steam field has undergone troublesome pressure declines and, in its northwestern sector, the evolution of high-chloride corrosive steam. Research is being conducted at the University of Utah Research Institute (UURI) to ameliorate conditions or, at least, to understand these developments and gain as thorough a knowledge as possible of the field's geologic and geochemical configuration, as well as its hydrothermal history. These critical elements of the field are intimately related to an underlying, Plio-Pleistocene-age, hypabyssal felsic intrusive complex known to field operators informally as "the felsite". The known, currently exploited vapor-dominated geothermal system at The Geysers forms an expanded envelope, coaxial with and centered upon the felsite and its contact-metamorphic, as well as hydrothermal, halos. For example, throughout much of the Franciscan (Late Mesozoic) graywacke hosted portion of the steam field above the felsite, porosity, now containing much of the field's liquid water reserves, was excavated by dissolution of metamorphic vein calcite and aragonite. Hydrothermal breccias, above the felsite in the Franciscan rocks, were also treated by magmatically-induced hydrothermal brecciation.

Virtually all the steam field's high temperature, high-chloride steam has been produced from the high-grade contact-metamorphic halo mantling the deep intrusion. There is minimal knowledge of the felsite's compositional and textural variations, as well as critical differences in styles of alteration, mineralization, and rock rupture in the pluton, in different sectors of The Geysers. By learning more about the felsite, steam field operators should be able to make more informed decisions about exploitation of known reserves and exploration for new ones.

This research seeks improved understanding of:

(1) controls on steam production related to the felsite;

(2) the causes of high-chloride, high-temperature steam genesis, particularly in the northwest Geysers; and,

(3) clues to the location of deep, felsite-hosted steam reserves.

Understanding the origin and evolution of the high-temperature, high-chloride steam would contribute to effective control and production of the resource, and would perhaps open up new areas of the northwest Geysers. Currently, deep production of such reserves is impractical. Discovery of deep felsite-hosted steam reserves, probably in association with relatively young, more deeply emplaced plutons, has the potential to add significantly to power on-line from The Geysers.

Better knowledge of lithologic, textural, mineralogical, and structural variations in the felsite could enable field operators to plan effective deep injection strategies, not only to avoid unnecessary cooling of currently productive reservoir volumes, but also, theoretically, to effect through dilution, a decrease in chloride content and acidity of deep, high-temperature steam.

Objectives

- **To identify whether the felsite is a relatively homogeneous stock or a composite pluton, and, for the latter, to identify the compositions, textures, and ages of the components' plutons.**
- **To find out whether specific plutons are associated with particularly productive sectors of the steam field, and if so, why.**
- **To identify whether portions of the field, with particularly high porosity and steam-entry frequency, are confined to areas of focused magmatic/hydrothermal or meteoric/hydrothermal brecciation, or to areas of selectively embrittled (hydrothermally or contact-metamorphically) or leached rocks above the ground.**
- **To identify the potential for discovery of additional deep felsite-hosted steam reserves beneath known reservoir rocks, and to find out whether there are clues to these potential deep resources preserved in higher levels of the pluton(s) or contact-metamorphic and hydrothermal hood zones.**
- **To identify and assess the potential for discovery of additional deep felsite-hosted steam reserves beneath known reservoir rocks, and to identify and assess the clues to these potential deep resources preserved in higher levels of the pluton(s) or contact metamorphic and hydrothermal hood zones.**

Expected Outcome

- **Increased efficiency in reservoir modeling as well as improved predictive capability in the search for additional geothermal reserves.**

APPROACH

Initially researchers concentrated on selecting a series of representative wells for the study. Some wells penetrate the felsite at shallow depths along the axis of the stock; others do so at great depth. Some wells penetrate several thousand meters into the intrusive body; others terminate within a hundred meters of the initial penetration. Upon obtaining cuttings and a few cores from the selected wells, researchers began logging the felsite intervals and 100m of the overlying contact-metamorphic halo in each well. The emphasis during this stage of the research is on lithology, textural characterization, evidence of

hydrothermal rock rupture, description of hydrothermal alteration effects, and definition of contact metamorphism. Closely-spaced samples (two 10-ft cuttings samples per 100 ft of felsite or hornfels penetrated) of cuttings and cores are then examined in detail in thin section. At this point in the investigation, individual samples will be selected for even more detailed ancillary analysis; for example, age-dating, X-ray diffraction analysis, and scanning electron microscopy. Combined results of these analyses will be plotted as a series of plan maps and cross sections of the felsite/hornfels zone for comparison with production data.

RESEARCH STATUS AND FINDINGS

Almost all of the felsite penetrations in the representative Geysers wells fall within the granite compositional field. A few are high-alkali-feldspar granodiorites, and one is apparently an alkali feldspar granite. Researchers suspect that the latter is not a pristine intrusive rock, however, but rather a potassium metasomalized hypabyssal quartz porphyry. With depth in almost all the sample wells, the composition of the felsite becomes more calcic, with oligoclase content increasing accordingly, at the expense of alkali feldspar.

Where the cuttings are large enough to permit this distinction, shallower portions of the plutons in the felsite are quartz porphyries, that is, with abundant, bipyramidal, commonly embayed quartz phenocrysts set in a sugary to granophyric or micrographic groundmass. These rocks strongly resemble those found at the hearts of "porphyry base-metal deposits".

All felsites in all the study wells are riddled with microfractures, many of which have healed to trap highly saline, halite-bearing, apparently high-temperature hydrothermal fluids. This is another affiliation with the "porphyry" deposits, which also commonly host such saline inclusions. Researchers believe that in The Geysers, these inclusions constitute a strong line of evidence for widespread exsolution of overpressured magmatic volatiles, which, as in the porphyry deposits, may have caused magmatic-hydrothermal brecciation, resulting in some of the porosity and permeability in the present steam field.

In the metamorphic halos above the felsites in several wells, hydrothermal breccias have transported fragments of felsite up to at least 100 meters upward from the pluton tops. This strongly suggests that high temperature magmatic/hydrothermal brecciation is an important porosity-enhancing process at The Geysers.

In the 200 feet of contact-metamorphic hornfels overlying the felsites, and in the upper 200 feet of the felsites themselves, borosilicate (tourmaline plus or minus ferroaxinite) percentages show in map view a dramatic northwesterly increase, and, in some of these intervals, account for nearly 20 wt % of the affected rocks. This borosilicate enrichment coincides with a northwesterly increase in "high-temperature" steam wells, with a concomitant increase in non-condensible gases in produced steam, and with an enrichment of $^{18}0$ in early steam. Researchers believe that the "porphyry connection" mentioned earlier could possibly provide an explanation. A hypothetical, young pluton, relatively recently emplaced in the northwest, could account for increased heat, sodium-chloride-rich fluids, and borosilicate mineralization (tourmaline-rich porphyry copper deposits are common, for example, in the Andean orogeny of South America).

