Geothermal Energy R&D Program

Annual Progress Report for Fiscal Year 1989

DRAFT

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Geothermal Technology Division
U.S. Department of Energy

Geothermal Energy R&D Program

Annual Progress Report for Fiscal Year 1989

DRAFT

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EXECUTIVE SUMMARY

This Annual Progress Report presents the research and development accomplishments of the U.S. Department of Energy's (DOE) Geothermal Energy R&D Program for Fiscal Year 1989. Its purpose is to provide a record of progress made toward meeting the research objectives previously established for the Geothermal Program.

Three levels of research objectives are applied to the Geothermal R&D Program, as defined in *Programmatic Objectives of the Geothermal Technology Division* (May 1989). Level I objectives are associated with geothermal resource categories and provide a target for decreasing the total cost of electric power generated from a particular type of resource. Level II objectives address incremental improvements in the cost and/or performance of major system components which comprise a geothermal power project. Level III objectives identify individual research activity targets for improvements in the cost, efficiency, and dependability of materials, tools, equipment, tests, and processes related to major system components. The Level III objectives and associated research activities are the most dynamic part of each year's program and provide a basis for documenting progress against the higher level (Levels I and II) objectives.

This Annual Progress Report was prepared from information provided by DOE Geothermal Technology Division program managers and researchers at the national laboratories. The information included the activities performed during FY89 as well as the progress made toward achieving the Level III research objectives. In general, incremental progress is difficult to quantify. Therefore, to the extent possible, the discussions of FY89 achievements present the qualitative value of the progress made against the governing research objectives.

The significant research accomplishments achieved in each resource category during FY89 include:

Hydrothermal Research

- Conducted a multi-well tracer test in the Dixie Valley geothermal field which examined the stability of four new tracers, tested automatic sampling equipment, demonstrated the breakthrough of a tracer between an injection well and a production well, and verified the usefulness of the new tracer methodology.

- Demonstrated the technique of integrating fluid inclusion data with chemical analyses of produced fluids to develop detailed geochemical and hydrogeologic models, and applied this technology to map fluid and steam distributions and recharge areas for both the Coso Hot Springs and Los Azufres geothermal systems.

- Conceptualized a system which will inject a cementitious mud accelerator and bridging materials downhole for lost circulation control.

Geopressured-Geothermal Research

- Constructed the Pleasant Bayou hybrid power system (1-MWe) and initiated testing.

- Began an industrial consortium for the utilization of geopressured-geothermal resources.

Hot Dry Rock Research

- Reanalyzed microearthquakes from the massive hydraulic fracturing experiment using improved mapping methods and the 3-point method, and initiated a programming effort toward automation.

Magma Energy Research

- Completed Phase I drilling at Long Valley to a bottomhole depth of 2,568 feet and initiated joint coring activities with participating groups (NSF, USGS, and DOE/OBES).

Future geothermal R&D will focus on technology for expanding the commercial development of geothermal resources. This will be accomplished through increased cost sharing of R&D with industry. Progress and achievements resulting from these activities will be documented in future releases of the Annual Progress Report.

SECTION I

INTRODUCTION

PURPOSE

Since 1971, the Geothermal Technology Division of the Department of Energy and its predecessor agencies have conducted a program of research in geothermal energy technology. The program functions on the basis of law which mandates the performance of activities for the purpose of providing an acceptable economic alternative source of energy for the nation. Considerable progress has been achieved in carrying out that mandate.

This Annual Progress Report presents the research and development accomplishments of the Geothermal Energy R&D Program during Fiscal Year 1989. Its purpose is to provide a record of progress made toward meeting the research objectives established within each geothermal resource category. The report summarizes geothermal activities funded and directed by the Geothermal Technology Division. Detailed information on the specific activities can be obtained by referring to the individual annual progress reports prepared by the research organizations or published technical papers which resulted from the research efforts.

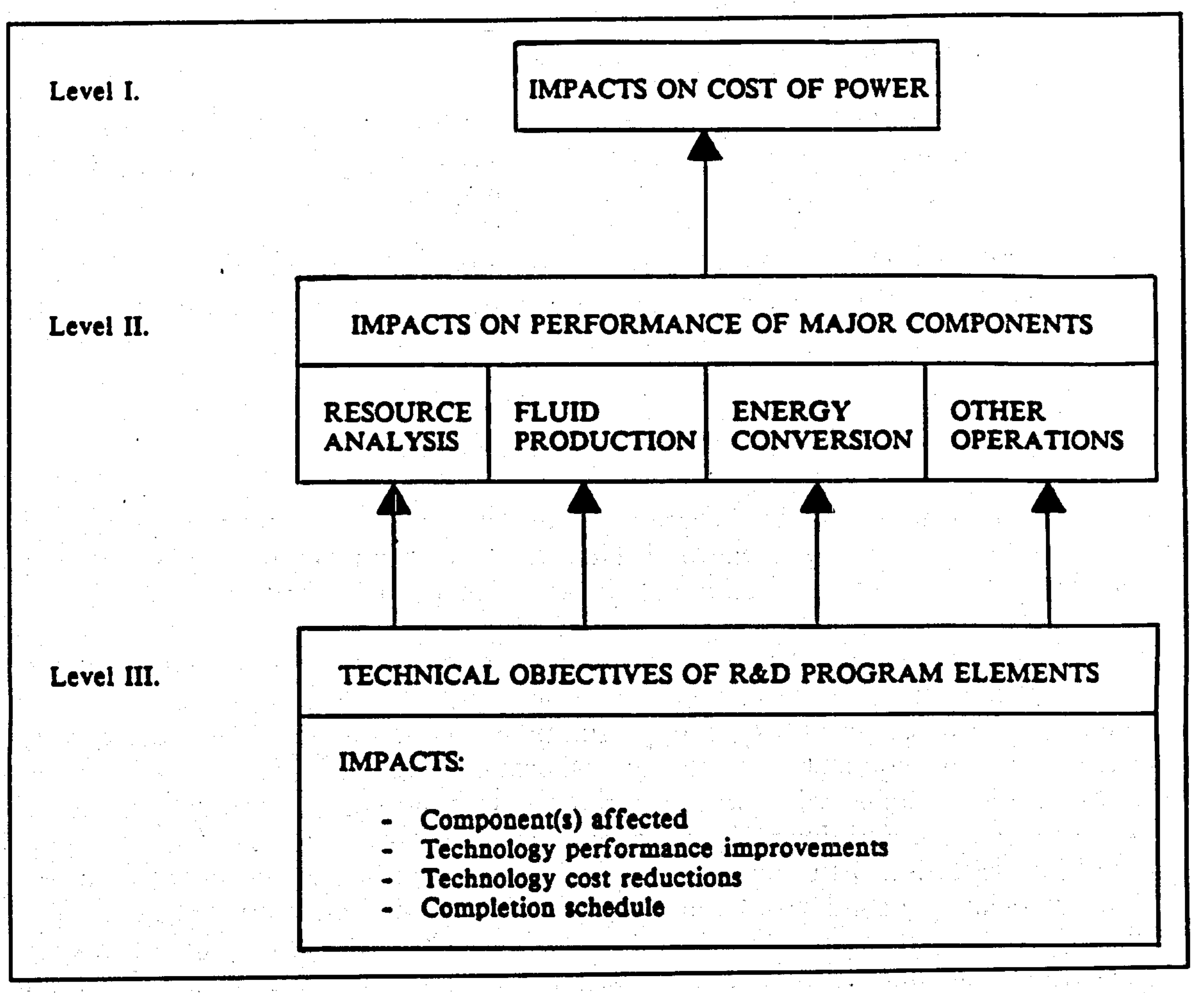
Section I of the report presents an overview of the Geothermal Energy R&D Program. It includes a summary of the program methodology employing research objectives, the program elements, and the program budget and management. Section II presents the FY89 achievements within each resource category (hydrothermal, geopressured-geothermal, hot dry rock, and magma energy). The task description, applicable research objectives, fiscal year accomplishments, and future plans are presented in the report for each task in the FY89 R&D program. Appendix A contains the key participants in the Geothermal Program. A summary of the legislative mandates relevant to the Geothermal Energy R&D Program and commercial geothermal development is provided in Appendix B. Appendix C consists of a listing, by resource category, of major reports and papers published as a result of the FY89 research activities.

BASIS FOR OBJECTIVES

The Geothermal Technology Division (GTD) of the Department of Energy employs management by objectives in the administration of its research program. Program objectives are defined on three separate levels as illustrated in Figure 1. Level I objectives are associated with geothermal resource categories and provide a target for decreasing the total cost of electric power generated from a particular type of resource. Level II objectives address incremental improvements in the cost and/or performance of major system components which comprise a geothermal power project. Level III objectives identify individual research activity targets for improvements in the cost, efficiency, and dependability of materials, tools, equipment, tests, and processes related to major system components.

FIGURE 1

GEOTHERMAL RESEARCH OBJECTIVES HIERARCHY



The achievement of Level I objectives depends on the achievement of the Level II and Level III objectives. The Level III objectives and associated research activities are the most dynamic part of each year's program and provide the basis for documenting progress. This document primarily addresses these activities. As of FY 1989, the Level I objectives[1] for each resource category are:

- **Hydrothermal** - The overall objective of the program is to reduce the cost of electric power from liquid-dominated, moderate-temperature hydrothermal resources to 3-7 cents per kilowatt-hour (kWh) by 1992. This compares with a cost range of 4-18 cents/kWh for hydrothermal electric power as of 1986.

- **Geopressured-Geothermal** - The objective is to improve the technology for producing energy from the geopressured-geothermal resource to a cost equivalent of 6-10 cents/kWh by 1995.

- **Hot Dry Rock** - The objective of hot dry rock R&D is to provide the technology to enable industrial hot dry rock projects to generate power at the equivalent of 5-8 cents/kWh by 1997.

- **Magma** - The R&D objective is the creation of a technology by which energy could be produced experimentally from magma at an equivalent cost of 10-20 cents/kWh by the year 2000.

PROGRAM OVERVIEW

The Geothermal Energy R&D Program is organized by the four resource types: Hydrothermal, Geopressured-Geothermal, Hot Dry Rock, and Magma. These categories, as shown in Figure 2, are further subdivided into projects, tasks, and activities.

The **Hydrothermal** category embraces four interrelated research projects: Industrialization, Hard Rock Penetration, Reservoir Technology, and Conversion Technology. The Industrialization project provides an opportunity for cooperative assistance in various commercial tasks in connection with hydrothermal development. The Hard Rock Penetration project deals with lost circulation methodologies and materials, rock penetration mechanics, and downhole instrumentation. This project also includes priority cost-shared industrial R&D through the auspices of the Geothermal Drilling Organization (GDO), an association of industrial concerns. The Reservoir Technology project supports research on geophysical interpretation and modeling techniques, injectivity and extended well life, and cost-shared industrial research through the Geothermal Technology Organization, a group patterned after the GDO. The Conversion Technology project addresses geofluid efficiencies in binary plants, cooling water makeup requirements,

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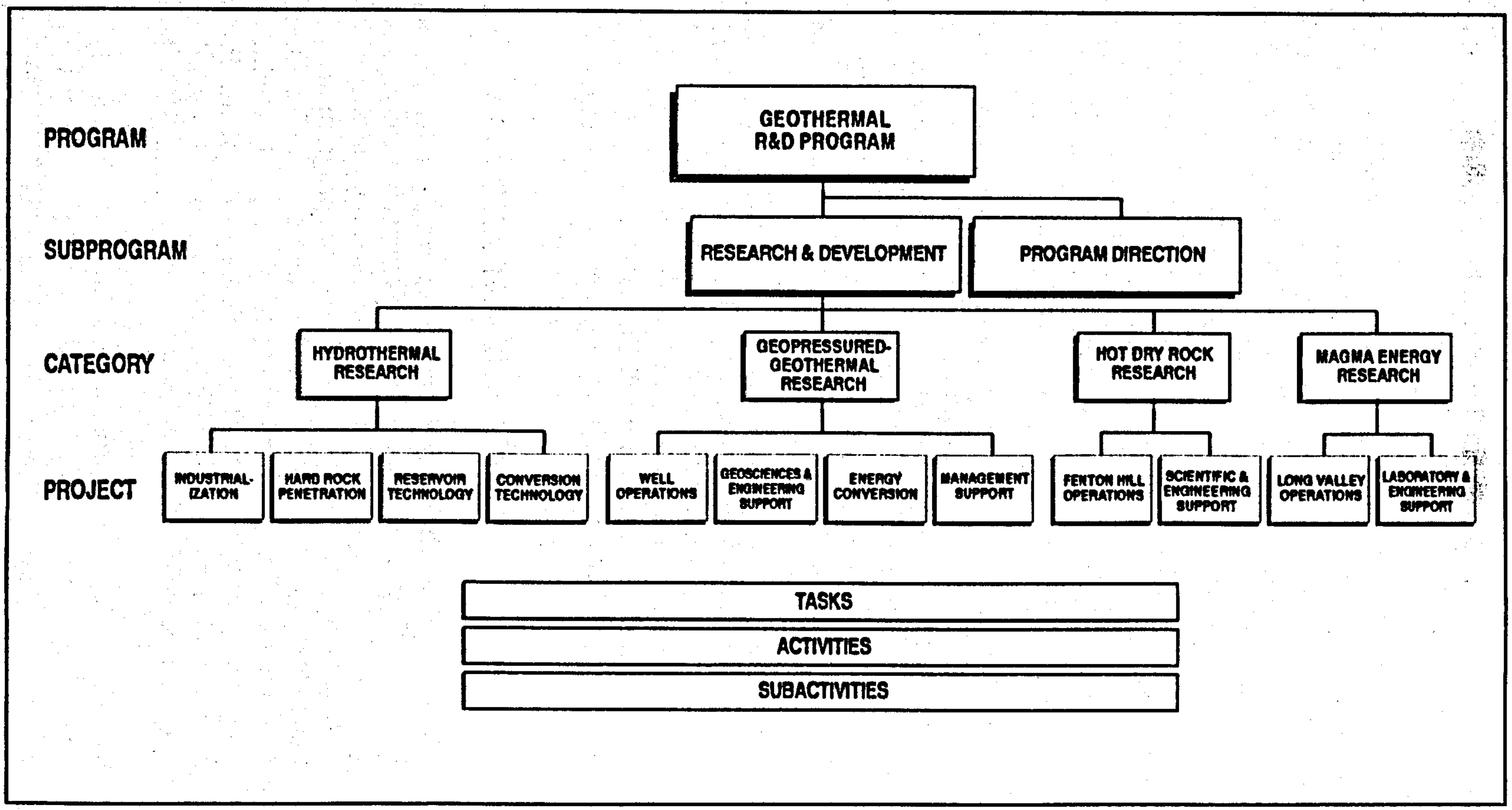
[1] Objectives at all levels are subject to review and revision. The objectives listed in this report reflect the policies and direction provided in FY89. These objectives may not be totally consistent with those in place at the time the report is issued.

FIGURE 2
GEOTHERMAL ENERGY R&D PROGRAM
WORK BREAKDOWN STRUCTURE



geothermal materials needs, thermodynamic behavior of geothermal brines, and techniques for handling residual waste.

Geopressured-Geothermal research includes four projects: Well Operations, Geosciences and Engineering Support, Energy Conversion, and Management Support. The Well Operations project conducts field experiments which demonstrate the viability of long-term fluid production for commercialization of geopressured-geothermal reservoirs. The Geosciences and Engineering Support project involves the refinement of predictive models for reservoir performance, research on rock mechanics, hydrocarbon studies, and environmental effects monitoring. The Energy Conversion project supports construction and operation of the Pleasant Bayou Hybrid Power System in Texas, which uses geopressured brines, including dissolved methane, to produce electric power -- the first plant of its kind in the world. The Management Support project provides general administration and technology exchange activities.

The **Hot Dry Rock** category is composed of two projects: Fenton Hill Operations and Scientific and Engineering Support. The Fenton Hill Operations project supports the second phase of the energy extraction system along with necessary ancillary activities at the Fenton Hill site near Valles Caldera, New Mexico. The Scientific and Engineering Support project involves the design and modification of tools and instrumentation, tracer studies, reservoir engineering work, and other technology support activities.