The felsites are mineralogically affiliated with certain of the Clear Lake volcanics to the immediate north

and northeast of The Geysers. If they do represent Clear Lake magmas which failed to breach the surface, they were emplaced relatively early in the history of this magmatic/volcanic suite. The USGS has determined that felsite samples dated by $^{40}Ar/^{39}Ar$ methods are in excess of 1.3 million years in age. This, however, does not preclude the more recent emplacement of young plutons beneath presently drilled depths in the felsite body. Three available felsite cores from The Geysers have been analyzed and results should be available in early FY 1993.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Russian River Energy Corporation Calpine Corporation Unocal Corporation NCPA (No. California Power Agency)	All these organizations have major land positions in The Geysers steam field. Those benefiting most from this research project in terms of high-temperature, high-chloride steam generation would be Russian River and Calpine, with major interests in the northwest. All but Russian River have extensive felsite-hosted reservoir, and would be most interested in further characterization of that intrusive body.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Successful outcome of this research project should enable steam-field operators to more efficiently and cost-effectively model field performance and productivity. A better understanding of the nature and distribution of high-temperature, high-chloride steam distribution, relative to the felsite and enveloping metamorphic halo, could open up new areas of the northwest Geysers for profitable development.

PUBLICATIONS AND PRESENTATIONS

UURI presented a detailed summary of the research results to date at the DOE-sponsored workshop on The Geysers in Santa Rosa, California, in March 1992. Formal publication of the results outlined in this overview has been withheld until all relevant data sets are complete, including new information anticipated from the recently acquired southeast Geysers sample set, and age-dating results from the cooperative study of the felsite being carried out by the USGS. Submission of a manuscript for publication in the Geothermal Resources Council Transactions volume is anticipated for 1993. A series of maps summarizing the results will be published in late 1993.

GEYSERS IMAGING

BACKGROUND

Geothermal operators believe that the efficiency of utilization of steam dominated geothermal fields can be increased if more is known about the location of steam and fluid saturated zones, and how they change with time.

Operators routinely collect seismicity data which may be useful for generating seismic velocity and attenuation images. Researchers at the Lawrence Livermore National Laboratory (LLNL) have successfully accomplished for an exploration-scale project. The current research is to determine if the techniques are applicable on a production scale.

Objectives

- **To determine whether micro-earthquakes can be used to construct both seismic velocity and attenuation images of an active geothermal field.**
- **To use wells within the field to validate that method and then to apply the method to areas where there is no ground truth or where conditions are changing due to reinjection.**
- **To provide the data to field operators who are conducting injection tests and determine its value to them -- if the method proves useful.**

Expected Outcome

- **If successful, this research will lead to a cost-effective approach to use surface measurements to gain information about the location and migration of steam in a geothermal field.**

APPROACH

LLNL's approach is to use data collected for micro-earthquake studies in geothermal areas to develop seismic velocity and attenuation images and to assess the value of those images by comparing them to laboratory studies of seismic properties, to observations in wells, and to production and injection data.

The work plan breaks out into two phases:

Phase I Researchers tested whether adequate seismic velocity and attenuation images could be easily developed using existing operator-run microseismicity networks and inverting the data using a slightly modified computer program. Then, researchers utilized pre-existing microseismic data collected at The Geysers by UNOCAL Geothermal, and modified the computer code to invert for attenuation as well as velocity. By using the initial pulse width of the seismic arrival as a measure of the attenuation along the travel path, researchers were testing an approach that could easily be implemented by operators who were already determining the times of those arrivals. It was realized that this simple approach was limited by the frequency content of the signals and that its application was limited by what was known of the seismic response of Geysers reservoir rocks to water and steam content. Researchers spent much of FY92 seeking ways to circumvent these limitations.

Phase II Researchers collect and interpret high-resolution seismic data recorded at The Geysers in a joint experiment with Lawrence Berkeley Laboratory. The main purpose of this experiment is the accurate determination of microseismicity locations. The high-frequency sampling of the data and the proximity of stations within the network also makes the data useful for a higher resolution image. These data are being collected and will be interpreted by a variety of inversion methods, and compared to new laboratory data.

This project has two ancillary activities: 1) the collection of seismic property measurements on rocks from The Geysers; and, 2) the development of a neural-network based picking algorithm to better estimate the P- and S-wave arrival times from these data.

RESEARCH STATUS AND FINDINGS

During the fiscal year, researchers completed the analysis of the Phase I velocity and attenuation. While the velocity image contains considerable information, the limited frequency content of the data and the simplicity of the approach for estimating attenuation have limited the image to a simple 1-D model where attenuation varies with depth.

A report entitled, "Velocity and Attenuation Structure within The Geysers Geothermal Field, California," has been completed and was submitted for internal review at the end of the fiscal year.

Results were shared with UNOCAL Geothermal. Researchers have installed their portion of the high-resolution seismic network at the SE Geysers, and have collected data for eight months. The equipment for measuring attenuation using Berea sandstone has been calibrated, and the measurements needed to characterize The Geysers field have been defined. Researchers have tested neural net algorithms and found they performed somewhat better than standard methods.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
UNOCAL Geothermal	Provided four years of selected microseismicity data from The Geysers.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Geothermal operators will have a method to estimate the distribution of steam and water away from the wellbores and can use images of The Geysers to contribute to reservoir engineering models of reservoir response to production and injection. Geothermal operators, required to collect seismicity data for environmental reasons, will be able to use picking algorithms and imaging methods. Improvement in injection strategy could significantly reduce the pressure decline of The Geysers geothermal field.

PUBLICATIONS AND PRESENTATIONS

Maurer, W. J., F. U. Dowla, and S. P. Jarpe, "Seismic Event Classification Using Self-Organizing Neural Networks," *Proceedings*, Third Annual Australian Conference on Neural Networks at the Australian National University, Canberra, Australia, 1992.

Zucca, J.J. and Evans, J.R., "Active High-resolution Compressional Wave Attenuation Tomography At Newberry Volcano, Central Cascade Range," *Journal of Geophysical Research-solid Earth*, July 10, 1992, V97Nb7:11047-11055.