Magma Energy research is also composed of two projects: Long Valley Operations and Laboratory and Engineering Support. The Long Valley Operations project handles the drilling and completion of an exploratory magma well at Long Valley caldera in California, including essential geoscience investigations. The Laboratory and Engineering Support project encompasses research on drilling techniques, geochemistry and materials, energy extraction, and other activities involving magma technology.

PROGRAM BUDGET AND MANAGEMENT

The Geothermal Technology Division operates under the administrative oversight of Assistant Secretary for Conservation and Renewable Energy, as depicted in Figure 3. The Division Director implements energy research policy at the program level and allocates the necessary technical and budgetary resources for program activities. The Division Director also establishes operating policy for the operations offices and national laboratories and approves annual plans for performing their assigned activities, providing the centralized leadership necessary to ensure that implementation of the Program conforms to national energy policy, priorities, and directives. Table 1 overviews the resources for the Geothermal Energy R&D Program for FY86 through FY90 by resource category.

For management purposes, program categories sharing closely related technology interests are grouped into two R&D teams at the division: Geosciences Research and Energy Conversion Research. The categories comprising each team, their managers, and team leaders are identified in Figure 4. Management of technical activities is decentralized so that specialized technical expertise can be utilized to implement research tasks.

FIGURE 3
GEOTHERMAL R&D PROGRAM PARTICIPANTS

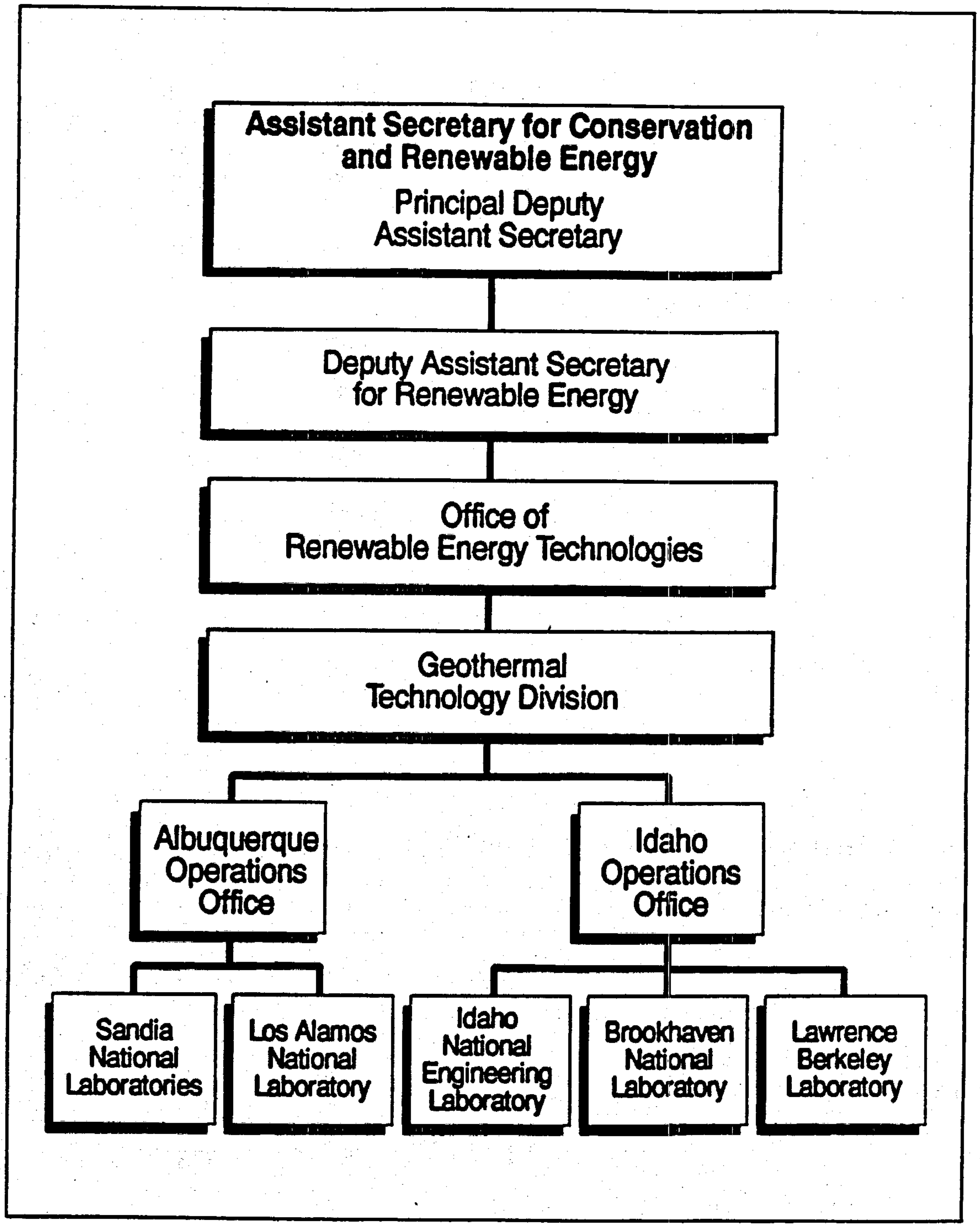


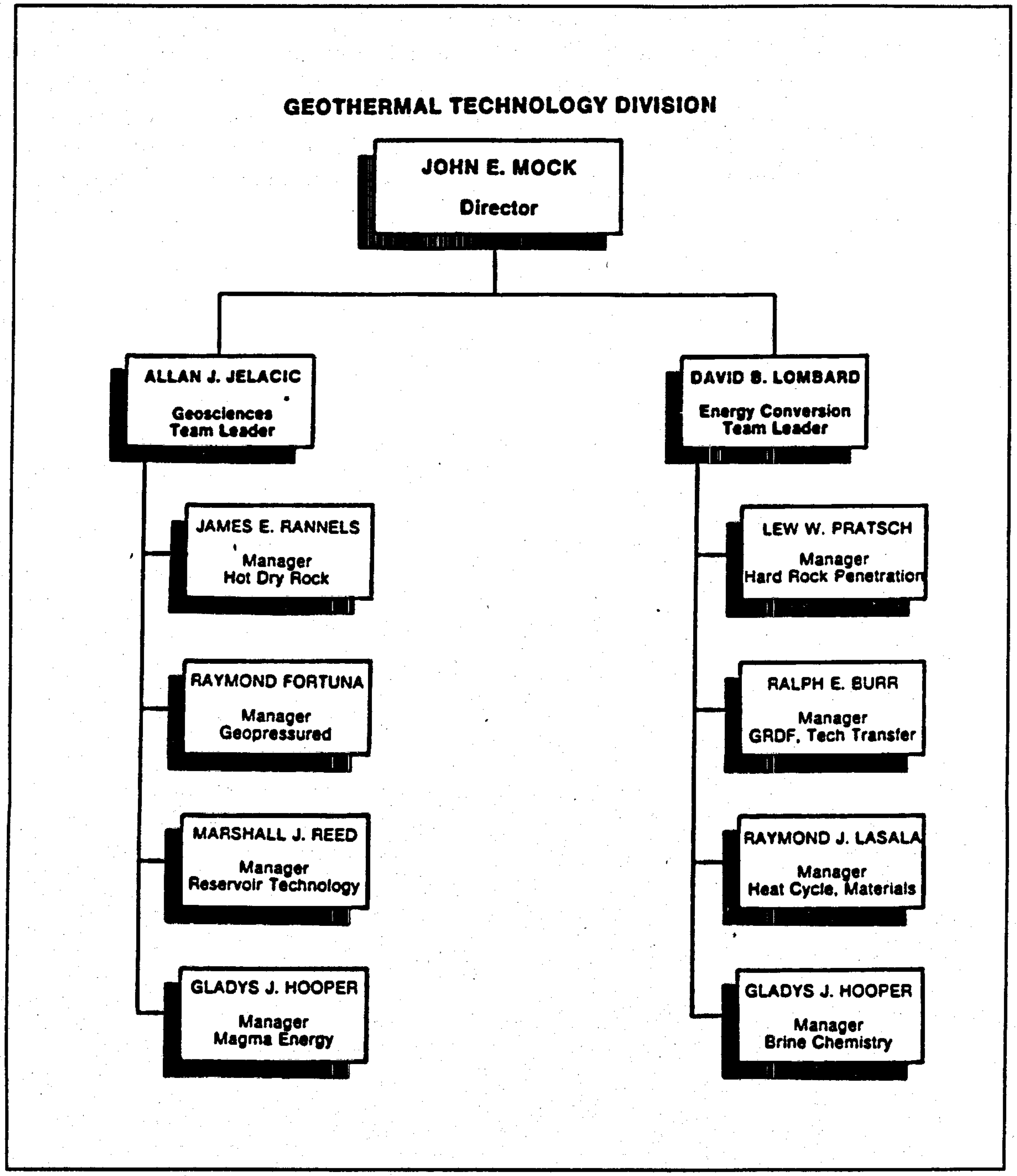
TABLE 1

GEOTHERMAL RESEARCH & DEVELOPMENT BUDGET
($1000)

	Actual				Est.
	FY86	FY87	FY88	FY89	FY90
HYDROTHERMAL:					
Industrialization	1,525	1,980	0	0	0
Hard Rock Penetration	2,415	1,350	1,800	2,250	2,233
Reservoir Technology	6,269	3,105	4,500	2,450	2,098
Conversion Technology	1,250	1,065	1,600	1,935	1,544
TOTAL	**11,459**	**7,500**	**7,900**	**6,635**	**5,875**
GEOPRESSURED-GEOTHERMAL:					
Well Operations	2,832	2,734	2,921	6,698	2,898
Geosciences & Engineering Support	1,087	781	1,164	1,504	1,826
Energy Conversion	108		538	1678	644
Management Support	399	455	377	500	487
TOTAL	**4,426**	**3,970**	**5,000**	**10,380**	**5,855**
HOT DRY ROCK:					
Fenton Hill Operations	4,578	3,916	3,876	2,520	2,570
Scientific & Engineering Support	2,206	2,959	1,344	980	856
Reserve & Misc.	847	1,125	580	0	0
TOTAL	**7,631**	**8,000**	**5,800**	**3,500**	**3,426**
MAGMA:					
Long Valley Operations	597	0	905	1,300	1,461
Laboratory & Engineering Support	1,200	480	495	335	202
TOTAL	**1,797**	**480**	**1,400**	**1,635**	**1,663**
OTHER:					
Capital Equipment	481	0	0	795	444
Program Direction	701	780	835	826	814
TOTAL:	**1,182**	**780**	**835**	**1,621**	**1,258**
TOTAL GEOTHERMAL R&D	**26,495**	**20,730**	**20,935**	**23,771**	**18,077**

FIGURE 4

MANAGEMENT STRUCTURE OF THE GEOTHERMAL TECHNOLOGY PROGRAM



Management also ensures that the technical activities are directed toward achieving all levels of the R&D programmatic objectives. DOE operations offices and national laboratories perform the management and technical activities. Field organizations implement program plans, execute prime contracts for R&D, direct contractors and review their performance, and provide the Geothermal Technology Division with recommendations on program needs and direction.

The division sponsors an annual program review to provide an opportunity for operations offices, national laboratories, universities, and industry contractors to present updates on their activities. It also issues this Annual Progress Report, the Annual Program Summary, and various other documents on a regular basis, publishes numerous technical papers, and supports organizations, such as the Geothermal Drilling Organization and the Geothermal Technology Organization, to ensure continual and effective exchange of information among interested parties.

SECTION II

GEOTHERMAL R&D ACHIEVEMENTS

FISCAL YEAR 1989

HYDROTHERMAL RESEARCH

In recent years, the geothermal industry has made appreciable strides in locating and developing hydrothermal reservoirs. However, even in relatively mature reservoirs such as The Geysers, unexpected drops in reservoir pressure and increased corrosivity of produced fluids have created needs for supporting research. In other geothermal systems, the lack of techniques to locate and characterize fractures, to define reservoir boundaries, to assess fluid recharge, and to understand complex reservoirs has resulted in low drilling success rates and consequently, high drilling costs. Many reservoirs have not reached full production potential because they cannot be sufficiently characterized to allow development of effective exploitation strategies.

The purpose of the hydrothermal research activities sponsored by the Geothermal Technology Division is to aid the geothermal industry by developing better means to explore for geothermal resources, to access these resources economically, to analyze the performance of existing reservoirs, to predict and manage the effects of injection of spent geothermal fluids, and to efficiently convert the geothermal heat into useful energy. These hydrothermal research efforts are organized into four interrelated projects and 15 tasks, as shown in Figure 5. The individual task activities are conducted to jointly accomplish the Level I objective to:

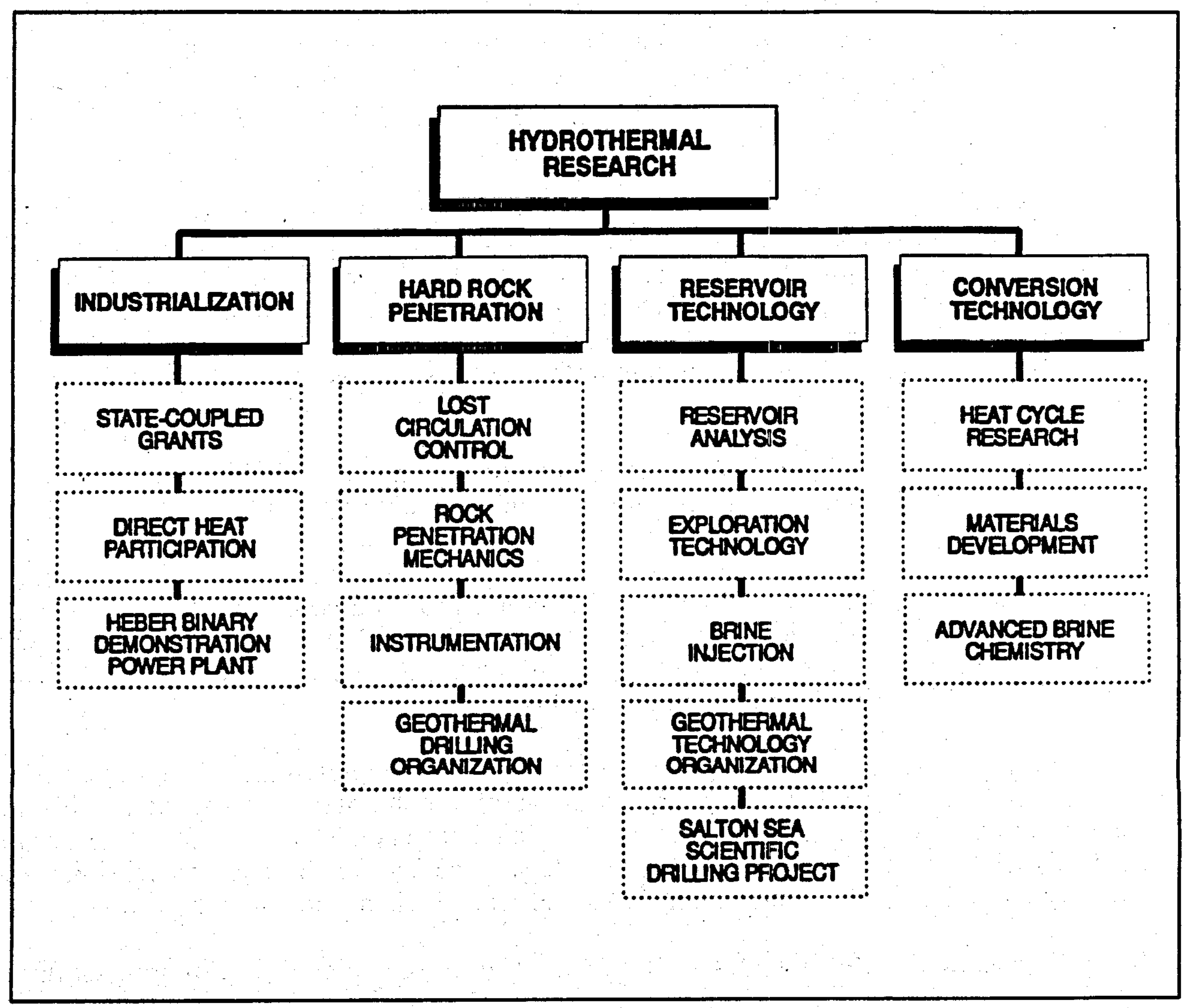
> **Reduce the life-cycle cost of producing electricity from liquid-dominated, hydrothermal resources to 3 to 7 cents/kWh by 1992.**

A two-fold strategy is used to attain this objective: (1) fund cost-shared research with industry in areas of greatest current need, and (2) conduct research to meet the higher-risk and longer-term needs of the geothermal industry. This approach satisfies the need for specific technology that can, in the short term, have a high probability of yielding market opportunities and economic benefits to the industry and, in the long term, provide a degree of energy security.