Harris, D.B., S. P. Jarpe and P.E. Harben, "Seismic Noise Cancellation In A Geothermal Field," Note. *Geophysics*, Oct 1991, V56N10:1677-1680.

J.R. Evans and J.J. Zucca, "Active Source, High Resolution (NEHT) Tomography: Velocity and Q," Chapter in *Seismic Tomography: Theory and Applications*," 1992.

GEYSERS RESEARCH I

BACKGROUND

In the late 1980s, it became known that there was an accelerated decline in production and a deterioration in the quality (increase in non-condensible gases) of the steam produced at The Geysers geothermal field of northern California.

Since FY 1991, DOE's Geothermal Division and Idaho National Engineering Laboratory (INEL) have been working with industry on research topics, whose final objective is to provide a technical basis for an improvement in reservoir management practices that could stabilize, reduce or eliminate the reservoir problems being experienced at The Geysers.

Objectives

- **To work with field operators and utilities at The Geysers to develop methodologies needed to determine field performance.**
- **To test and evaluate historical injection and reservoir practices.**
- **To develop management strategies to maximize energy recovery and extend the commercial lifetime of this high quality vapor-dominated geothermal field.**
- **To demonstrate to utilities and industry the long term viability of geothermal energy as a clean, reliable energy source.**

Expected Outcome

- **A set of suggested reservoir and injection testing and management practices that could extend the reserves that can be produced economically over the lifetime of the geothermal project and that could optimize the use of limited steam condensate and surface waters for injection and energy recovery.**

APPROACH

INEL researchers are meeting the objectives by :

1. Developing geologic, geochemical and geophysical data to establish conceptual models of The Geysers system. They are also conducting numerical investigations to predict reservoir response under different management practices.

2. Gathering and interpreting data on The Geysers, working in close cooperation with the field operators.

3. Discussing results of the analysis and predictions with industry and, together with industry, developing new approaches.

RESEARCH STATUS AND FINDINGS

An analysis of historical field injection data indicates that liquid injection into this vapor-dominated geothermal system has shown mixed results. The data seem to suggest that a positive response to injection is mainly restricted to the areas where exploitation has reduced reservoir pressures to significantly low values and in areas of greatest permeability. Also, the evidence suggests that reservoir structure and geometry strongly influence injectate movement.

Analogous studies at Larderello indicate that an injection response is extremely difficult to predict in advance. One successful injection project (Valle Secolo) at Larderello has injected into the same area for over 12 years with an increase in reservoir pressure, moderation of the production decline, an increase in steam production in many of the surrounding wells, and a reduction in the non-condensible gas content of the produced steam. This location was evaluated through a global review of reservoir parameters and extensive testing of individual wells in an area of favorable conditions.

Studies of both reservoirs are extremely hampered by the scarcity and poor quality of the geologic and petrophysical database. Important modeling parameters have simply not been measured to date. Model studies rely on engineering judgement, analogous reservoirs, and intuition to compensate for the deficiencies in the database.

In both reservoirs, it is possible to estimate the amount of injectate being returned to the production wells by monitoring the amount of non-condensible gases and stable isotopes in the produced steam.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Unocal Geothermal Division	Field Operator
Central California Power Agency	Utility & Field Operator
Northern California Power Agency	
Calpine Corporation	Field Operator
Pacific Gas and Electric Co.	Utility
ENEL (*Italian National Electric Utility*)	Utility & Field Operator

IMPLICATIONS FOR FUTURE DEVELOPMENT

INEL researchers envision developing a set of procedures or recommendations for fluid injection and production practices. Proper use of the procedures and recommendations can stabilize or increase the amount of electricity generated at The Geysers. Further, optimum injection practices could more efficiently use the limited amount of water available for injection.

PUBLICATIONS AND PRESENTATIONS

Faulder, D. D., "Model Study of Historical Injection in the Southeast Geysers," *Proceedings of the 17th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, 1992.

Faulder, D. D., and J. L. Renner, "Comparison of Reinjection Experience at Larderello and The Geysers.", in preparation.

Shook, M. "Parametric Study of Reservoir Properties and Their Effect on Energy Recovery," *Proceedings of the 17th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, 1992.

GEYSERS RESEARCH II

BACKGROUND

Since FY 1991, DOE's Geothermal Division and Lawrence Berkeley Laboratory (LBL) have been working with industry to provide a technical basis for reservoir management practices that could reduce or eliminate the problems observed at The Geysers.

Objectives

- **To develop methodologies needed to determine field performance through working with field operators and utilities at The Geysers.**
- **To test and evaluate injection and reservoir management strategies to maximize energy recovery and extend the commercial lifetime of this vapor-dominated geothermal field.**

Expected Outcome

- **A set of suggested reservoir management practices that could extend the reserves that could be produced economically over the lifetime of the geothermal project.**

APPROACH

Working in close cooperation with field operators, LBL researchers gather and interpret data on The Geysers. Results of analysis and predictions are discussed with industry and new approaches are developed.

RESEARCH STATUS AND FINDINGS

Preliminary analysis of microearthquake data suggests that this type of information might be useful to identify high-permeability paths and to track fluid flow in The Geysers reservoir.

A significant amount of data still has to be collected from the operators' files, incorporated into databases, and analyzed. The monitoring of microearthquakes at different areas of The Geysers has to be continued over several more years to get a consistent picture of the seismic behavior of the reservoir in response to injection and production operations.

Additional joint DOE/industry reinjection experiments have to be carried out in the field to optimize the beneficial effects of injection in this vapor-dominated reservoir.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Unocal Geothermal Division	Field Operator
Central California Power Agency	Utility & Field Operator
Northern California Power Agency	
Calpine Corporation	Field Operator
Pacific Gas and Electric Co.	Utility

IMPLICATIONS FOR FUTURE DEVELOPMENT

Development of suggested fluid injection and production practices could be implemented by The Geysers field operators to stabilize or even increase the amount of electricity generated.

PUBLICATIONS AND PRESENTATIONS

Bodvarsson, G.S., Lippmann, M.J., Majer, E.L. and Pruess, K., "LBL Research on The Geysers: Conceptual Models, Simulation and Monitoring Studies," *Proceedings, DOE Geothermal Program Review X*, pp. 31-36, San Francisco, CA, Conf/920378, March 24-26, 1992.

Pruess, K., "Grid Orientation and Capillary Pressure Effects in the Simulation of Water Injection into Depleted Vapor Zones.", *Geothermics*, pp. 257-277, 20 (5/6), 1991.