INDUSTRIALIZATION

The Industrialization project provides technical and financial assistance to programs which demonstrate and promote the commercial application of geothermal energy. There are three tasks associated with this project. The **State-Coupled Grants** task provides funds to state agencies for cost-shared research within their purview. **Direct Heat Participation** provides technical assistance to businesses and individuals for the development of nonelectric applications that utilize low- to moderate-temperature resources. The **Heber Binary Demonstration Power Plant** is a 45-MWe demonstration of binary conversion technology funded by DOE and the electric utility industry.

FIGURE 5
HYDROTHERMAL RESEARCH
WORK BREAKDOWN STRUCTURE



State-Coupled Grants

Task Description
Funding was provided to several state agencies for the State Cooperative Reservoir Analysis Program. In this cost-shared research, the state researchers develop a greater knowledge of and information base for the geothermal resources within their purview. Most of this research is directed toward low- and moderate-temperature (less than 150°C) geothermal systems which can be used directly as a source of thermal energy. Current research groups are: University of Alaska (Geophysical Institute), Alaska Division of Geological and Geophysical Surveys, Idaho Department of Water Resources, University of Hawaii (Institute of Geophysics), University of Nevada (Desert Research Institute), University of Nevada (Division of Earth Science), New Mexico Research and Development Institute, University of North Dakota, Utah Geological and Mineral Survey, Washington Division of Geology and Earth Resources, and University of Wyoming.

Fiscal Year Accomplishments
A cooperative resource assessment of Geyser Bight in the Aleutian Islands was completed by the Alaska Division of Geological and Geophysical Surveys and the Geophysical Institute. These two agencies conducted geological, geophysical, and geochemical studies to characterize the largest hydrothermal system in Alaska. Results show two separate reservoirs in the system, and a new fumarole field was discovered 4 km south of the main system.

Idaho Department of Water Resources completed a data review and numerical simulation of the Boise geothermal system, and a geochemical study of the Wood River geothermal system is nearly complete.

Researchers at the Hawaii Institute of Geophysics reported considerable progress on the control of silica precipitation from fluids produced at the Puna geothermal system on the Island of Hawaii. Using their experimental data, the geochemists have completed a preliminary design of a brine treatment facility.

University of Nevada (Earth Science) researchers have completed a study to determine the genesis of hydrothermal fluids in the major geothermal systems of Nevada. This study integrated carbon-14 dating, stable isotopes, and fluid chemistry to identify the origin of hydrothermal water. Results indicate late Pleistocene age for the geothermal fluids and a recharge system along basin margin faults and from Pleistocene lakes.

Hydrologists at the Nevada Desert Research Institute completed a 13-month monitoring program to measure fluid production and pressure changes in the Moana geothermal system in Reno, Nevada. This monitoring data will be combined with geologic information for the area to develop a numerical model to predict future reservoir changes in response to development.

New Mexico State University researchers are performing soil gas surveys to evaluate time-integrated radon measurements for use in a geothermal resource assessment of the southern Rio Grande rift. The radon survey has resulted in the discovery of a subsurface temperature anomaly which has been confirmed by drilling.

University of North Dakota geophysicists drilled eight heat flow holes in South Dakota and two in North Dakota to understand the distribution of geothermal resources in the Williston Basin. Researchers have also measured the temperature distribution in several holes of opportunity to determine regional heat flow. A geothermal resources map of South Dakota is in the final phase of preparation.

Utah Geological and Mineral Survey investigators completed a study delineating the low-temperature geothermal resources in the Newcastle area of southwest Utah. This detailed characterization of the Newcastle resource combined investigations of fluid chemistry, hydrology, structure, geophysics, and soil chemistry.

Washington Division of Geology and Earth Resources completed the analysis of eight temperature gradient holes in the southern Washington Cascades. A study was completed that integrated radiometric dating, geologic mapping, and water chemistry data from the Indian Heaven Quaternary volcanic field to evaluate magmatic activities.

The University of Wyoming is developing an improved three-dimensional model for evaluation of heat conduction combined with convective heat and mass transfer to determine subsurface temperatures in geothermal systems.

Future Plans
Activities in the State-Coupled Grants task no longer receive funding from congressional appropriations. The work has entered its final phase and the task should essentially conclude in FY90.

Direct Heat Participation

Task Description
The Direct Heat Participation task provides technical assistance to businesses and individuals for geothermal resource development using low- to moderate-temperature brines. Direct heat applications include space and district heating systems, greenhouses, aquaculture applications, and geothermal heat pumps.

Fiscal Year Accomplishments
The Geo-Heat Center at the Oregon Institute of Technology continued to provide technical assistance for direct heat applications. Hundreds of inquiries were received for technical information pertaining to the direct use of geothermal resources. Efforts were initiated with the National Rural Electric Cooperative Association (NRECA) to develop techniques for low-cost vertical drilling for installation of geothermal heat pump systems. The goal is

to develop a drilling system which will permit a vertical loop system to be installed in one day.

Future Plans
FY90 activities include an assessment of low- to moderate-temperature reservoirs, as well as geopressured-geothermal resources, located near population centers.

Heber Binary Demonstration Power Plant

Task Description
The Heber Binary Demonstration Power Plant is a cost-shared demonstration task involving DOE and the electric utility industry (principally the San Diego Gas and Electric Company [SDG&E] and the Electric Power Research Institute). The participants have built a 45-MW geothermal power plant based on binary cycle conversion technology near the town of Heber in California's Imperial Valley. Chevron Geothermal Company owns the geothermal reservoir and has contracted with SDG&E to supply hot brine.

Fiscal Year Accomplishments
Construction of the plant has been completed for some time. To date, it has operated at half of its capacity with a plant availability of over 90 percent. Chevron has stated that because of unforeseen difficulty with the reservoir there would be a delay of about two years in providing 100 percent of the brine requirements. SDG&E stated that such a delay would be too costly and has put the plant up for sale. It has been shut down since 1987.

Future Plans
Efforts will continue to find a buyer for the plant. After the plant is sold, or if SDG&E decides to operate the plant, DOE plans to arrange for publication of technical operating data based on the commercial operation.

HARD ROCK PENETRATION

A significant percentage of the cost of generating electricity from geothermal resources is associated with drilling and completing wells for exploration, production, and injection. Current drilling and completion technology is derived primarily from the oil and gas industry and often does not perform well in the hostile geothermal environment which includes high temperatures, hard rock, and highly corrosive fluids. The Hard Rock Penetration project addresses these elements and assists in the development of drilling and completion technology that will result in a considerable reduction in the cost of geothermal wells in order to achieve the Level II objective to :

> **Reduce the life-cycle cost of hydrothermal electricity by 10 to 13 percent through improvements in fluid production technology by 1992.**

The most costly problem routinely encountered in geothermal drilling is lost circulation, whereby drilling fluid used for cooling the bit and flushing rock chips out of the borehole is lost to the rock formation rather than circulated to the surface. This loss of fluid is expensive in terms of drilling fluid costs and can cause other problems, such as loss of continuity and integrity of the cement used to bond the wellbore casing to the rock formation. These problems can lead to casing failure. The **Lost Circulation Control task** supports research which fosters the development of plugging materials and techniques applicable to massive or small aperture lost circulation zones.

In addition to these activities, the **Rock Penetration Mechanics** task investigates advanced drilling techniques and improved core recovery technology. The **Instrumentation task** develops sophisticated tools and probes for operating in high temperature boreholes and for identifying fractures and formation boundaries. Those items which are anticipated to make near-term contributions to geothermal drilling or have near-term commercialization potential are often sponsored by the **Geothermal Drilling Organization**, a nonprofit consortium whose membership is drawn from the geothermal and drilling industries.

Lost Circulation Control

Task Description

Approaches to controlling lost circulation include the development of lost circulation materials, pumpable setting fluids, polyurethane foams, cements, and the placement of lost circulation materials. The Level III objective of the Lost Circulation Control task is to:

Reduce costs associated with lost circulation episodes by 30 percent by 1992.

Methods for lost circulation control and recovery will be pursued to reduce drilling time lost in diagnosing and ameliorating lost circulation problems in zones dominated by minor fractures as well as those consisting of large fractures, vugs, and caverns. The R&D efforts include evaluating the high-temperature plugging characteristics of specific lost circulation materials; characterizing lost circulation hydraulics and zones by developing wellbore hydraulics models for evaluating drilling fluid losses; developing hardware/software to acquire and analyze on-site drilling data; comparing hydraulic model predictions with physical attributes; and conducting full-scale laboratory and field tests using foams, cements, and pumpable setting fluids.

Many potential lost circulation materials have been tested for high temperature and pressure durability, and fracture plugging capabilities. Recent tests indicated that lost circulation material performance is often improved by using a mixture of different materials, sizes, and shapes. A pumpable cement test facility is being designed to duplicate typical field conditions, with testing of cements to start in late 1989.

Fiscal Year Accomplishments

Researchers designed and fabricated a high differential pressure cement tester for evaluating cementitious muds using an encapsulated accelerator for lost circulation control.

A concept was developed and a patent application filed for a system to inject a cementitious mud and bridging particles downhole. The particles will be larger than the current limitations of one-third the bit nozzle diameter.

A patent application was filed for a porous packer concept, illustrated in Figure 6, that may prevent excessive mixing downhole and allow a foam or other material to be successful in eliminating lost circulation areas. To date, polyurethane foams fail to expand many-fold when mixed with the ambient water under high pressure.

Investigators successfully tested a composite ground tire rubber lost circulation material at the Long Valley, California, well. The ground tire rubber sealed lost circulation zones where other traditional lost circulation materials were unsuccessful. The importance of solving lost circulation was demonstrated at the Long Valley site -- about half of the total drilling cost was attributed to lost circulation problems.

Researchers developed flow models for cementitious muds in planar and radial fractures in an effort to understand the dynamics of lost circulation setting fluids under downhole conditions.

Future Plans
The development of a computer model of transient wellbore hydraulics will continue. Work will concentrate on transient testing methods that may be capable of providing information to identify and characterize lost circulation zones in order to determine the most cost-effective treatment.

Identification and testing of various lost circulation materials will continue. The activities will include testing to determine the plugging characteristics at room temperature and at elevated temperatures.

The development of rapid-setting cementitious muds for lost circulation control will continue. The high differential pressure cement tester will be used to test the capability of the bit nozzle shear stresses to strip the encapsulation of the accelerator and start the cement-hardening reaction downhole. Analytical work will continue to develop practical flow models capable of predicting the setting of cementitious muds in the high temperature fracture environment.

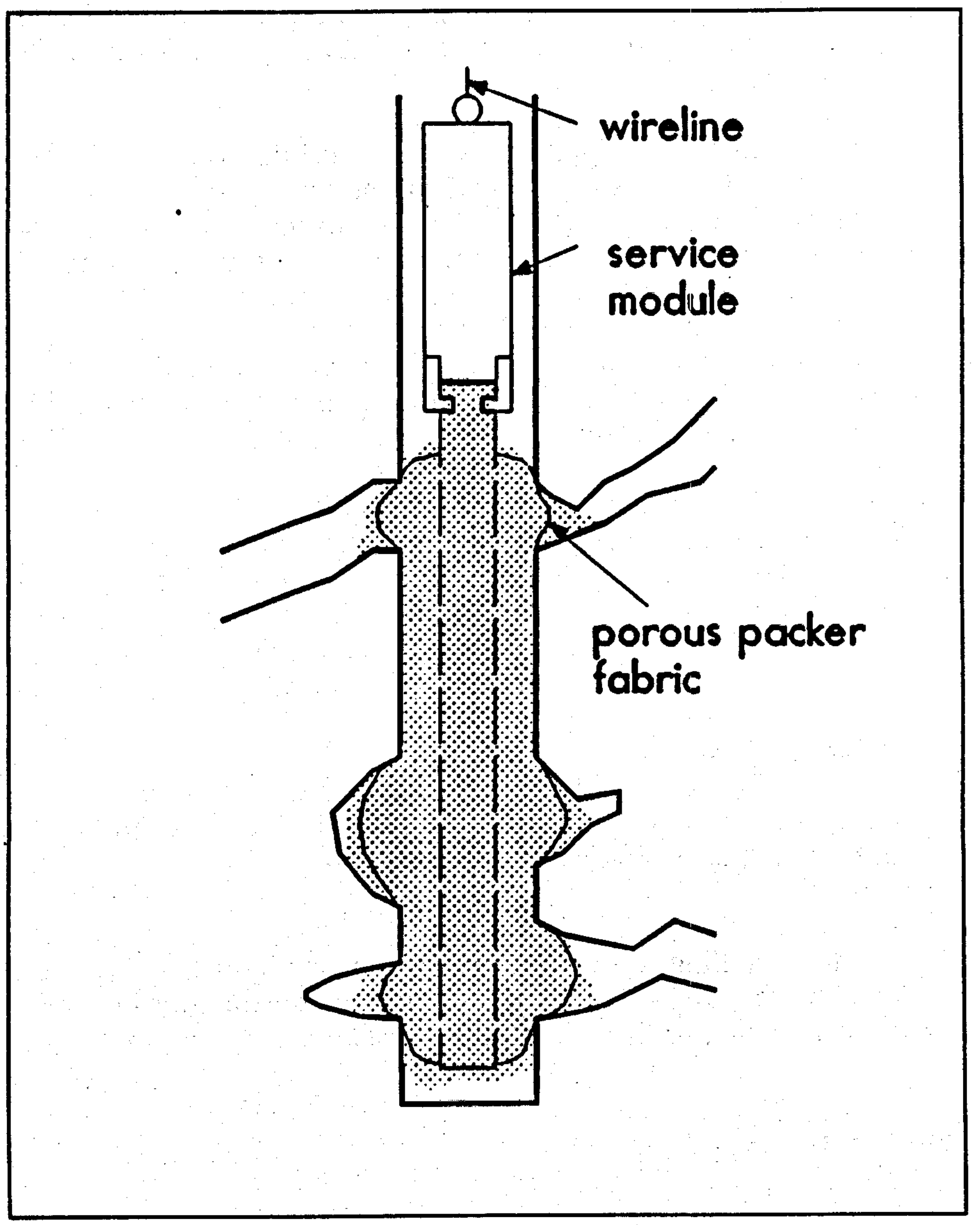
Work will also continue to determine the feasibility of the porous packer concept and, if feasible, to develop the hardware necessary to deploy the concept in the field. Laboratory testing will be conducted to evaluate candidate porous packer materials and associated hardware.

Rock Penetration Mechanics

Task Description
Conventional drilling fluids, drill strings, and hole stability are adversely affected by deep, hot formations, and drilling wells in this environment is costly. This task supports studies

FIGURE 6

SCHEMATIC OF POROUS PACKER CONCEPT



of advanced drilling concepts, improvements in coring technology for exploration, and investigations of methods for transmitting data to the surface while drilling. The Level III objective of the Rock Penetration Mechanics task is to:

> **Reduce costs of deep wells and directionally drilled wells by 10 percent by 1992.**

By directly measuring the environment and bottomhole forces, better tool design, selection of components and drilling parameters, and trajectory predictions are conceivable. Research efforts include the development of advanced data transmission methods for measurement while drilling systems and incremental advancements in drilling and coring systems.

Measurement while drilling can significantly reduce drilling times and costs. Mud pulse systems having transmission rates of one-half to one bit per second are the only reliable, commercially available telemetry systems. The key to improvement of this technology is to increase data transmission rates between the downhole transducers and the surface rig. The transmission characteristics of metal drill strings are not well understood and have hindered the development of an acoustical telemetry system. Previous efforts have provided insight into the transmission characteristics and have enabled the design and fabrication of a set of transducers which may be capable of transmitting data through drill string at rates up to 50 times greater than conventional mud pulse technology.

The development of drilling/coring systems built with insulated drilling pipe is being evaluated. The use of insulated drill pipe will keep the fluid and tubulars cooler than their critical values. Calculations have indicated feasibility, and the concept may be tested using prototype joints of insulated pipe. Working with industry suppliers, two designs were completed for insulated drillpipe in FY89. Prototype pipe will be purchased and the thermal performance and mechanical strength will be evaluated in the laboratory.

Fiscal Year Accomplishments
Both scale-model and full-scale drill string transducers were fabricated. Laboratory tests to send and terminate acoustic signals within the drill pipe were initiated. Active echo cancellation and noise suppression were demonstrated.

Future Plans
Current practices for installing vertical heat exchangers for geothermal (ground source) heat pumps in rock will be evaluated. This will result in recommendations for new development efforts directed at reducing drilling installation costs.

Instrumentation

Task Description
The research activities conducted in the Instrumentation task focus on the development or modification of technology for geothermal exploration. Efforts include the development of

probes to operate in very high temperature environments and tools to map fractures and major boundaries. The Level III objectives are to:

> **Decrease the cost of drilling production-related geothermal wells by about 5 percent by 1992 through better identification of fractures.**
>
> **Decrease the uncertainties in measurements of downhole and wellhead temperature, pressure, and flow measurements for moderate temperature reservoirs by 25 percent by 1990. Decrease the uncertainties for similar measurements at reservoir temperatures greater than 250°C, by 50 percent by 1992.**

Some wells have been drilled as close as 100 to 300 feet from a commercial producer and have failed to encounter commercially by productive fractures. This inability to identify and locate fractures near a wellbore indicates a need for a high-resolution, fracture-mapping technique. Once fractures can be located, directional drilling may turn a dry hole into a producer. Conventional seismic techniques do not provide the necessary resolution. A radar fracture-mapping tool and flow meters will be developed to improve the drilling of the borehole near fracture zones, and thereby improve completion-zone siting.

A prototype wireline radar fracture-mapping tool with high-energy pulse and directional capabilities has been assembled. The tool uses directional antennas for both the transmitter and the receiver to provide both the distance (one-foot accuracy) and direction of a fracture in a downhole application. Recent tests conducted in a rock quarry and a lake demonstrated that the tool does perform as predicted. A second generation tool will be designed using a modular concept with variable antenna spacing, a diameter of less than five inches, and an upgraded electrical system. Additional field tests will be conducted to evaluate the tool's directional characteristics and ability to discriminate a reflecting surface in a fractured formation. Cost-sharing with the private sector will be sought for final development.

Other activities involve pressure and flow rate measurements in geothermal wells which suffer accuracy and reliability problems due to the high downhole temperatures and corrosive fluid environment. Downhole flow measurements using propeller and turbine type flow meters often fail due to the high flow rates and erosion/corrosion. All downhole measurements above 300°C are difficult since this is the practical upper limit for wireline cables. The development of advanced downhole logging instruments capable of withstanding hydrothermal environments is being pursued.

A series of "slickline" tools was developed to measure temperature, pressure, and flow in the DOE Salton Sea Scientific Drilling Project at temperatures up to 400°C. These tools, which store data downhole for later retrieval at the surface, included mechanical Kuster tools for measuring temperature, pressure, and flow; a temperature and pressure tool built around an electronic memory; and a timing and control unit to power a downhole sampler. The electronic tools with downhole memory were found to offer the most promise for future development. The concept of self-contained downhole memory tools will be expanded to develop a modular downhole instrumentation system. This modular system will be designed to meet future instrumentation requirements for the magma energy exploratory well (temperatures up to 500°C). Design of the microprocessor and memory module is under way and testing will start in 1989. Also, fiber optic cables and sensors will be investigated for higher temperature capabilities.

Fiscal Year Accomplishments
The radar fracture mapping tool was extensively redesigned during FY89 to improve field operational characteristics. In addition, the fabrication of new hardware was initiated. This activity was cost-shared with the Nuclear Treaty Verification task.

The high temperature borehole televiewer system was successfully tested in wells in the Salton Sea area at temperatures up to 293°C. The surface data acquisition system for the televiewer, which digitizes, displays, and stores data in real time during logging operations, was completed.

It was successfully demonstrated that downhole memory tools can provide high resolution temperature logs with quality similar to Sandia's precision wireline system.

Future Plans
Fabrication and assembly of the second generation radar fracture-mapping tool will be completed in FY90. Performance evaluation of the tool will commence and will include bench testing of the mechanical hardware and electronic functions, antenna testing, complete systems testing in a uniform medium (water), and complete systems testing in wellbores in fractured media.

The high temperature borehole televiewer will be used to investigate methods for inspection of multi-component casing being used by geothermal operators in the Salton Sea. This study will require televiewer measurements on actual casing samples in the laboratory and data interpretation of multiple reflections.

The downhole memory unit to support a line of modular high temperature tools for geothermal applications above 300°C will be designed and built.

Geothermal Drilling Organization

Task Description
The Geothermal Drilling Organization (GDO), a non-profit consortium of industrial firms, and DOE jointly fund activities which are designed to transfer technology to industry vendors. GDO members often become extensively involved in the field-test phase of these activities which improves the transfer of technology to industry. The Level III objective of this task is to:

> **Develop and transfer other related technology to effect an additional 5 percent reduction in well costs by 1990 and 10 percent by 1992.**

GDO activities currently include an acoustic borehole televiewer, a foam lost circulation tool, a downhole air turbine, and high-temperature elastomer products. Acoustic borehole televiewers are used in water/mud-filled wells to map formation fractures in open boreholes and to inspect internal casing surfaces in cased wells. Two high-temperature televiewers have been fabricated and were initially tested successfully in a 4,000-foot well at 260°C. After additional testing, a logging company will be able to adopt the technology and offer it to the geothermal industry.

Two downhole foam lost circulation tools have been assembled and field testing has been initiated. In field and laboratory tests, a two-component, rigid urethane foam has been shown to be ineffective in bridging and cementing unconsolidated material under downhole conditions. Development of an acceptable foam was not successful.

Downhole air turbines capable of operating in environments up to 260°C have been developed and will be field tested at The Geysers. They were designed to improve directional drilling capabilities and to drill with air in production areas where lost circulation would be a major problem. Three field tests were completed at The Geysers in 1988. Since then, several modifications have been completed, and a third prototype is being designed with testing planned for FY90.

High-temperature elastomers will be fabricated and tested for use as drill pipe protectors, rotating head seals, and blow-out preventors.

Fiscal Year Accomplishments
Drill pipe protectors manufactured using a high-temperature elastomer were successfully tested at a Unocal well at temperatures up to 350°C. The overall performance is superior to the standard drill pipe protectors currently available.

The fourth field test of the downhole pneumatic turbine at The Geysers was completed. This field test led to extensive redesign of the turbine and gear reduction assembly.

A special test fixture was built to evaluate new rotary head seals under actual geothermal well conditions.

Future Plans
A final field test of the redesigned downhole air turbine is planned prior to commercialization.

Full-scale rotary head seals will be fabricated and tested in both geothermal brine and steam environments. Each field test will include 24 hours of drill pipe cycling in the actual environment.

The drill pipe protector activity will be concluded following final testing of the new protectors at The Geysers.

A commercial logging company is being sought to adopt the high-temperature borehole televiewer technology and offer it as a service to geothermal operators.

RESERVOIR TECHNOLOGY

The Reservoir Technology Research project supports basic and applied research to solve reservoir characterization problems which hinder the widespread use of geothermal resources. Project activities focus on the development and verification of new technology for exploration, fluid production and injection, and prediction of reservoir lifetime. These activities are directed at accomplishing the Level II objective to:

> **Reduce the life-cycle cost of hydrothermal electricity by 15 to 22 percent through improvements in exploration and reservoir confirmation technology and procedures by 1992.**

The efforts combine laboratory and analytical investigations with field testing to develop various reservoir techniques and evaluate their utility. Exploration and reservoir assessment techniques developed by the petroleum, mining, and groundwater industries are reviewed and selected for potential application to geothermal systems. New exploration and analytical techniques are developed for specific application to the unique geothermal environment. Validation in the field is critical in determining the usefulness of new technologies developed by the research efforts.

Most of the Reservoir Technology research is conducted by national laboratories, universities, and industrial research organizations. Idaho National Engineering Laboratory (INEL), Lawrence Berkeley Laboratory (LBL), and Stanford University provide research in various aspects of reservoir engineering and the physics of fluid flow. Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory (LLNL), and University of Utah Research Institute (UURI) provide innovative research in geophysics. University of Utah Research Institute and Oak Ridge National Laboratory (ORNL) conduct research in geochemistry and chemical thermodynamics, and University of Utah Research Institute provides a geologic framework for the understanding of geothermal reservoirs. The Reservoir Technology Research program is coordinated with and makes use of the ongoing geothermal research conducted by the U.S. Geological Survey (USGS). During FY89, funds were provided to the USGS to augment the research activities having direct bearing on exploration technology, reservoir analysis, and injection technology.

The Reservoir Technology Research project is divided into five interrelated tasks. **Reservoir Analysis** research seeks to reduce the risks associated with reservoir characterization and reservoir evaluation through the development of analytical techniques and predictive models of the reservoir. **Exploration Technology** aims to provide better tools and methods for resource identification through the development of integrated models of the resource system for both exploration and reservoir analysis and the improvement of methods for exploration and reservoir characterization. The research conducted in **Brine Injection** strives to gain a better understanding of fluid injection into producing reservoirs. The **Geothermal Technology Organization** supports cost-shared cooperative research with industry which has a high probability of attaining results in the near term. The **Salton Sea Scientific Drilling Project** (SSSDP) offers insight into the geochemistry and productivity of hot, hypersaline brines found in the deeper portions of the Salton Sea hydrothermal reservoir.

Reservoir Analysis

Task Description

This task provides analytical and interpretive tools which will determine reservoir characteristics and reservoir performance with greater certainty. Research efforts included in this project are the development of geothermal reservoir models based on field and laboratory data; the evaluation of geophysical methods to locate and characterize fractures in geothermal reservoirs; the development of conceptual geologic models which incorporate observed fracture parameters and fluid chemistry; and improvements in numerical models to interpret well measurements and laboratory data. These activities strive to achieve the following Level III objectives:

> **Reduce the number of wells needed to define the resource by 33 percent by 1992.**
>
> **By increasing the accuracy and precision of information required for models of reservoir characteristics and performance, decrease uncertainties in forecasting short-term and long-term reservoir changes in fluid temperature, pressure, flow rate, and chemistry by 10 percent by 1992.**
>
> **Reduce uncertainties in predictions of reservoir capacity by 15 percent by 1992.**
>
> **By improving reservoir evaluation methods, decrease uncertainties in forecasting short-term and long-term reservoir changes in fluid temperature, pressure, flow rate, and chemistry by 15 percent by 1992.**
>
> **Reduce the number of wells needed to evaluate a reservoir by 10 percent by 1992.**

Seismic and electromagnetic methods are being evaluated for their effectiveness in locating and characterizing fractures. Methods are being developed to interpret vertical seismic profiles which provide information about the orientation of fractures, their spacing, and other parameters. New instrumentation provides greater sensitivity to well testing measurements and provides geoscience data that were previously not available.

Information gathered through several types of well testing is being used in numerical models to predict reservoir behavior in response to fluid withdrawal. Well testing methods and the required instrumentation are being developed to provide critical data for use in predictive models. Actual operating histories are used to verify existing reservoir models and to develop more accurate prediction capabilities. New approaches to the analysis of well tests have provided some of the parameters needed in improved models.

Long-term production and injection testing was conducted jointly with Oxbow Geothermal in Dixie Valley, Nevada. Cost-shared research with industry allows access to operating fields where new methods and equipment can be tested.

Fiscal Year Accomplishments
During FY89, Stanford University researchers successfully completed the application of the boundary element method for pressure transient analysis of complex reservoirs. Accurate pressure solutions were obtained for arbitrarily shaped reservoirs with multiple sources/sinks. The capability to handle internal boundaries and composite reservoirs was also established.

The results of other activities related to pressure transient analysis were completed and reported. Included was research pertaining to the application of the boundary element method to streamlines and pressure transient testing and the comparison of pressure transient response in intensely and sparsely fractured reservoirs.

To locate fractures in the subsurface, LBL developed a crosshole fracture-mapping technique that combines seismic (diffraction tomography) and electromagnetic (diffusion tomography) methods. This approach was tested and validated using numerical modeling. The next test, field demonstration, will require industry participation and cooperative research. The developments from this research will be crucial in locating and designing the completion of production and injection wells.

An international research agreement between the Comision Federal de Electricidad (CFE) of Mexico and the DOE Geothermal Technology Division has provided access to the Los Azufres geothermal field in the fractured volcanics of central Mexico and to the Cerro Prieto field in the deltaic sediments of the Salton Trough in Baja, California. Working with CFE researchers, LBL, UURI, Stanford, INEL, and USGS researchers have developed comprehensive case studies of two major types of geothermal systems. The researchers have been able to characterize the long-term behavior of the Cerro Prieto geothermal system in response to large-scale exploitation. Hydrogeologic models of the field were tested by LBL and combined with geochemical models of the USGS to characterize the change in reservoir permeability and to quantify the natural mass and heat recharge of the reservoir.

The flow of steam and water in geothermal reservoirs is dominated by fractures, but very little is known about the properties of these fractures when both phases are flowing simultaneously. As part of a combined program of experimental and theoretical studies, LBL created conceptual models of multiphase flow in rough-walled fractures. In addition, laboratory techniques to visualize and quantify pore geometry and multiphase flows in these types of fractures were developed. Well testing is an integral part of the evaluation of a geothermal system, and both LBL and Stanford have a continuing effort in well testing and the development of new techniques to evaluate well tests.

Capabilities were improved to model fluid and heat flow in fractured media and refinements were also made to the LBL multiple feedzone wellbore model to incorporate noncondensible gases and dissolved solids.

Other LBL research confirmed predictions based on numerical simulations of a geothermal system in fractured volcanic rocks (Olkaria, Kenya; 1984-87) and verified approximate analytical solutions for nonisothermal injection with variable flow rate, injection temperature, and temperature-dependent rock and fluid properties. This is the first documentation in the geothermal literature to show the effectiveness of numerical simulation in quantifying the future behavior of geothermal systems.

Further developments during FY89 included the completion of an analysis by researchers at LLNL of seismic observations before and during the flow test at the site of the Salton Sea Scientific Drilling well. It was concluded that of the many sources of noise detected, none came from the test area.

Stanford University completed a preliminary study and instrumentation (including automatic data gathering system) of the apparatus for measurement of the relative permeability of fractures.

Development of both a multi-array borehole resistivity system and algorithms to assist in interpreting thermometric data from fluid inclusions was conducted by University of Utah Research Institute (UURI) researchers.

The University of California at San Diego (UCSD) is conducting development research on cryogenic gravimeters for the detection of mass withdrawal through fluid production from geothermal reservoirs and their corresponding decrease in gravity. Two gravimeters have been constructed for deployment at the Hawaiian Volcano Observatory of the USGS. The one unit was installed in Hawaii during FY89 and began testing to detect small mass changes during magma movement. The USGS will work with UCSD to compare the results of the gravimeters to the leveling, seismic, and tilt measurements used to measure magma movement and to calibrate the gravimeters. This testing is necessary before the instruments can be used in a hydrothermal system.

Future Plans
LBL and UURI will develop new equipment and field test its use for the downhole measurement of induced polarization, time-domain electromagnetics, and DC resistivity, and will continue the testing of vertical seismic profiling techniques and microseismic monitoring for detection and mapping of fractures in geothermal systems. They will develop and verify computer-based methods to evaluate the use of borehole geophysical techniques for locating fractures and permeable zones in geothermal systems.

Stanford, INEL, and LBL will analyze field data from individual production well tests and interference tests, and will refine computer modeling techniques for identifying reservoir processes and evaluating their impact on the response of hydrothermal systems to development. UURI, LBL, and INEL will interpret field data on geology, geophysics, geochemistry, and hydrology of specific systems and attempt a synthesis of knowledge about general reservoir processes.