Romero, A.E., Majer, E.L., McEvilly, T.V., Daley. T.M. and Peterson, J.E., "Initial Results of the Microseismic Monitoring at The Geysers," Lawrence Berkeley Laboratory report, LBL- 31500, pp. 29-32, 1992.

ADSORPTION AND INJECTION STUDIES AT THE GEYSERS

BACKGROUND

This research, conducted at Stanford University, is aimed at understanding the performance of The Geysers vapor-dominated steam reservoir, with a view to forecasting future output. Specifically, it has been found that adsorption has a major effect, and is likely to significantly influence reservoir productivity and longevity. This research project has undertaken two principal sub-tasks: 1) observing the effects of adsorption on production; and 2) observing the effects of adsorption on injection.

Objectives

- **To determine the nature and extent of the effects of adsorption on field performance.**

Expected Outcome

- **A series of models of the reservoir physics that will enable operators at The Geysers to recover the thermal resources of the field more efficiently.**

APPROACH

Stanford researchers are undertaking this research in two ways:

1. Quantifying the extent and behavior of water adsorption through laboratory experiments. Measurements indicate that liquid water can almost fully saturate the available pore space (in the rock matrix, rather than in the fractures) at pressures at which the steam would normally be considered to be superheated. This liquid water provides a fluid source for greater reservoir life. On the other hand, reinjected water can also be "locked up" by the same mechanism, and, therefore, may provide less than the expected performance enhancement.

2. Measuring the transient response under conditions that represent production from the actual field. In this reinjection subtask, researchers are using a mathematical model, and are comparing the theoretical results with observations of tritium tracer experiments conducted in the field itself.

The experimental work consisted of a series of measurements, both steady state and transient, of steam adsorption in Geysers rock samples. The theoretical work focused on developing a mathematical model to represent observations of tritium transport in the field.

RESEARCH STATUS AND FINDINGS

The equilibrium adsorption experiments proved difficult to achieve at first, but success was attained in June 1992. Several series of measurements using The Geysers core material from different locations and at different temperatures were completed. Researchers found that the adsorption curves differed from traditional Langmuir behavior, since they include the effects of vapor pressure lowering and capillarity.

The most significant difference is that the amount of liquid adsorbed increases dramatically at higher pressures (approaching saturation pressure). The transient experiments were successful during the summer of 1992, and, to date, eight different experiments have been run on The Geysers and other comparable systems. The transient experiments indicate adsorption behavior consistent with calculations based on the equilibrium measurements. The injection task produced a mathematical model, the solution to which is still in progress.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

The results of this research will be of interest to all of the operating companies, public utilities, and state resource commissions involved in the development of The Geysers geothermal resource. UNOCAL, Calpine, and PG&E have each contributed $10,000 per year towards this research.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The results of the research will be particularly important in the implementation of the proposed Lake County waste water injection project. Understanding the effects of adsorption and injection will enable the establishment of a better resource recovery strategy. In particular, by determining the relationship between adsorption and injection, injection can be evaluated more precisely, and may result in several additional years of useful life of the field.

PUBLICATIONS AND PRESENTATIONS

Michael Harr, "Laboratory Measurements of Sorption in Porous Media."

Shubo Shang, "Interim Report on Measurements of Adsorption in Geysers Rocks."

CORROSION MITIGATION AT THE GEYSERS

BACKGROUND

Increased HCl concentrations in the steam produced from geothermal wells at 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. In some cases, this has resulted in the shutdown of wells, causing reduced steam supply and, therefore, decreases in electric power generation. Increased operating costs, and safety and environmental concerns have also resulted.

Brookhaven National Laboratory (BNL) is conducting research to find means of mitigating the corrosion problems at The Geysers. If the research objectives are achieved, wells that presently cannot be operated due to excessive operating costs or environmental/safety concerns may be restarted, thereby increasing the steam supply available for electric power generation. In addition, the life expectancies of currently utilized wells and other components will be extended, thereby decreasing operating costs.

Objectives

- **To decrease the operating costs of steam production, transmission and utilization at The Geysers by the identification and subsequent demonstration of low cost materials of construction, which will withstand the highly corrosive acidic environments being encountered in some areas of the geothermal field.**

Expected Outcome

- **Low cost corrosion protective coatings for well casing, turbine blades and above-ground piping and process components.**

APPROACH

BNL's approach to meet the project objectives is to optimize polar and polymer cement formulations, previously developed under DOE's Geothermal Division sponsorship, for specific end-use applications at The Geysers. BNL is undertaking the identification of needs, performance of prototype and full-scale field evaluations, and subsequent economic studies as cost-shared activities with firms active at The Geysers.

The work plan breaks out into three phases:

Phase I	The identification of specific materials problems, elucidation of the fluid environments, and the selection of candidate materials systems. Researchers then conducted laboratory testing under simulated process conditions to establish technical feasibility. Based upon these results, modifications were made to the systems to maximize corrosion resistance.
Phase II	Small-scale field testing, and contingent upon the results, prototype component testing.
Phase III	Studies to incorporate the technology into components, cost estimates, and documentation, and to identify potential commercial suppliers of the new technology.

RESEARCH STATUS AND FINDINGS

Emphasis during FY 1992 was directed toward field evaluations of prototype and full-scale components. Researchers are conducting these ongoing tests at the Northern California Power Agency (NCPA) facility in Middletown, CA, and, the Russian River Energy Co. (RREC) Facility in Cloverdale, CA. Results to date are summarized below.

A. *NCPA Field Tests*

Two 12-in.-diam. "T" sections supplied by NCPA and lined at BNL were installed. Both sections had a 5/16-in. thick cast-in-place polymer (PC) cement liner consisting of styrene, trimethylolpropane trimethyacrylate (TMPTMA) and Type III cement. One liner also contained 1/4-in.-long graphite fibers as reinforcement.

Both sections were installed in a steam collection line late in April 1992. The steam conditions included flow rate 30,000 lb/hr, pressure 120 psi, and temperature 173 °C. The first visual inspection of the liners is anticipated for January 1993. To date, no problems with either unit have been reported.

B. *RREC Field Tests*

Four 8-in.-diam. casing spool sections were installed at RREC for evaluation. Two were lined with a nominal 0.125-in. thick layer of PC; the others with a 0.002-in. thick coating of polyphenylene sulfide (PPS) polymer that was bonded to the casing using a transition metal modified zinc phosphate conversion process. After testing, the PC sections were returned to BNL for analysis.

Field test conditions are listed below.

Parameters	Well Prati 37	Well Prati 5
Spool Number	S1	S2
Wellhead Pressure	123 psi	131 psi
Wellhead Temperature	176°C	175°C
Flow Rate	70,000 lb/hr	54,000 lb/hr
Line Pressure	122 psi	122 psi
Chloride Content	90 ppm	40 ppm
Injection Fluid Rate	11.7 gpm	4.1 gpm

Researchers installed section S1 in the most chemically aggressive RREC well, a location where the service life of a 0.5-in. thick carbon steel wall is 14 days. After being in test for 23 days, a leak developed in the PC-lined section. The leak occurred just above one of the injection ports at the top of the section and may have been caused by backpressure which forced fluid under the PC and subsequent corrosion of the steel. Severe attack on the PC liner was also apparent.

Section S2 was in a slightly lower corrosive environment for 52 days. Visual examination indicated very little chemical attack on the liner but some delamination from the metal substrate.

The two PPS-lined sections, identified as P1 and P2, were placed into test in October 1992, one in the same well as S2, the second in Well Prati 4. To date, neither section has been inspected.

C. *Laboratory Testing*

Laboratory-scale testing of PPS and various PC systems continued throughout FY 1992. These tests, which are conducted in pH 2 HCl at 200°C, were performed to obtain preliminary information regarding potential field performance. To date, carbon steel tubes coated with PPS have been in test for seven months without any apparent corrosion. PC samples exposed for six months exhibited increases in strength compared to the controls, due to continued hydration of the cement, slight increases in volume, and increased porosity. Chemical attack due to the acidic environment was not evident.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Russian River Energy Company	Cost-shared testing collaborator and potential user of technology.
Northern California Power Agency	
Pacific Gas and Electric Company	
UNOCAL Corporation	Current user of technology.
Consolidated Edison Co. of N.Y.	Potential user of technology in steam district heating systems.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The results of this project should yield corrosion protective liners for well casing, steam collection piping and turbine blades. The materials will become available to the geothermal industry and will expand the exploitable geothermal resource base.

PUBLICATIONS AND PRESENTATIONS

Webster, R.P., Kukacka, L.E., and Reams, W. "Development of Polymer Concrete Liners and Coatings for use in Geothermal Applications," BNL 48002, September 1992. Accepted for publication in American Concrete Institute Special Publication "Recent Innovations in Polymer Concrete Technology".

Kukacka, L.E., "Materials for Geothermal Applications," Proceedings, *Geothermal Program Review X*, San Francisco, March 24-26, 1992, DOE CONF/920378, Washington, 97-104, 1992.

INDUSTRY COST-SHARED RESEARCH

BACKGROUND

The geothermal industry needs Federal support to carry out needed research. DOE has entered into an agreement with the Geothermal Technology Organization (GTO) and the Geothermal Drilling Organization (GDO) to cost-share selected research projects.

Objectives

- **To develop specific technology that, in the short term, can have a high probability of yielding benefits to the geothermal industry.**

Expected Outcome

- **Decreased cost of producing geothermal energy through such cooperative projects as developing geothermal tracers and monitoring reservoir performance with microseismic systems.**

APPROACH

DOE, industry or other entities propose specific research projects to the GTO and the GDO. Members of the GTO and the GDO decide whether to participate on a case by case basis. When two or more GTO members agree to fund a project, the proposal is sent to DOE for approval. Upon GTO, GDO and DOE approval, Idaho National Engineering Laboratory (INEL) conducts the proposed research or subcontracts the research to an appropriate subcontractor.

Contributions have included payments of funds to DOE, provision of services to the research project by the participating companies, and in-kind payment in the form of access to property and data.

RESEARCH STATUS AND FINDINGS

A project was initiated near the end of FY 1992. No findings are available at the present time.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All US industrial organizations involved in domestic and international geothermal exploration and development will be interested. The following companies have directly participated through specific

research projects: California Energy Co., UNOCAL Geothermal Division, Central California Power Agency, Northern California Power Agency, Calpine Corporation, and the U.S. Navy.

IMPLICATIONS FOR FUTURE DEVELOPMENT

Tracers and microsiesmic monitoring are now used independently by the industry.

GEOTHERMAL HEAT PUMP ECONOMICS

BACKGROUND

Geothermal heat pumps may be one of the most attractive alternative technologies to reduce peak demands on utilities. This study, conducted at George Mason University, will advance the understanding of the economics of such systems, particularly in Northern Virginia.

Objectives

- **To develop a more accurate method to assess cost efficiency of geothermal heat pump heating/cooling technology, based on consumer and utility data in Northern Virginia.**
- **To investigate the extent to which the regulatory environment faced by utility companies retards the adoption of the technology.**

Expected Outcome

- **A report discussing public policy issues and economics of using geothermal heat pumps in Northern Virginia. The report should heighten private and utility sectors awareness.**

APPROACH

Analysts initially contacted utilities and geothermal heat pump users to determine the economics and load patterns of geothermal heat pump use, and then to develop economic models. Secondly, they reviewed regulatory and public policies which affect the use of geothermal heat pumps.

RESEARCH STATUS AND FINDINGS

The final report is in preparation. Results will be available at completion anticipated February 1993.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All U.S. utilities and developers of residential and commercial buildings should be interested in the results of this project.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The success of this project will mean more rapid penetration of geothermal heat pumps into heating and cooling needs of both residential and small commercial buildings.

LOW-TEMPERATURE GEOTHERMAL RESOURCES & TECHNOLOGY TRANSFER

BACKGROUND

Low- and moderate-temperature resources are widely distributed throughout the 15 western states, and the enormous potential of these resources is greatly under-utilized. Conversion of fossil-fuel energy to geothermal energy for collocated users, and relocation to resource areas will reduce hydrocarbon energy consumption and associated environmental degradation. Potential industrial and community users require an inventory of known resources as they will not initiate exploration. The last national resource inventory concluded in the early 1980's and is badly outdated.

Objectives

- **To achieve greater utilization of the nation's widely distributed low- to moderate-temperature geothermal energy resources.**

Expected Outcome

- **Identification of resources suitable for near-term utilization.**
- **Preliminary reservoir information (temperature, depth, flow rate) for selected resources.**
- **Updated state resource inventories, ten states.**
- **Initial contacts between potential resource users, state resource teams, OIT, UURI and IWRRI.**
- **Assistance to potential resource users.**

APPROACH

The University of Utah Research Institute (UURI), the Geo-Heat Center of the Oregon Institute of Technology (OIT), and the Idaho Water Resources Research Institute (IWRRI) initiated and conducted this cooperative R&D and technology transfer project. DOE\Geothermal Division provides funding through the Idaho National Engineering Laboratory (INEL). Principal activities include Low-Temperature Resource Assessment (described here) and Geothermal Heat Pump Technology Transfer, conducted by OIT and IWRRI.