Stanford and LBL will continue development of theoretical and computer models to predict reservoir performance from combined well testing and production history data. They will improve existing downhole instrumentation to measure pressure, temperature, and flow rate. Laboratory studies to evaluate tracer and multiphase flow in fractures will be conducted and laboratory physical models to develop techniques for simulating the response of geothermal systems to different reservoir management programs will be used. Stanford and LBL will evaluate the usefulness of these techniques for estimating the generating capacity and longevity of these systems.

Stanford will begin studies of steam adsorption and its effect on reservoir productivity and will continue work on gravity segregation and its effects on pressure transients. LLNL and UCSD will continue the development of gravimeters for use in reservoir monitoring. UURI will study fluid inclusions at various geothermal fields, including The Geysers, to assist in predicting fluid circulation and determining the history of hydrothermal systems.

Exploration Technology

Task Description
Through the study of active and fossil hydrothermal systems, better generic models can be developed and used to devise new exploration methods, techniques, and strategies. The activities conducted within the Exploration Technology task are associated with accomplishment of Level III objectives to:

> **Increase the success ratio of wildcat exploration wells, especially in frontier areas such as the Cascades, by 20 percent by 1992.**
>
> **Devise better methods and strategies for discovering hidden hydrothermal systems, and for exploring the deep extensions of known systems so that industry can locate three such hidden reservoirs by 1992.**

Researchers will develop new rock, water, and gas geochemical techniques to identify hidden hydrothermal systems and will improve regional geophysical methods and interpretive techniques for exploring to depths greater than 2 km. Cost-shared R&D between DOE and industry, especially in frontier areas, will be pursued.

GTD has worked with industry to drill and core several holes to depths of 1.2 to 1.5 km to obtain accurate heat flow values. Geophysical logs and surface electromagnetic surveys are being examined to determine which correlates best with critical parameters of geothermal reservoirs. Low resistivity has been correlated with both low-temperature and high-temperature alteration mineralogy, and physical measurements of cores show subtle differences in the electromagnetic response. Combinations of several geophysical methods are being tested to identify characteristics of high-temperature geothermal systems, and to reduce the ambiguity of individual methods. New equipment and interpretation methods are being developed for magnetotelluric surveys, electromagnetic measurements, remote sensing for structural analysis, and conceptual models of geothermal systems. New geochemical geothermometers are being evaluated through laboratory and field studies and new refinements in sampling and analysis of surface water samples are being investigated.

Fiscal Year Accomplishments
An analysis of the feasibility of using cross-correlation methods to locate discrete scatterers in volcanic areas using teleseismic and regional data from Long Valley and Medicine Lake was completed and reported by LLNL during FY89.

Work at LLNL is centered on analysis of the seismicity associated with fluid production and injection at geothermal systems and on analysis of the effects of geothermal systems on seismic signals passing through them. Research is continuing on the suspected relationship between seismic attenuation and the presence of steam in the reservoir at The Geysers. LLNL is working closely with Unocal seismologists in this research.

Construction of a 3-D model of seismic attenuation based on previously collected seismic data from Newberry Crater, Oregon, was initiated by LLNL in cooperation with the U.S. Geological Survey. Other activities conducted by LLNL included the use of previously collected seismic data to look for sources of geothermal noise at Medicine Lake Caldera, the use of data from a small array in Long Valley to look for upper crustal scattering from possible magma bodies, and the completion of a report examining the value of source and receiver arrays for analyzing converted seismic phases in Long Valley, California.

During FY89, tomographic mapping of the Long Valley volcanic caldera was commenced with the installation and initial operation of a high resolution seismic borehole array. This effort was undertaken by LBL.

UURI conducted and interpreted low- and high-altitude aeromagnetic surveys in conjunction with Mexican researchers at the Los Azufres geothermal field to identify the fault system thought to underlie the field, to determine flow in the reservoir from the structural information obtained, and to assess the effectiveness of this technique in determining structural controls and alteration in fractured, volcanic-hosted geothermal systems.

A new technique was developed for determining the state of stress in geothermal reservoirs through the use of the commercially available oriented caliper log. Analysis of this stress information is important in predicting which fracture sets will be open and will control fluid flow in geothermal reservoirs.

Chemical studies of drill chips from the Los Azufres geothermal system were performed which led to a new method for the correlation of rock units between drill holes. Prior to this time, geologic studies of the rocks had been unable to develop such a correlation.

A comparative field study was performed that indicated that clay-mineral geothermometry and fluid-inclusion geothermometry provide valuable information on the thermal evolution of hydrothermal systems.

Detailed geochemical and hydrogeologic models were developed by integrating fluid inclusion data with chemical analyses of produced fluids. This technique was used to map fluid and steam distributions and recharge areas for both the Coso Hot Springs and Los Azufres geothermal systems.

Detailed chemical studies of the present-day fluids at the Heber geothermal system were conducted which related the chemical data to data derived from fluid-inclusion studies to develop a model for the fluid flow.

A Landsat-5 Thematic Mapper satellite image of the Los Azufres area was analyzed to identify new fractures in the area. A close correlation of processed images with known occurrences of hydrothermal alteration was observed.

Future Plans
UURI will collect and analyze existing data from geothermal exploration activities and will integrate them with geological, geophysical, and geochemical data from field and laboratory investigations to develop conceptual models for exploration of geothermal systems. UURI will also utilize this data to prepare case studies of resource exploration for the industry.

UURI and LBL will perform numerical analyses to determine theoretical responses from fluid-filled fractures and will design and conduct field tests of surface geophysical techniques to verify the responses expected. They will investigate the use of new interpretation methods for use with new geophysical techniques for locating fractured hydrothermal systems. UURI and LBL will also concentrate on electromagnetic and passive seismic methods of exploration and will combine the observed geophysical data with laboratory measurements of physical properties and existing geologic data to provide exploration plans for regions like the Cascades volcanic province for which data sets are available.

Brine Injection

Task Description
The Brine Injection task involves the improvement of methods for detecting and mapping fractures and permeable zones to optimize well siting and addresses industry needs for effective and environmentally acceptable injection systems. The activities aim to satisfy Level III objectives to:

> **Increase the success ratio of in-fill wells for production and injection, i.e., decrease the dry-hole ratio for in-fill wells for production and injection by 33 percent by 1992.**
>
> **Improve methods for positioning and designing geothermal production and injection wells in order to reduce the aggregate cost of wells by 15 percent by 1992.**
>
> **Improve reservoir monitoring methods to decrease uncertainties in forecasting short-term and long-term reservoir changes in fluid temperature, pressure, flow rate, and chemistry by 10 percent by 1992.**
>
> **Reduce the number of low-flow and short-lived production and injection wells drilled after production begins by 15 percent in 1992.**

Improve the efficiency of the production and injection schemes to reduce the number of make-up wells by 10 percent by 1992.

Reduce uncertainties related to long-term reservoir changes in fluid temperature and injection breakthrough by 10 percent by 1992.

Reduce the number and severity of unexpected environmental problems, especially those related to potential seismicity and subsidence.

The task involves increasing the reliability and reducing the cost of downhole instrumentation for use in high-temperature wells up to 350°C, including emphasis on drilling and completion information, methods to couple wellbore models to reservoir numerical simulation models, improved well designs, and better methods to monitor well performance. Other efforts are directed toward the development of low-cost tracers for liquid- and gas-phase flow; new techniques for conducting and interpreting tracer tests; methods for monitoring subsurface changes due to production, such as encroachment of cold water; new geochemical methods for detecting changes in the reservoir as production proceeds; and methods to predict and track chemical and thermal fronts in the reservoir.

Theoretical and numerical models have been used to identify geophysical methods to map fractures from the surface and between boreholes. Several of these methods look promising for field testing. Instruments using fiber optics are being investigated for long-term downhole monitoring of pressure, temperature, and water chemistry in high-temperature wells. Tracer testing has proven useful in one field for the selection of optimum sites for production and injection wells. Numerical models have been developed to predict the results of various sites for injection wells, and these models are being tested with field data. Chemical tracer tests are being used to determine actual flow paths through a reservoir and to determine parameters needed for modeling. Geophysical methods are being tested for the possibility of tracking injected fluid.

Fiscal Year Accomplishments

A long-term research effort culminated in FY89 with the injection tracer test at the Dixie Valley geothermal field in Nevada. The development and laboratory testing of organic chemicals for use as geothermal tracers was conducted at UURI over a period of several years. Several organic compounds were identified that could be detected in minute quantities, were stable in the geothermal environment of high temperature and reducing conditions, and were compatible with the environment. Of the 44 tracers identified, 24 tracers remain functional at temperatures up to 200°C, 15 at temperatures up to 250°C, and five at temperatures up to 300°C.

Researchers at UURI, Stanford, INEL, and LBL had used tracers to evaluate the flow paths in several geothermal reservoirs, but the previous field tests had major drawbacks in identifying fluid flow from separate injection wells. In cooperative research with Oxbow Geothermal Corp., LBL and INEL were given existing field data to use in preliminary modeling of the reservoir. They used their reservoir models to predict the tracer breakthrough times between wells and the quantity of each tracer that would be needed to determine breakthrough. INEL purchased the necessary tracers and UURI worked in the field with Oxbow to inject the tracers into different injection wells. UURI and Oxbow monitored the chemistry of the produced fluid from several production wells using an automatic sampler modified from those used by Stanford. The first chemical front was detected eight days after tracer injection began, but the temperature front has still not arrived. Stanford will use the tracer recovery data to model fluid flow and to examine the dispersion and diffusion of the tracer in the reservoir.

Theoretical studies at LBL are being conducted to evaluate the effects of injection on the reservoir pressure decline and enthalpies of produced fluids. A cooperative study with visitors from the Philippine National Oil Company (PNOC) on the Palinpinon geothermal field has resulted in a comprehensive evaluation of chemical and thermal breakthrough at producing wells. These studies yielded detailed evaluation of fracture porosities, permeabilities, and spacings which are critical parameters controlling the movement of fluid and the arrival time of chemical and thermal fronts.

LBL and Stanford combined reservoir modeling and well test data from Los Azufres to evaluate the increase in permeability due to cold water injection and to map the flow of injected water into the producing zone.

Completion of thermal cooldown applications for several moderate-temperature hydrothermal and petrothermal fields in the United States, Mexico, England, and the Soviet Union were achieved by Stanford University researchers. These have been helpful in evaluating recharge parameters.

Further analysis of the production and chemical data from the Maritaro and Tejamaniles zones in the Los Azufres geothermal field was continued in order to estimate the extent of thermal drawdown around the two 2-phase wells. An analysis of available injection test data from the field was completed during FY89 by LBL to verify the approximate analytical solutions for nonisothermal injection with variable flow rate, variable injection temperature, and temperature-dependent rock and fluid properties.

In conjunction with the Geothermal Technology Organization, LBL also completed high frequency microearthquake monitoring of fluid injection at The Geysers. This effort greatly increased the precision in locating fracturing events in the field.

INEL developed a reservoir simulation code, FRACSL, together with a user's manual for release to industry, which predicts heat and solute transport in fractured and porous media.

Future Plans

INEL, LBL, and Stanford will investigate injection methodologies and their effectiveness at The Geysers.

UURI will continue development of vapor-phase tracers useful for vapor-dominated systems.

UURI will evaluate potential geothermal tracers in laboratory experiments simulating natural geothermal systems. They will develop, with industry, techniques for tracer injection, sampling, and interpretation to track the transport of injected fluid. INEL and Stanford will apply computer modeling techniques to the tracer-return field data for the determination of reservoir physical properties and fluid interactions in the reservoir.

LBL and UURI will perform theoretical studies of geophysical techniques to determine if injection of spent geothermal fluids can generate signals which can be detected at the surface with existing geophysical equipment. They will also begin design of equipment capable of detecting the theoretically determined signals if existing equipment is found to be unsuitable.

INEL and LBL will continue to develop computer models with the capability to analyze and predict the flow of injected fluids through reservoirs. INEL researchers will investigate the potential for coupling the fluid flow computer model with models of chemical interactions between rocks and the injected fluid. LBL will continue developing well testing techniques and mathematical models to identify and quantify the processes associated with cold brine injection into geothermal reservoirs.

Geothermal Technology Organization

Task Description
This task stems from an agreement with the Geothermal Technology Organization (GTO), an association of firms with interests in geothermal development, and the DOE. Two or more GTO members select priority geothermal research and development activities and share the costs with DOE. The participants from GTO fund at least 50 percent of the costs of each activity; and they have the right to royalty-free licenses in any ensuing patents.

Fiscal Year Accomplishments
The first GTO cooperative task, an effort to collect high-frequency seismic signals from producing fractures at The Geysers field, was completed in FY89 by Lawrence Berkeley Laboratory under the sponsorship of Unocal, Geothermal Resources International, and the DOE. Analysis of the data was initiated.

Future Plans
INEL will continue as the DOE representative to the industry's Geothermal Technology Organization. The geothermal industry works with DOE through a cooperative research agreement between the DOE Idaho Operations Office and the Geothermal Technology Organization. Research selected for funding will have a high likelihood of yielding near-term benefits.

Salton Sea Scientific Drilling Project

Task Description
The Salton Sea Scientific Drilling Project (SSSDP) was performed through the Interagency Accord on Continental Scientific Drilling whose signatories include the Department of Energy, the National Science Foundation, and the U.S. Geological Survey. All three agencies provided support during execution of the project. The project was designed to study the physicochemical properties of deeply buried rocks and fluids of the Salton Sea Known Geothermal Resource Area, located in California's Imperial Valley. Activities centered around the drilling and testing of a deep well coupled with sampling and analysis of rocks and hydrothermal brines. The objectives of the SSSDP were to:

(1) Define the size of the hydrothermal system and test for an extension of the system at depth;
(2) Improve hydrothermal resource estimates;
(3) Improve understanding of the genesis of hydrothermal ore deposits;
(4) Investigate possible "superconvection" within the system;
(5) Study the origin and nature of earthquake swarms in the vicinity; and
(6) Evaluate the productivity of the deep hydrothermal system.

The project was executed in two phases. Initially, a deep test well, designated State 2-14, was drilled to a depth of 10,564 feet on leased land provided by Kennecott Corporation. Several potential reservoir horizons were tested and samples of formation fluids were collected. The scientific results of the first phase were widely reported in journals and at a meeting of the American Geophysical Union.

The second phase began in FY88 and included an attempted redrilling of the well to sidetrack around an obstruction. The attempt was unsuccessful, but the well remained in suitable condition for an extended flow test of the open portion of the wellbore. Upon the drilling of an injection well, a 20-day test was performed in June 1988. Reservoir data and brine samples were collected during the course of the test.

Fiscal Year Accomplishments
Field activities centered on site cleanup, especially the disposal of sludge which had accumulated in a brine holding pond. A total of 1,800 tons of sludge and salt cake was processed and disposed of at a nearby Class I dump. The site, including the well and surface equipment, was turned over to Kennecott in accordance with the terms of a cooperative agreement.

Future Plans
Work on the SSSDP will conclude with the organization of a workshop on the project's major findings and the distribution of a final report.

CONVERSION TECHNOLOGY

Because of the variable nature of geothermal resources, a variety of technologies is used to convert its heat to electricity. Dry steam conversion technology is mature and has been in commercial use for many years. The basic technology for flash steam plants is also well advanced and is usually used when the resource temperature is over 200°C (400°F). Binary cycles are more thermodynamically efficient than flash cycles below 200°C (400°F); however, the larger sizes and higher costs of equipment required for lower temperature fluids and the economic advantages of developing the hotter resources first have inhibited the deployment of binary systems. Conversion Technology research activities are expected to lead to advancements in binary technology that will permit it to operate more efficiently than flash steam technology on the more abundant moderate-temperature reservoirs.

The Conversion Technology project is separated into three research areas. **Heat Cycle Research** seeks to improve conversion cycle efficiency and focuses on binary cycle technology. The **Advanced Brine Chemistry** task addresses problems associated with the production and use of highly saline brines. Efforts in the **Materials Development** task are directed toward the development of materials capable of withstanding geothermal environments (high temperatures and highly saline brine). The tasks in the Conversion Technology project are focused on achieving the Level II objectives to:

> **Reduce the life-cycle cost of hydrothermal electricity by 10 to 13 percent through improvements in fluid production technology by 1992.**
>
> **Reduce the cost of power by 17 to 28 percent for binary plants at reservoirs in the temperature range of 150°C to 200°C through improvements in efficiency and in operation and maintenance (O&M) by 1992.**
>
> **Reduce the cost of power by 0 to 4 percent for flash plants through improvements in materials and equipment subject to scaling, corrosion, and other brine-handling requirements by 1992.**

Areas of major concern to geothermal power producers are the problems associated with handling chemically aggressive geofluids within production wellbores, well field pipelines and steam separators, power plant plumbing and valves, and injection wells. The combined effects of thermal stress and corrosion and scaling on equipment and components limit their durability such that plant availability, lifetime, power output, and heat exchange capability may be seriously affected. Any of these problems decrease the cost-effectiveness of the operation through downtime and costly replacement.

Heat Cycle Research

Task Description

The emphasis of the Heat Cycle Research task is directed primarily at the utilization of the liquid-dominated, moderate-temperature hydrothermal resources for the generation of electric power. The task investigates and develops the technology required to improve conversion cycle efficiency, as well as to expand the resource base to include subeconomic and marginally economic resources that are not being developed because of technical or institutional barriers. The Level III objectives for the Heat Cycle Research task are to:

> **Increase net geothermal fluid effectiveness of binary plants by 20 percent by 1992.**
>
> **Increase net geothermal fluid effectiveness of binary plants by 8 percent by 1992 through the use of supersaturated vapor turbine expansions.**
>
> **Reduce heat rejection system cooling water make-up requirements for geothermal power plants by 20 percent by 1991.**

The research activities focus on improving the performance of binary cycle technology to levels approaching the practical thermodynamic maxima. The purpose of this effort is to develop advanced conversion systems that will extend the economics of commercial geothermal power generation to the more abundant lower temperature resources not suitable for flash steam technology. These systems would also provide a more efficient alternative for some resources currently being converted with flash steam technology.

The incorporation of advanced plant concepts will increase the amount of electric power produced from a unit mass of geothermal fluid (geothermal fluid effectiveness). Process-related improvements, such as the use of supercritical vaporization, countercurrent integral condensation with recuperation, and optimization of operating parameters and working fluids, will substantially improve cycle efficiencies. Testing completed thus far has confirmed design methods for supercritical vaporization of mixed working fluids; current testing is investigating countercurrent integral condensation. Improvements in the accuracy of heat exchanger performance ratings will reduce losses and costs due to over- or under-sized equipment.

Field investigations of the effects of supersaturated vapor expansions on radial-inflow reaction turbine performance will be conducted. A small radial-inflow turbine will be obtained from a commercial manufacturer and tested under operating conditions not presently considered to be part of the normal operating envelope. Other efforts pertain to heat rejection schemes that require less cooling water make-up without incurring significant performance penalties. Theoretical studies and analysis will be used to select one or more schemes for field testing to establish the feasibility of the selected heat rejection schemes.

Fiscal Year Accomplishments

During FY89, activities to relocate the INEL Heat Cycle Research Facility (HCRF) from the DOE Geothermal Test Facility in California's Imperial Valley to a nearby commercial facility, the B.C. McCabe binary power plant, were completed. The move was dictated by declining resource temperatures at the DOE site which were insufficient to complete the test program as planned. Operation of the HCRF resumed at the new location in September 1989.

In FY89, INEL attempted to locate a site for field testing polymer-concrete lined heat exchanger tubes designed by the Materials Development task at Brookhaven National Laboratory (BNL). Institutional problems, however, made it impossible to conduct testing at the site originally selected. The search for a suitable site was resumed, and selection of a site is anticipated in FY90.

Kalina cycles were evaluated relative to their potential application in geothermal binary cycles. The initial results of the study were published early in FY89. They were subsequently updated to reflect several additional configurations using Kalina cycle technology specifically for geothermal power cycles. The INEL researchers determined that the DOE and Kalina approaches would yield similar efficiencies, but that the binary Rankine systems incorporating the advanced concepts evaluated by Heat Cycle Research task would be less complex than the Kalina cycles that were evaluated. The applicability of Kalina cycles for exploitation of geopressured resources was also considered.

Other research activities at the HCRF planned by the INEL and North Carolina A&T State University (NCA&T) relating to the condensation behavior of supersaturated turbine expansions were less extensive than planned because of the HCRF relocation activities. A problem was identified in the design of the two-dimensional expansion nozzle which resulted from attempting to provide both a window (for visual monitoring) and multiple pressure sensing ports along the nozzle length; the program modified its requirements to accept fewer pressure ports. A new nozzle, to be received at the HCRF in mid-FY90, is being fabricated. A Laser Droplet Illumination System, which will be used in conjunction with the nozzle to determine whether condensate droplets form during that portion of the turbine expansion that passes through the two-phase region, was shipped to the HCRF by NCA&T. If future investigations show that these types of expansions can operate without condensate forming, it may be possible to achieve a projected additional 8 percent performance improvement (a Level III objective).

Also advanced in FY89 were analyses of the data generated in the supercritical cycle investigations. Existing "state-of-the-technology" design codes developed by Heat Transfer Research, Inc. were found to inadequately model the in-tube condensation with internally enhanced heat exchanger surfaces at the non-vertical condenser orientation. To complete the analysis of the HCRF condenser performance, it was necessary to modify an older model. Results will be reported in FY90.

Future Plans
During the coming year, full operation of the Heat Cycle Research Facility will resume with the final phase of the planned supercritical cycle testing. Results of the testing at the first non-vertical condenser orientation will be reported. Investigation of the condensation behavior of the supersaturated turbine expansions will be initiated. A reaction turbine will be solicited and purchased. Investigation of the fouling resistance of the polymer-concrete lined heat exchanger tube will be initiated at the new site.

Materials Development

Task Description

A serious problem in the development of geothermal resources has been the lack of cost-effective durable materials of construction for handling hot brine, steam, cooling water, and binary fluids. Hot brine and other geothermal fluids frequently are highly corrosive, especially when aerated, and they attack many conventional materials of construction. Corrosion and scaling have been encountered in all geothermal plants and, to various degrees, they adversely affect plant availability, lifetimes, power output, and heat exchange capability. It is expected that these problems will become more acute as hotter, chemically aggressive fluids are encountered.

The purpose of the Materials Development task is to provide the technical and managerial basis for the development of materials that will perform in the thermal and chemical regimes encountered in the production and utilization of geothermal fluids. The Level III objectives are to:

> **Reduce costs associated with lost circulation episodes by 30 percent by 1992.**
>
> **Develop well cementing materials with a service lifetime of 30 years at 400°-600°C by 1991.**
>
> **Develop a corrosion-resistant and low-fouling heat exchanger tube material costing no more than one-third the cost of high alloy tubes by 1991.**

Work is being done to develop rapid-curing, high temperature cements that can be introduced through the drill pipe into lost circulation zones. This will eliminate the need to remove the drill string, reduce downtime (and therefore cost), and aid in the location of the fractured zone. To date, two promising formulations have been identified and characterized in the laboratory. Larger-scale tests are planned in a cooperative effort with private industry.

Improvements in the effectiveness of geothermal well completion procedures by the development of CO_2-resistant, lightweight, high-temperature cements will help to transfer limitations on well life from materials constraints to reservoir productivity. Work is being performed as a cooperative research effort with the New Zealand Department of Scientific and Industrial Research (DSIR). GTD researchers are developing the cement formulations and performing physical, chemical, and mechanical evaluations. DSIR is conducting the downhole tests in wells at their Rotokawa geothermal field.

The development of high thermal conductivity, corrosion-resistant, nonmetallic liners on carbon steel substrates will reduce the costs of binary plants operating on chemically aggressive brines. Heat exchanger economics can be improved with low-cost, corrosion-resistant, low-fouling heat exchanger tubing. Tubing liner formulations based on polymer-concrete materials are being developed and fabricated for testing. The intent of this research is to minimize cost while maintaining adequate thermal conductivity and resistance to chemical attack from geothermal brine. Field tests of polymer-concrete lined tubes, in cooperation with the Heat Cycle Research task, will be performed to measure corrosion and fouling rates at temperatures and fluid velocities typical of binary plants.

Fiscal Year Accomplishments
During FY89, laboratory evaluations of lightweight cements exposed to low CO_2-containing (<500 ppm) brines were completed. The most promising advanced formulation, which was developed by BNL researchers, consists of a calcium aluminate cement modified by the addition of a carboxylated styrene-butadiene copolymer. This formulation was found to be the most effective for minimizing strength degradation and carbonation reactions; these improvements are due to the formation of a calcium-complexed polymer structure which results from the addition of the acrylic polymer. Downhole testing of the cements, scheduled to be done in New Zealand as part of a cost-shared program with DSIR, was delayed due to problems with the wellhead equipment, but these tests are now in progress.

Pumpability tests on lightweight cements using a high pressure consistometer on loan from Sandia National Laboratories continued in accordance with American Petroleum Institute (API) standards. The results to date indicate that the cements are pumpable and can be placed downhole using conventional well completion techniques.

Experiments to measure the physical, mechanical, and chemical properties of several non-portland ceramic-like cements for use as well completion materials in magma regions continued. Tests to measure mechanical and physical properties under dry and hydrothermal conditions at temperatures up to 1000°C were performed, and the results were documented. Strength values exceed the API criteria for well completion materials and the strengths remain constant at temperatures between 300° and 1000°C.

Laboratory evaluations of thermally conductive polymer-concrete lined tubing in simulated geothermal fluids continued. After 15 months in brine at 150°C, liners with a thickness of 0.020 inch have provided excellent corrosion protection for the steel substrate. Planned field testing of the liner material in a tube-and-shell heat exchanger at a test site in Hawaii was delayed and will be initiated when a suitable test site is identified. (See "Heat Cycle Research" task).

Experiments conducted in FY89 confirmed the technical feasibility of incorporating high temperature anti-oxidants into polymer-concrete formulations as a means of reducing scale deposition. Tests were performed on samples after exposure to highly concentrated brines at 150° and 200°C. The results indicate that the modification of the polymer-concrete surface by the inclusion of 0.02 percent by weight diphenyl phenylenediamine significantly reduced calcium deposition from 200°C brine and reduced silica deposition by 50 percent.

Work continued on the development of techniques to allow the introduction of lost circulation control formulations through the drill pipe and drill nozzle rather than using conventional techniques. The most promising lost circulation control formulation identified to date is composed of bentonite, ammonium polyphosphate (AmPP), borax, magnesium oxide (MgO), and water. The appropriate combination of the components results in the formation of slurries with viscosities and thickening times adequate to allow placement. Since the pumpability and curing times for the system can be closely controlled over a wide temperature range (150°-350°C) by varying the MgO concentration, methods for the microencapsulation of the MgO in epoxies and other polymers have been investigated.

Improvements have been produced in the performance of elastomers for static and dynamic seal applications. The use of these hydrothermally resistant materials is limited by the lack of hydrolytically stable coupling systems needed to bind the elastomers to steel reinforcing substrates. For example, variations of the Y-267 FPDM developed under GTD sponsorship exhibit properties that make them suitable for use in drill pipe protectors; however, when reinforced with steel, complete disbondment of the rubber from the reinforcement occurred within 24 hours in a static hydrothermal environment at 200°C.

Future Plans

Work to develop lightweight CO_2-resistant cements for well completions will be continued. The most promising high-alumina cement formulations identified in FY89 will be exposed downhole for one year to brine containing sufficient CO_2 to cause deterioration of conventional calcium-silicate-hydrate-based cements within a short time. This work will be performed as part of the continuing cost-shared cooperative effort with the New Zealand DSIR.

The cements will be evaluated on the basis of their mechanical properties and chemical phases formed after exposures for 3, 6, 9, and 12 months. BNL will supply the cured samples, perform the evaluations, and document and publish the results. DSIR will furnish the wells, install and remove the samples, and perform some evaluations.

Based on the results of work initiated in FY89 to determine the technical feasibility of modifying the characteristics of thermally conductive polymer-concrete surfaces to make them less susceptible to scale deposition, larger-scale testing will commence. Initial tests will consist of autoclave exposure of small (approximately 6 inches long) pieces of unmodified and modified tubing surfaces to simulated hypersaline brines at temperatures up to 250°C. Subsequently, an 80-foot-long, single-tube shell-and-tube heat exchanger will be fabricated, operated, and the results compared with those obtained with the unmodified surfaces field tested earlier in FY90. Measurements to determine scaling factors, heat-transfer coefficients, and corrosion rates will be made. These tests will be performed cooperatively by BNL and INEL (see "Heat Cycle Research" task).

The cooperative effort between Sandia National Laboratories and private industry to develop advanced high-temperature chemical systems for lost circulation control will be continued. Contingent upon the results from FY90 tests, arrangements for performing drilling fluid displacement tests as a cost-shared effort with private industry will be made.

Advanced Brine Chemistry

Task Description

Many of the most significant problems limiting the development of geothermal power are related to the chemical properties of the high-temperature, high-pressure formation fluids from which the energy is extracted. When the pressure and temperature conditions on these fluids are changed either during the production or extraction phases of the operation, the fluids which were originally in equilibrium with formation minerals return to chemical equilibrium under the new conditions by precipitation of solid materials (scales) or release of dissolved gases in the formation, wellbores, or plant equipment. Various strategies (e.g., binary cycles, crystallizers, scale inhibitors) are available to control scaling problems in geothermal operations and generally additional costs are required in terms of disposable materials (scale inhibitors), additional equipment (crystallizers), or downtime (well cleanup), as well as the cost of waste disposal.

The Level III objectives of the Advanced Brine task are concerned with the properties of geothermal brines. These objectives are to:

Reduce geothermal production well maintenance costs related to scale deposition by 20 percent by 1992.

Reduce geothermal field surface equipment costs related to scale deposition by 20 percent by 1992.

Reduce geothermal power plant maintenance and equipment replacement costs related to scale deposition by 20 percent by 1992.

Reduce costs of surface disposal of sludge from geothermal brines by 25 percent or more by 1995.

Research has been conducted to determine the chemical equilibrium state of the brine at any point in the wellbore, the power plant, or the injection system before development of the geothermal resource occurs. Chemical models are being designed to determine the degree of chemical disequilibrium and the amount of scale formation to be expected during plant operation. These same models are also useful in predicting chemical problems that may occur when spent brines are disposed of by injecting them into chemically incompatible rock formations and in determining the degree of thermodynamic incompatibility between an injected spent brine and the receiving formation. When fully developed, these models will provide the geothermal industry with valuable process design tools that can be used to control the plant's chemistry and avoid plant failures due to scaling and/or corrosion.

Currently, a dynamic model of brine chemistry thermal equilibria and kinetics is being formulated which synthesizes the observed behavior of major ionic species at temperatures up to 250°C and provides reliable estimates of scaling potential. A model of brine chemistry in a system composed of sodium, calcium, chlorine, sulfate, carbonate, carbon dioxide, and water has almost been completed from 25°C to 200°C. Comparison of the model with laboratory data has shown the model to be highly reliable. The model will become an even more valuable cost-saving tool as other species, including gases such as methane and hydrogen sulfide, are added.

Research is also aimed at developing methods to concentrate and remove toxic materials and valuable metals from solid waste residues which form from the use of hypersaline brines. These wastes must be analyzed for regulated metals, and if found to be hazardous, they must be disposed of off-site in an approved waste management facility. The disposal of these wastes can cost more than $1 million per year for a 50-MWe geothermal flash power plant operating in the Salton Sea region of California and, therefore, the development of low-cost, environmentally acceptable means of disposing toxic geothermal residues is needed.

The biotechnical detoxification activities for handling geothermal waste are based on biochemical methods which utilize microorganisms that interact by surface adsorption, oxidization, reduction, solubilization and/or precipitation. The overall experimental strategy involving this emerging technology is depicted in Figure 7. Using waste samples supplied by various geothermal developers, bench-scale laboratory experiments have been conducted using biochemical processes. Different strains of microorganisms have been studied that have the ability to efficiently remove metals, including copper, chromium, zinc, lead, and arsenic from geothermal wastes. Research has also been conducted with mixed cultures. Preliminary results indicate that metal removal efficiency can be greatly enhanced by the use of selective mixed cultures of toxic metal-resistant microorganisms. Large-scale experiments are planned in the future for the study of scale-up kinetics.