The approach is to issue subcontracts through OIT to eight state resource teams which will result in an updated low- to moderate-temperature resource inventory for 10 key western states. OIT will direct and also provide guidance to the state teams and require an updated resource inventory and database suitable for collocation studies. Next, OIT will prioritize resources for new data gathering and near-term development. Finally, OIT will announce and distribute statewide resource inventories.

The work plan consists of three phases:

Phase I Define Statement of Work for state resource teams and complete subcontracts with OIT. Complete resource inventory and update and form into computer database. Perform collocation with communities and prioritize resource areas for detailed study.

Phase II Evaluate high-priority collocated resources. Identify and evaluate applications. Complete reporting and present results at GRC and locally.

Phase III Expand study to include 5 to 7 other western states. Undertake new detailed studies on priority resources identified in Phase I states.

RESEARCH STATUS AND FINDINGS

Resource assessment began late in FY92, and a pre-resource inventory is in progress. OIT has completed a preliminary review of collocated resources and communities for four states.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
California Division of Mines & Geology	Participants in updating the resource inventory.
Colorado Geological Survey	
Montana Bureau of Mines & Geology	
Southwest Technology Development Inst.	
Oregon Dept. of Geology & Mineral Industries	
Utah Geological Survey	
Nevada Bureau of Mines & Geology	
Washington Div. of Mineral Resources	
Idaho Water Resources Institute	
Oregon Institute of Technology	
University of Utah Research Institute	

IMPLICATIONS FOR FUTURE DEVELOPMENT

Achieving the objectives of this project throughout the 15 western states could result in conversion of 500 MWt from hydrocarbon to geothermal energy utilization for greenhouse, space, and industrial heating by the year 2000. In addition, rapid growth of geothermal heat pump technology throughout the United States, at a rate of 200,000 to 400,000 units per year, could amount to 12.3 trillion Btu per year or approximately 1.0 Quad by the year 2010. Another 100 MWt is possible from increased geothermal heating for greenhouses, direct heating systems, and agricultural/industrial processing.

PUBLICATIONS AND PRESENTATIONS

- Announcement/publication in popular and trade media: newspapers, engineering and contractor periodicals, etc.
- Announcement and carrying out of a workshop in each state near project conclusion.

GEOTHERMAL DIRECT HEAT UTILIZATION ASSISTANCE

BACKGROUND

The Geo-Heat Center located at the Oregon Institute of Technology (OIT) conducts research and provides assistance to stimulate utilization of the large direct-heat resource base in the United States. OIT's activities include: (1) technical and development assistance; (2) research to aid in devising solutions to resource and technical development problems; and, (3) distribution of information and educational materials to stimulate development.

Objectives

- **To provide technical assistance to developers of direct use projects for space heating, geothermal heat pumps, greenhouses, aquaculture and industrial applications;**
- **To perform appropriate R&D to reduce the cost of operating direct use projects;**
- **To publish informational and educational materials and maintain a library to aid researchers and developers of geothermal direct use projects.**

Expected Outcome

- **Transfer of technology, related to direct use of geothermal resources, to the developers of geothermal projects.**
- **Heightened awareness of geothermal energy's benefits in the private and utility sectors.**

APPROACH

OIT's approach is to provide technical assistance to prospective geothermal users on resource data, preliminary engineering design, analysis of operational problems and technical information. OIT develops guidelines for data acquisition of geothermal well tests and long-term monitoring, and for equipment and material selection. Further, OIT publishes educational materials to aid engineers in the design of direct use projects.

RESEARCH STATUS AND FINDINGS

In addition to providing technical assistance to 30 to 40 persons per month, OIT published a revised edition of the "Geothermal Direct Use Engineering and Design Guidebook." Several papers in geothermal literature were published. Publication of the Quarterly Bulletin of the OIT Geo-Heat Center was continued. OIT developed a greenhouse heating equipment selection spreadsheet, and studied corrosion effects on brazed plate heat exchanger.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

All U.S. utilities and developers of geothermal direct use projects have interests in this project.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The success of this project will mean more rapid penetration of geothermal direct use into the energy sector.

PUBLICATIONS AND PRESENTATIONS

Lienau, P. J. and B. C. Lunis, eds., "Geothermal Direct Use Engineering and Design Guidebook," 2nd ed. Klamath Falls, OR: Geo-Heat Center, 1991.

Lienau, P. J. and J. W. Lund, eds., "Geo-Heat Center Quarterly Bulletin," Vols. 13-14. Klamath Falls, OR: Geo-Heat Center, 1992.

Lienau, P. J., "Data Acquisition for Low-Temperature Geothermal Well Tests and Long-Term Monitoring." Klamath Falls, OR: Geo-Heat Center, 1992.

Rafferty, K., "Greenhouse Heating Equipment Selection Spreadsheet." Klamath Falls, OR: Geo-Heat Center, 1992.

Rafferty, K., "Heatools." A spreadsheet which provides calculations of heat transfer from bare pipe and heat loss from ponds. Klamath Falls, OR: Geo-Heat Center, 1992.

GEOPRESSURED WELLS OPERATION

BACKGROUND

The Gulf of Mexico basin contains large reservoirs of abnormally high pressured (geopressured), hot (geothermal) brines. These reservoirs contain gas, primarily methane, dissolved in the brine, with the amount in solution dependent on brine salinity, pressure, temperature and source of the methane. The geopressured-geothermal (GPGT) fluid consists of moderate- to high-temperature methane-saturated brines, typically around 300°F. Because the rocks above the GPGT layers isolate the brine thermally and mechanically, the pressure and temperature of the fluid are both significantly greater than would be expected. The reservoirs may also contain free gas.

Free gas is usually accumulated at the geologic structural top of the reservoir and has been commercially exploited for years by the petroleum industry. The geopressured-geothermal brines containing dissolved gas, however, have not been commercially utilized. Geopressured-geothermal reservoirs have been tested along the Louisiana-Texas Gulf Coast under three prior DOE programs:

- In the "Wells of Opportunity Program" (1977-1982), twelve wells were taken over by DOE from industry, before being abandoned as not being commercial for initial or continued hydrocarbon production. Nine of these wells were tested for short terms of less than a month. Another well, the Willis Hulin well in Vermilion Parish, LA, was acquired in 1984, but was not tested until recently.