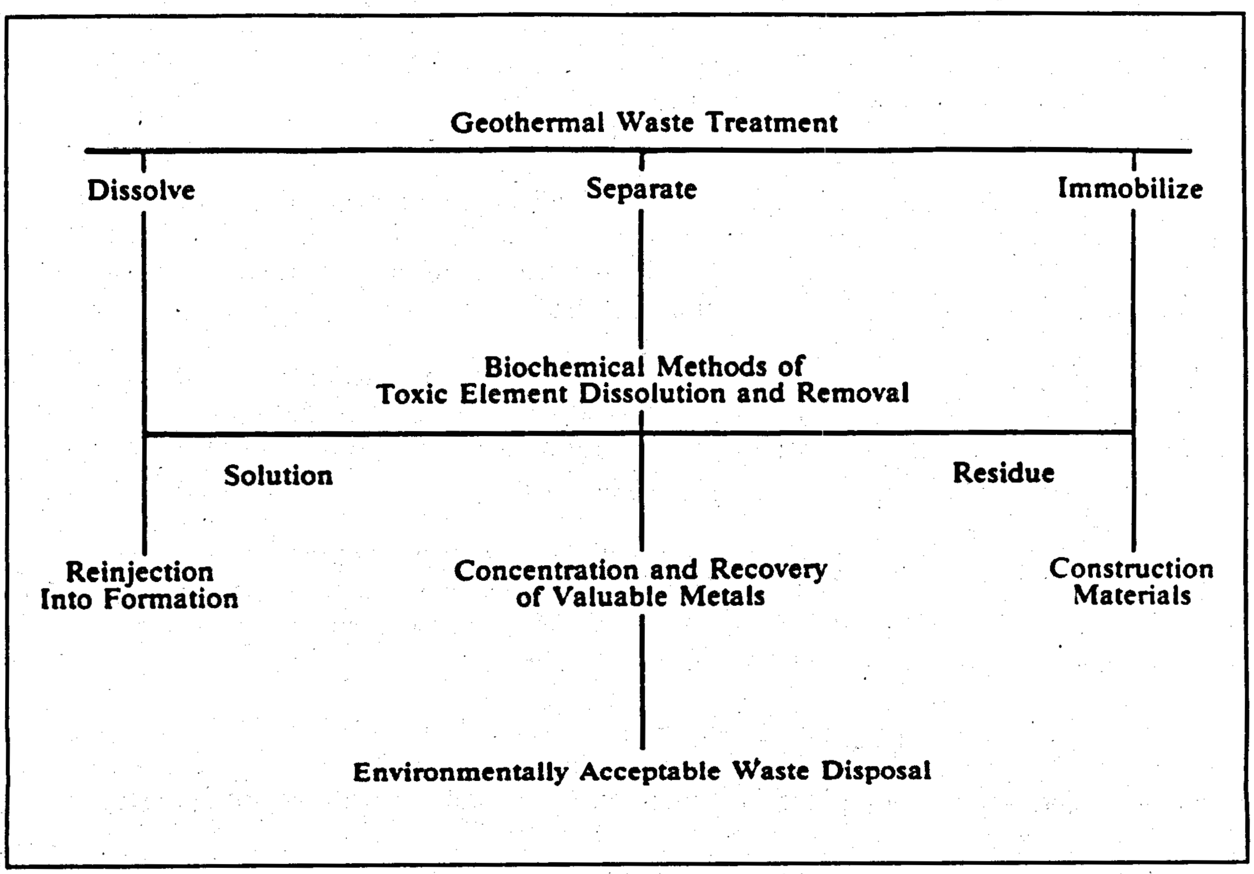
Fiscal Year Accomplishments
UCSD researchers made good progress in modeling a $CaCO_3$-SiO_2-$CaSO_4$-NaCl-CO_2-H-H_2O system over a temperature range of 0° to 250°C and to high ionic strength. This system contains most of the important carbonate, sulfate, and silica scale-forming minerals and provides a reliable model for estimating the scaling potential of many geothermal systems. The model can also calculate the conditions for boiling or onset of two-phase flow of CO_2-dominated geothermal fluids. Efforts to incorporate potassium into the model have been started.

During FY89, researchers at BNL studied the effects of a number of variables which influence the optimization of toxic metal removal by biomass. These included reactor sizes and types as well as experimental conditions controlling the bioprocesses used in the development of biotechnology for detoxification of geothermal brines. Other experiments demonstrated that mixed cultures of selected microorganism strains are the most efficient toxic-metal removers.

BNL investigations have shown that the attainment of maximum microorganism growth in a separate bioprocessor before introduction to the geothermal sludge greatly reduces the time needed to remove the metal. Studies have also shown that the removal rate is enhanced when the pH of the solid waste is low.

FIGURE 7

ADVANCED BIOCHEMICAL PROCESSES FOR GEOTHERMAL BRINES



Initial work using strains of microorganisms which tolerate high temperatures suggests that detoxification rates are faster at elevated temperatures. A typical example of the temperature influences on the rate of toxic metal removal is shown in Figure 8.

Preliminary evaluation of data from the use of a rotating blade countercurrent flow bioreactor was made during FY89. Results indicate that microbes migrate toward the food source and that both microbes and sludge flow concurrently through the system. Modification of this type of bioreactor may be worthwhile.

Currents results indicate that different processes for detoxification of geothermal brines are subject to the optimization of at least nine process variables. These nine process variables are: reactor size, effect of agitation, efficiency of mixed cultures, concentration of pregrown biomass, pH and dissolved oxygen, effect of pH on cell growth, concentration of residual sludge, minerals/metal salts, and temperature.

Future Plans

Development of the equilibrium model and the documentation that will implement its distribution to the geothermal community will be continued. Modifications of the code to execute on a Macintosh computer have started and preliminary results suggest that the isothermal versions will be implemented in FY90.

The equilibrium model will also be improved to include a wider range of species as the data base improves. Inclusion of the $S0_4$-$HS0_4$-H_20 system will allow the handling of pH effects in brines with substantial $S0_4$. Completion of the high temperature seawater system, without carbonate, is expected by the end of FY90.

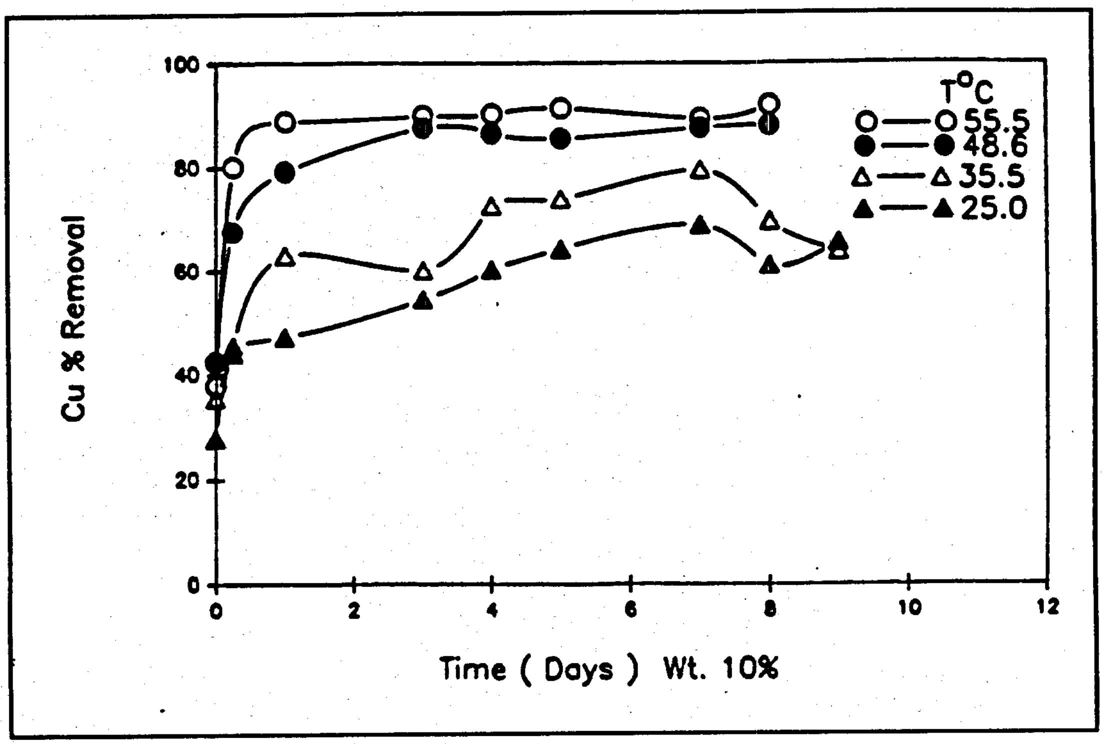
A program to model the pressure dependence of scale deposition processes will be developed. The gas phase CO_2-CH_4-H_20 system, which is of great importance in the analysis of geopressured systems, will be initiated first. Also, a program to model the solubility of sulfide gases in aqueous solutions will commence.

In the biotechnology program, experiments using column and flat-bed bioreactors with different sludge loading and mixing times will be conducted to study bioreactor designs capable of accommodating large volumes (greater than 350 gallons) of sludge.

Studies dealing with the optimization of sludge concentration, the decrease in residence time, and the use of thermophilic and thermo-adapted microorganisms will continue. Studies aimed at developing conditions for the use of mixed cultures and decreased residence times in bioreactors at elevated temperatures will be further optimized.

FIGURE 8

RATE OF COPPER REMOVAL AT 10 PERCENT WEIGHT OF SLUDGE LOADING AND DIFFERENT TEMPERATURES



GEOPRESSURED-GEOTHERMAL RESEARCH

The geopressured-geothermal resource consists of large reservoirs containing moderate- to high-temperature pressurized brines saturated with dissolved methane. The U.S. Geological Survey estimates the geopressured-geothermal energy in Gulf Coast sandstones to a depth of 7 km (approximately 22,500 feet) to be 5,700 trillion cubic feet of methane and 11,000 quads of thermal energy. Research efforts are focused on evaluating the geopressured reservoirs and developing the technology for extracting and using the thermal, chemical, and hydraulic energy from the resource. The activities support the Level I objective to:

Improve the technology for producing energy from the geopressured-geothermal resource at a cost equivalent to 6 to 10 cents/kWh by 1995.

The strategy for the program has been to identify a significant number of sites having the most promising reservoirs within the Gulf Coast and to test them by drilling and completing design wells. Previous work has confirmed the size of the resource, demonstrated the capability to produce brine and recover gas using conventional technology, and substantiated the feasibility of long-term, high-rate brine production. Significant progress has also been made in developing technology for controlling calcium carbonate scale and in injecting spent brine into saline aquifers.

Additional research is still needed to reliably predict the life and productivity of a geopressured reservoir and to perfect the technology needed to determine overall economic factors. To address these issues, the Geopressured-Geothermal Research program is organized into four interrelated projects which contain a total of 11 tasks. This organization is presented in Figure 9. University-based research supports the current program activities which are focused on long-term testing at two design wells.

WELL OPERATIONS

The Well Operations research project involves field experiments which demonstrate the viability of long-term fluid production for commercialization of geopressured-geothermal reservoirs. The associated research includes studies of the injectability of large volumes of spent brine, scale inhibition procedures, fluid handling facility improvements, material specifications, and environmentally acceptable disposal methods. The activities strive to achieve the Level II objectives to:

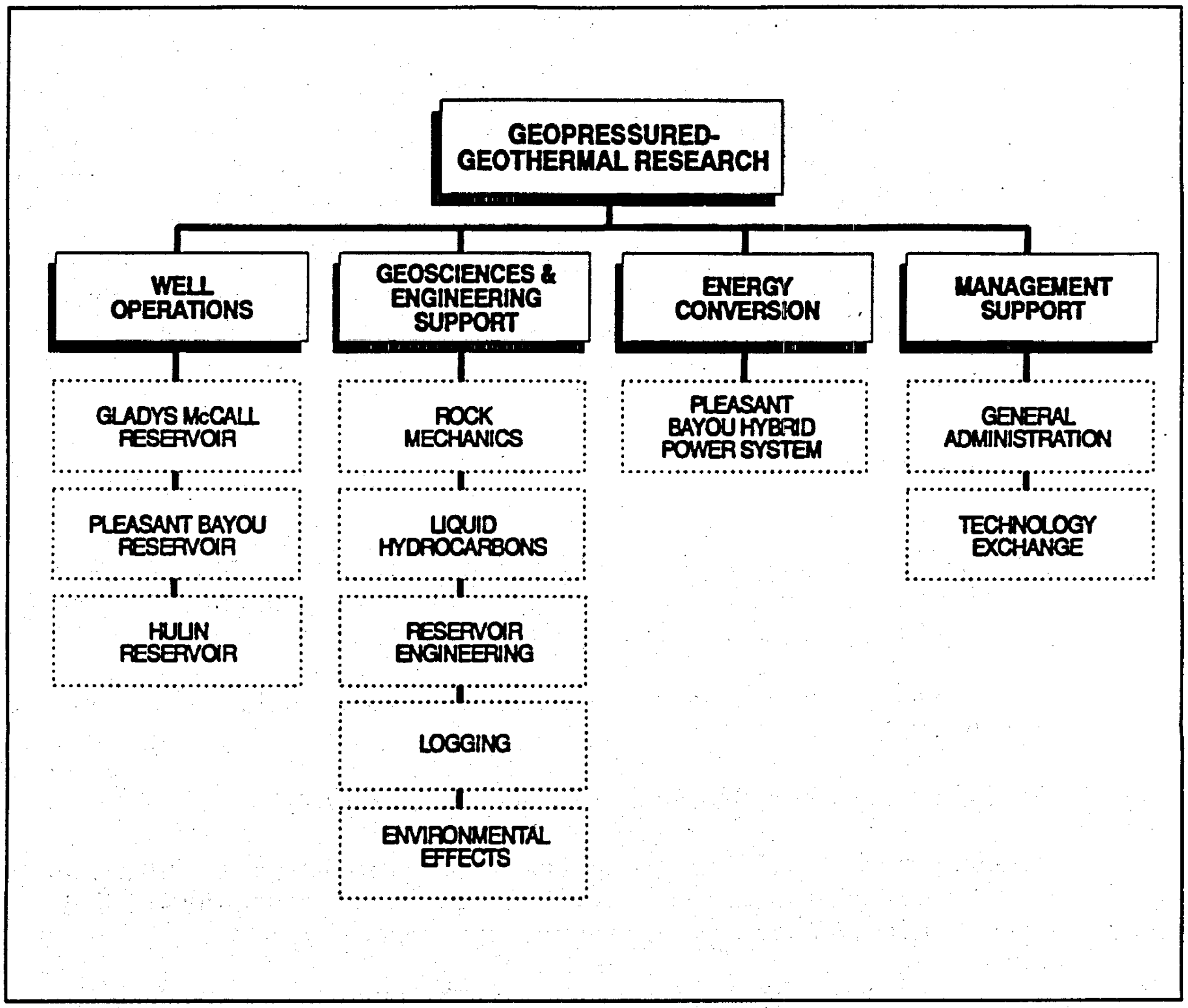
Prove the long-term injectability of large volumes of spent fluid at multiple sites by 1992.

Minimize fluid production operating expenses by 1989.

FIGURE 9

GEOPRESSURED-GEOTHERMAL RESEARCH

WORK BREAKDOWN STRUCTURE



Determine environmental acceptability of production and disposal of fluids by 1995.

Develop technology for automated operation of geopressured production systems by 1993.

Initially, a "Wells of Opportunity" test program was established whereby geopressured reservoirs were tested using wells drilled by industry in search of petroleum or natural gas. These wells were flow tested for short periods of time to determine brine flow rates, natural gas content, brine chemistry, reservoir pressures and temperatures, and other parameters. Since 1977, ten wells of opportunity have been tested successfully; nine of these wells are now plugged and abandoned or returned to their previous owners. The tenth well, the Willis Hulin, remains a candidate for further testing.