- The original "Design Well Program" (1979-1985) drilled and completed four wells for long-term testing. Tests were completed on two wells and were continued on the other two under this contract (FY 1986-1990). The two design wells currently undergoing testing are the Gladys McCall Well No. 1 in Cameron Parish, LA, and the Pleasant Bayou Well No. 2 in Brazoria County, TX.

- The "Contractor for Geopressured-Geothermal Sites Program" (1985-1992) tests were continued on the Gladys McCall and Pleasant Bayou wells. A Hybrid Power Electrical Generation System was operated on the Pleasant Bayou well. A "Well of Opportunity," the Willis Hulin well, was cleaned out and recompleted, but not long-term tested due to lack of funding.

Objectives

- **To confirm the existence of the geopressured-geothermal resource, to establish its magnitude, and measure its characteristics.**

- **To develop a technology to recover energy from the geopressured-geothermal resource and to formulate a predictive model of the recovery process.**

Expected Outcome

- **Increased ability to locate and evaluate geopressured-geothermal resources.**

APPROACH

The approach had two thrusts: (1) plans to conduct long-term (several years), high volume flow testing of the wells, followed by long-term shut-in pressure buildup tests; and, (2) comparison of formation cores with original cores to determine alteration from production.

The long-term production test was conducted on the Gladys McCall well. A long-term pressure buildup test is in progress. The long-term flow testing of the Pleasant Bayou well was terminated.

Present plans are to plug and abandon all wells.

RESEARCH STATUS AND FINDINGS

The Gladys McCall well in Cameron Parish, LA, produced over twenty-five million stock tank barrels (4,000,000 m^3) of brine. This well was shut-in for three years, and has almost recovered its original reservoir pressure. In addition, as of September 1992, and prior to shut-in, the Pleasant Bayou well produced over twenty-five and a quarter million barrels STB (4,020,886 m^3). This has established that long-term, high volume of 20,000 to 40,000 BPD, or 3,000 to 6,400 m^3/day production is possible from these reservoirs.

A binary cycle Hybrid Power Electrical Generation System (HPS) was installed and successfully operated for several months at the Pleasant Bayou site. This system utilized the geothermal energy of heat and gas, as well as using exhaust heat from gas engine generators. The produced gas was used as fuel and gas. Sales were made at both Pleasant Bayou and Gladys McCall.

All of the wells tested to date, with the exception of the Hulin well, were tested in intervals from 9,700 feet (2,970 m) to 16,700 feet (5,101 m), with bottom hole pressures of 13,000 psi (91.03 Pa) or less, and temperatures of 300°F (149°C) or less. The design wells had solution gas/water ratios less than 30 ft^3/bbl (5.3 m^3 /m^3 corrected to stock tank volume).

DOE acquired the Willis Hulin No. 1 well in Vermilion Parish, LA, from The Superior Oil Company in 1984 as a "Well of Opportunity". The well had ceased natural gas production in 1983 and had mechanical problems requiring rework to restore it to production. Restoration was done under this contract. This well contains several deep, geopressured-geothermal brine reservoirs.

In a short-term flow test in 1990, these reservoirs demonstrated characteristics of greater magnitude than any well tested to date in this program:

- greater depth: ~21,000 feet (~6,400m)
- higher pressures: ~17,300 psi (~119.3Pa)
- higher temperatures: ~340°F (~171°C)

The Willis Hulin No. 1 well has more potential for proving the economic feasibility of geothermal energy than any well tested to date. Scale deposition problems, which had plagued the earlier tests at Gladys McCall and Pleasant Bayou, were overcome in the Hulin well. At Hulin, the scale index, developed by Rice University personnel, indicates that scale inhibition will not be effective in surface facilities at pressures below about 500 psi unless the brine is cooled to below ±300°F.

No further testing will be done because the program was terminated.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
The University of Texas (Austin, TX)	As Participants
Texas Bureau of Economic Geology (Austin, TX)	
University of Southwestern Louisiana (Lafayette, LA)	
Louisiana Geological Survey, LA State University	
Institute of Gas Technology (Chicago, IL)	
EG&G Idaho, Inc. (Idaho Falls, ID)	
S-Cubed (La Jolla, CA)	

IMPLICATIONS FOR FUTURE DEVELOPMENT

Methane dissolved in the water offers an energy resource, in addition to the thermal energy. For example, the U.S. Geological Survey estimates that the geopressured-geothermal energy reservoirs in Gulf Coast sandstones contain 5,700 trillion cubic feet (ft^3) of methane and 11,000 quadrillion BTU (quads) of thermal energy. Another form of energy possible from this resource is the mechanical energy from the pressure of the liquid, but this form of energy offers much less of a resource than the first two forms. Its main advantage is in minimizing the need for pumping.

Geopressured-geothermal energy can be used in hot water aquaculture/agriculture systems, desalination plants, hybrid electrical generation systems, gas production, and various other industrial applications.

HOT DRY ROCK RESEARCH

BACKGROUND

Hot Dry Rock (HDR) is by far the largest geothermal energy resource in the United States, with a resource base of about a million quads. (Total U.S. energy consumption is less than 100 quads annually.) Researchers at the Los Alamos National Laboratory (LANL) patented a concept to access and extract this energy in 1974. This concept involves drilling into water-deficient hot rock, followed by hydraulic fracturing of the formations to open natural joints or create new fractures in a large volume of rock. One or more wells are then drilled into the fractured rock zone at some distance from each other. The system works by pumping water down one well, through the fractured rock reservoir, and up the other well(s). As it passes through the reservoir, the water mines heat from the rock. The hot water may serve for direct thermal use or to produce electricity. Typically, the water is recirculated through the reservoir to mine more heat.

Since 1974, work on HDR has been directed toward demonstration and perfecting the HDR heat mining technique. A small system (Phase I) was developed in the early years to show that the process was feasible. During the 1980s, a larger underground reservoir (Phase II) was created and a surface plant was constructed. A long-term flow testing program (LTFT) is now underway to prove that, in addition to energy production being possible, the technology is also practical. The LTFT should address important issues including: (1) sustainability of energy delivery, (2) water consumption, (3) impedance to flow, and, (4) long-term operational characteristics.

With an aggressive program, the technology could be fully commercial by the year 2000. A 1990 interlaboratory white paper (SERI/TP-260-3674) estimated that, under such conditions, 0.23 quads (more than 65 million megawatt-hours) of primary energy for electricity generation could be produced from HDR by 2010, and 0.94 quads (more than 275 million megawatt-hours) by 2020. Thermal energy uses could amount to another 0.13 and 0.32 quads in 2010 and 2020, respectively. Electric power could be provided at estimated costs as low as 3-4 cents/KWh (Tester and Herzog, MIT-EL-90-001, 1990) for multi-well plants.

Objectives

- **To evaluate the sustained performance of the Fenton Hill Phase II HDR reservoir with regard to system operating characteristics including energy production, thermal lifetime, flow impedance, and water loss.**
- **To evaluate the economics of the technology in light of the most recent technical developments.**
- **To confirm the environmental acceptability of the technology.**

Objectives (continued)

- To evaluate the various modes of operation of HDR systems, such as continuous, cyclic, and high backpressure, for efficiency, power potential, effect on reservoir lifetime, and operational reliability.
- To show the general application of HDR technology by demonstration at a second site in a different geographical setting with different geological characteristics.
- To evaluate the concept of multiple production wells per single injection well as a means to significantly improve system performance and economics.
- To develop reservoir modeling, seismic analyses, tracer techniques and logging technology, and to demonstrate their utility in the development of HDR systems and to the geothermal industry in general.
- To improve the performance of drilling and completion operations under conditions typical of hot dry rock environments.

Expected Outcome

- An understanding of how to build, characterize and operate HDR production systems.
- Demonstrated economic potential so that the private sector will see the economic benefits of investing in HDR power plants.
- An energy producing demonstration plant constructed jointly with private industry and operating at economically competitive costs.

APPROACH

The LANL research team has constructed a pilot-scale reservoir and a surface plant built to industrial specifications. A long-term flow test (LTFT) underway in FY 1992 and FY 1993 will: (1) provide an experimental basis for refining cost estimates; (2) document operational water needs, (3) demonstrate that sustained energy production from HDR is possible; and, (4) point up remaining problems to be attacked.

If the LTFT proves successful, a second site is planned in cooperation with private industry to produce and market electricity from HDR at competitive prices. Subsequently, direct thermal uses of HDR energy will be demonstrated. These efforts will set the stage for additional commercial HDR facilities built entirely with private funding on the basis of sound investment considerations.

The work carried out this past year was in accordance with:

(1) the Fiscal Year 1992 HDR Annual Operating Plan (AOP);
(2) the Long-Term Flow Test Plan as developed in 1992;
(3) the Fenton Hill Site Operations Plan; and,
(4) various environmental, safety, and health documents.

The LANL Hot Dry Rock research consists of five phases:

Phase I (1974-1980) consisted of a feasibility demonstration of the HDR concept at the Fenton Hill site.

Phase II (1981-1986) involved the creation of a much larger, deeper, and hotter underground system. This phase entailed the development of drilling and completion equipment to construct the system, and analytical tools to adequately characterize it.

Phase III (1987-1991) consisted of the construction of a surface facility, built to industrial standards, to enable the underground system to be evaluated under conditions simulating commercial operations.

Phase IV (1992-1994) the present phase, is concerned with demonstrating that HDR can provide energy on a sustainable basis with reasonable quantities of water use. It involves a long-term flow test (LTFT) which will prove that it is practical to commercialize the technology, provide operating experience with which to refine economic models, and identify up remaining problems to be addressed in the construction of HDR plants producing energy for sale.

Phase V (1995-1998) will involve the construction, in cooperation with private industry, of an HDR plant to produce and sell electricity at competitive costs (1995-1997) and of an HDR facility to provide energy from a lower quality resource for direct thermal applications (1996-1998). These plants can be fully competitive in both electricity generation and thermal energy production. At this point, the technology will have both the certainty of success and the operating economics to make commercial HDR facilities attractive for full private-sector support.

RESEARCH STATUS AND FINDINGS

The work to date has resulted in the development of specialized drilling and logging equipment to drill and characterize wells in hard granitic rock. Technologies for fracturing hard rock in a controlled manner have been demonstrated. Tracer, geochemical, and seismic methods have been advanced to the stage that HDR reservoirs can be well characterized in regard to size, dimensions, and many flow characteristics. Models have been constructed based on analytical and operational data to explain the behavior of reservoirs during pressurization and fluid circulation. All of these developments have moved HDR from the purely speculative stage of 20 years ago to a well-grounded, predictable technical state. Flow testing now underway will provide additional information in regard to sustainable heat production

and water consumption, which should set the stage for the construction of an HDR facility capable of producing power at competitive costs.

Researchers completed a number of short- and long-term flow tests to establish operating parameters for the continuous test phase. They conducted the tests under conditions designed to maintain reservoir stability and obtain useful operational data. Tracer results indicate that a significant fraction of the water loss during flow tests goes into the reservoir flow paths, contributing to the heat extraction process. The total volume of all flow paths transmitting fluid from the injection to the production wells increased. This increase could be attributed to thermal contraction of the rock in the region of the outlets to the reservoir from the injection wellbore. Additional flow paths connecting the wellbores may also have contributed to the increased fluid volume. Logging results indicate an increase in fluid access to more remote portions of the reservoir, enhancing its thermal performance. Cooling of the circulating fluid during passage through the production wellbore has proven to be strongly related to the flow rate. There was no net cooling of the production zone of the reservoir. Seismic monitoring verified that the flow tests were not leading to reservoir growth.

INDUSTRY INTEREST AND TECHNOLOGY TRANSFER

Organization	Extent of Interest
Geoelectric Corporation	Interested in being an industrial partner for development of a second HDR site.
Utilities	Representatives of Pacific Gas and Electric, Southern California Edison, San Diego Power and Light, Ellicotville Energy Company, Texas Ohio Power Company, Iowa Power and Light, and Plains Electric have all expressed interest in HDR in the past year.
Other Industry	Other industrial contacts during the past year have included UNOCAL, ASARCO, Copar Pumice, Aggieland Saltwater Disposal, Cold-Water Operating Company, and Thermasource.

IMPLICATIONS FOR FUTURE DEVELOPMENT

The project has advanced through a long research and development phase to a demonstration stage. An idea (the extraction of the thermal energy of the earth) has been transformed into reality in the form of the Fenton Hill HDR site. The final steps in the process entail a convincing demonstration that HDR technology can provide energy on a sustainable basis. The establishment of a second HDR facility in the United States would establish that the technology can be implemented in a variety of geographic and geological settings. The long-term flow test at Fenton Hill is currently demonstrating sustainable energy production. With adequate funding, an industrial partnership can be formed to construct an HDR plant to produce and market power. Work on the development of the facility could begin in 1995 and be operational by 1997.

PUBLICATIONS AND PRESENTATIONS

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