Between 1979 and 1982, four "Design Wells" were drilled to investigate long-term, sustained flow from geopressured aquifers. Testing at two of the wells has been completed, and the wells were plugged and abandoned. The remaining two design wells, the Gladys McCall well in Louisiana and the Pleasant Bayou well in Texas, are still being tested. Figure 10 shows the location of the initial "Wells of Opportunity" and "Design Wells."

Currently, there are three tasks in the Well Operations project. These tasks are performed at the **Gladys McCall** site in Cameron Parish, Louisiana; the **Pleasant Bayou** site in Brazoria County, Texas; and the **Hulin** site near Erath, Louisiana.

Gladys McCall Reservoir

Task Description

Activities associated with this task include long-term injectability studies, the development of scale inhibitors, the establishment of specifications for high availability of equipment, and the acquisition of reservoir data. The Level III objectives for this task are to:

Prove the long-term injectability of large volumes of spent fluid into injection wells by 1992.

Develop an effective scale inhibition procedure by 1989.

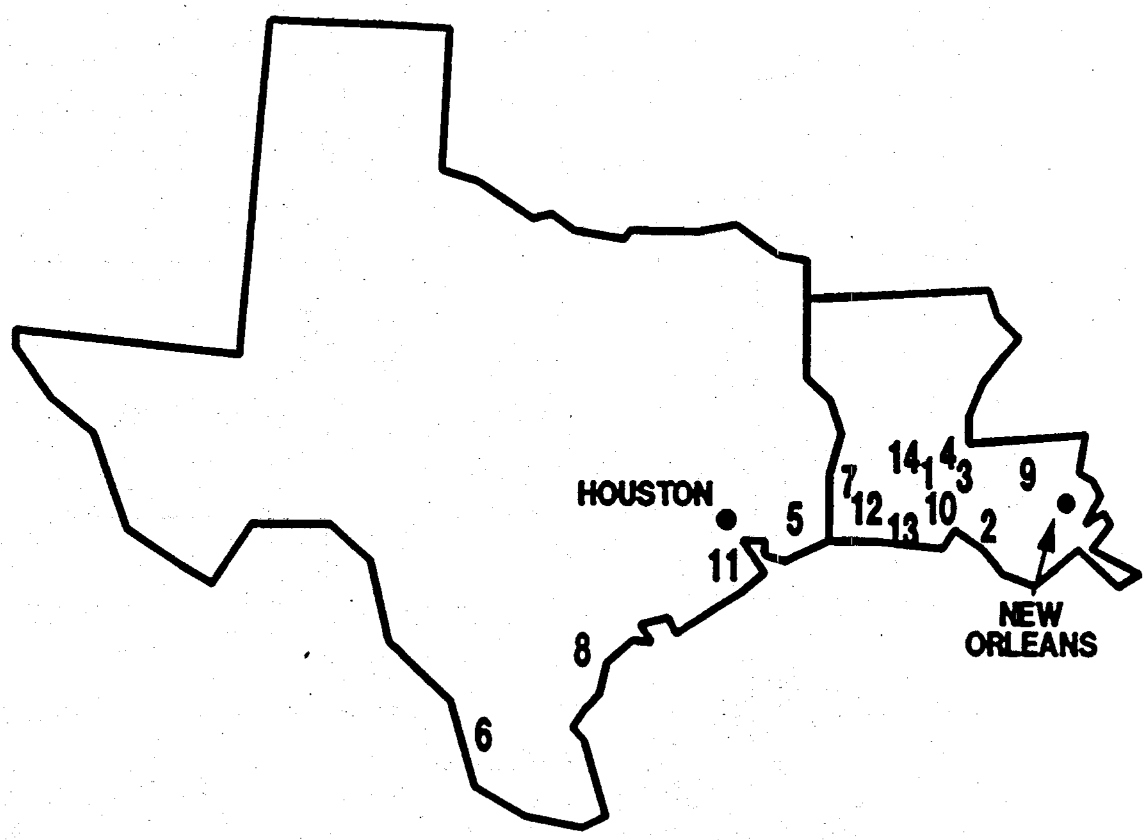
Develop material specifications, equipment specifications, and maintenance procedures which will guarantee over 95 percent annual availability with only a two-week annual shutdown for routine maintenance by 1993.

Geopressured brine is produced in large volumes of 20,000 to 40,000 barrels per day from a single well. After the dissolved methane is removed from the brine by gravity separation and the thermal energy is recovered, the brine must be disposed. As depicted in Figure 11, this is accomplished by injecting the spent brine into a normally pressured formation that is shallower than the producing formation, via a disposal well. The spent brine should be at a sufficiently high pressure to allow injection without the use of pumps. Operators of

FIGURE 10

GEOPRESSURED-GEOTHERMAL

WELLS-OF-OPPORTUNITY AND DESIGN WELLS

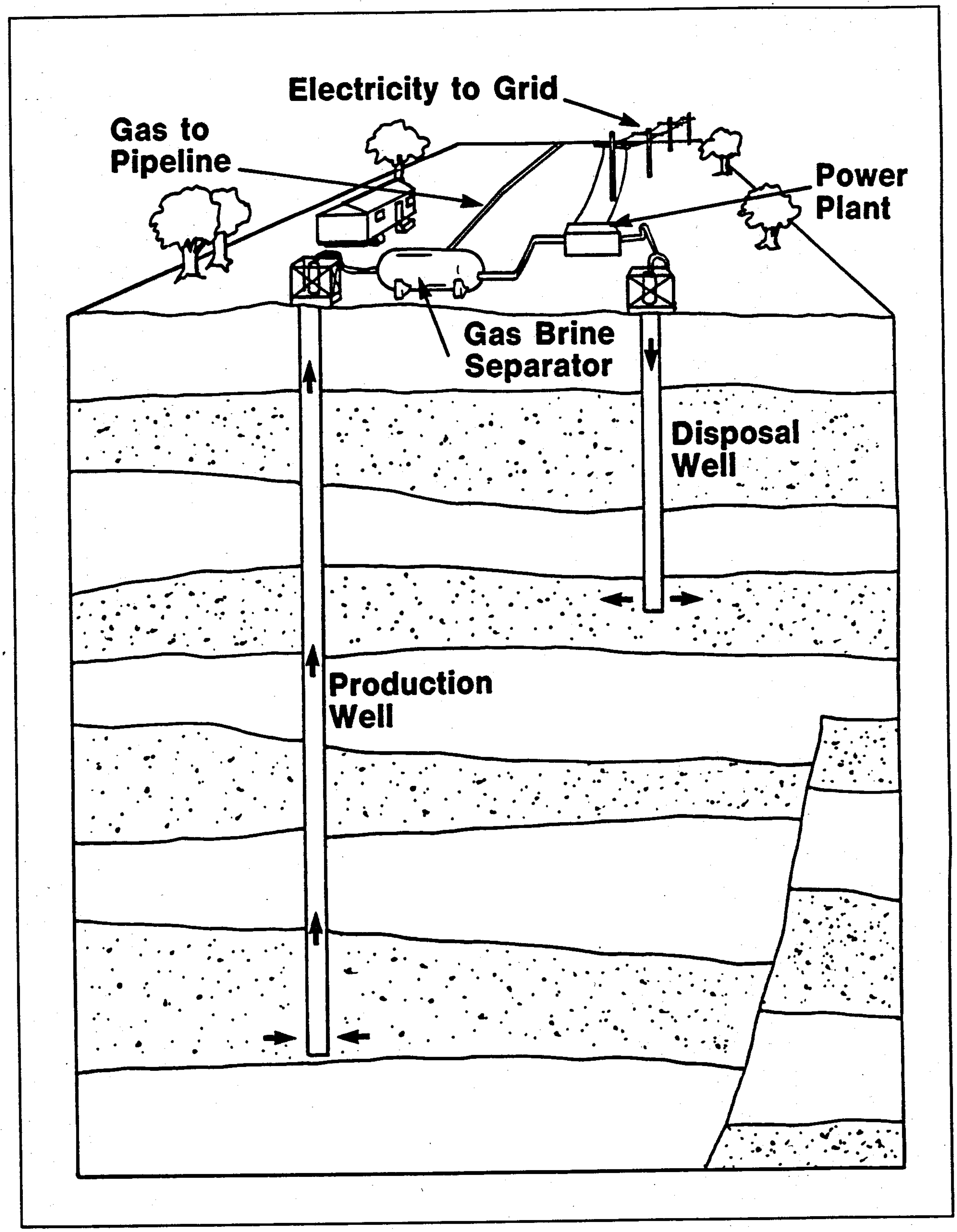


WELLS OF OPPORTUNITY
1. Edna Delcambre #1
2. Fairfax Foster Sutter #2
3. Buelah Simon #2
4. Wainoco Girouard #1
5. Lear Koelemay #1
6. Riddle Saldana #2
7. Prairie Canal #1
8. Pauline Kraft #1
9. Crown Zellerbach #2
10. Hulin #1

DESIGN WELLS
11. Pleasant Bayou #2
12. Amoco Fee #1
13. Gladys McCall #1
14. Sweezy #1

FIGURE 11

GEOPRESSURED-GEOTHERMAL POWER PRODUCTION SITE



such injection wells can minimize operating costs and prevent potential problems by using inhibitors to prevent scaling, filtering the brine to prevent particulates from plugging the receiving formation, and preventing backflow into the injection well.

The injection well at Gladys McCall was drilled originally as a hydrocarbon exploratory prospect in 1965. The well was plugged back to 3,460 feet and recompleted with perforations between 3,050 to 3,500 feet. A minor problem encountered was the sanding up of the injection well because of sand back flowing into the wellbore due to a leaking check valve during a shut-in period. From October 1983 through October 1987, 27 million barrels of brine were injected into the disposal well. The Level III objective of proving the long-term injectability of large volumes of spent fluids has been successfully completed for the McCall reservoir.

Calcium carbonate scale on surface facilities piping is easily handled by injecting scale inhibitor into the flow lines. However, scale in the producing formation or in the production well tubing is a more difficult control problem. The coating of the production tubing with scale decreases the flow rate and also degrades the wellhead pressure data making interpretation difficult or meaningless. Scale in the producing formation increases the skin effect and may result in plugging of the formation. The first attempts at phosphorate inhibitor squeezes into the producing formation at Gladys McCall were unsuccessful because downhole plugging prevented the pumping of all the inhibitor into the formation. The problem was solved by using a brine spacer ahead of the inhibitor to force the formation water away from the wellbore and injecting good quality water that had been filtered to remove iron hydroxide. The first successful phosphorate inhibitor squeeze in 1985 allowed the production of 5.4 million barrels of brine without any scaling on the high-pressure portion of the surface facilities. A simplified phosphorate inhibitor treatment was designed and used in 1986. A total of 13 million barrels of brine was produced after the second treatment without any indication of scaling in the downhole production tubing. These activities successfully completed the Level III objective of developing an effective scale inhibition procedure for the Gladys McCall reservoir.

High availability of surface facilities allows for the effective use of the facilities and results in increased revenues. Researchers will use the experience gained from the operation of surface facilities at existing sites to develop materials specifications, equipment specifications, and maintenance procedures that will enable high facilities' availability. The surface facilities at Gladys McCall operated with greater than 98 percent availability during the period February 1986 through October 1987 which successfully completed the Level III objective pertaining to annual availability for the McCall reservoir.

Fiscal Year Accomplishments
During FY89, the bottomhole pressure was measured periodically to determine the pressure recovery of the reservoir after producing 27 million barrels of brine and 676 million cubic feet of gas. The data obtained supports activities conducted within the Reservoir Engineering task.

Future Plans
At the Gladys McCall well, the monitoring and evaluation of the pressure buildup will continue into FY90. Plans for additional studies of reservoir drive mechanisms and reservoir changes due to long-term, high-volume production will be decided at a later date. The investigation may include pressure testing adjacent sand zones, coring the production sand and confining shales, and logging the well.

Pleasant Bayou Reservoir

Task Description
Activities associated with this task include investigations of sanding, scaling, and corrosion problems, the use of phosphate inhibitors to control calcium carbonate scaling, an evaluation of the effects of turbulence on corrosion, and the acquisition of reservoir data. The Level III objectives for this task are to:

> **Prove the long-term injectability of large volumes of spent fluid into injection wells by 1992.**
>
> **Develop an effective scale inhibition procedure by 1989.**
>
> **Develop material specifications, equipment specifications, and maintenance procedures which will guarantee over 95 percent annual availability with only a two-week annual shutdown for routine maintenance by 1993.**

Geopressured brine is produced in large volumes which must be disposed after the dissolved methane is removed from the brine and the thermal energy is recovered. This is accomplished by adding scale inhibitors to prevent scaling, filtering the brine, and injecting the spent geofluid into a normally pressured formation that is shallower than the producing formation, via an injection well. The Pleasant Bayou injection well has been used to dispose of 4 million barrels of brine from 1980 through 1983. It has also been used for the disposal of 10 million barrels of brine from 1988 through March 1990.

A simplified phosphorate inhibitor treatment was designed and used at Gladys McCall in 1986. An ongoing test of the simplified phosphorate inhibitor began at the Pleasant Bayou site in 1988. Coupons in the surface facilities brine stream at Pleasant Bayou are examined on a regular basis to monitor any scale formation.

A large portion of the cost of operating surface facilities is the labor needed to oversee the system. Automating the surface facilities so that no on-site personnel are required would result in significant cost savings. Therefore, during the design and construction of the Pleasant Bayou surface facilities, a file was maintained detailing how to automate the surface facilities for the production of brine, separation of gas, and disposal of waste brine. Automated surface facilities are tentatively planned for the Hulin well site.

High availability of surface facilities allows for the effective use of the facilities and results in increased revenues. Researchers will use the experience gained from the operation of surface facilities at existing sites to develop materials specifications, equipment specifications, and maintenance procedures that will enable high facilities' availability. Piping at the Pleasant Bayou surface facilities has been designed to reduce areas of erosion, and stainless steel piping has been used in areas with high erosion rates. Availability at Pleasant Bayou should equal or exceed the availability at Gladys McCall.

Pleasant Bayou brine samples are analyzed for sodium, magnesium, calcium, potassium, strontium, barium, iron, manganese, zinc, fluorine, iodine, lithium, boron, chlorine, silica, ammonia, bromide, sulfate, and alkalinity. Gas samples are analyzed for carbon dioxide, hydrogen, helium, and various hydrocarbons. Surface pressure and temperature data are recorded electronically using a computer-based data acquisition system. Downhole pressure and temperature measurements are made periodically using a Panex gauge. The pressure and temperature data are used in determining reservoir response to long-term production.

Fiscal Year Accomplishments
Flow testing of the Pleasant Bayou Well No. 2, in Brazoria County, Texas, was continued in FY89 at flow rates of 16,000 to 20,000 barrels of brine and 325,000 to 390,000 cubic feet of gas per day. During FY89, the well produced 5 million barrels of brine and 103 million cubic feet of gas.

Future Plans
During FY90, flow testing will continue in conjunction with the operation of the hybrid power system (HPS). Following shutdown of the HPS, the flow rate may be increased to accelerate drawdown of the reservoir.

Hulin Reservoir

Task Description
The Hulin well task activities involve characterizing the geopressured reservoir which is the deepest and hottest reservoir in the research program. Parameters to be measured are the gas/water ratio, brine composition, temperature, pressure, permeability, hydrocarbon composition, and the pressure decline and buildup of the reservoir. Other activities include the long-term injectability of large volumes of spent brine, determining the effectiveness of developed scale inhibitors, and the automation of surface facilities. The Level III objectives are to:

Prove the long-term injectability of large volumes of spent fluid into injection wells by 1992.

Develop an effective scale inhibition procedure by 1989.

Develop surface fluid handling facilities (pumps, separators, valves, compressors, etc.) which can be safely operated from a remote monitoring location by 1993.

Develop material specifications, equipment specifications, and maintenance procedures which will guarantee over 95 percent annual availability with only a two-week annual shutdown for routine maintenance by 1993.

Automated surface facilities are tentatively planned for the Hulin well site if the reservoir is capable of supporting long-term flow testing. Field testing at the Hulin site will determine the feasibility of fully automated surface facilities.

Fiscal Year Accomplishments
The Hulin well, originally a deep gas well, was successfully renovated as a test well after being shut-in for 6 years. Three-and-one-half inch tubing was installed in the wellbore in preparation for flow testing the geopressured reservoir at 20,000 feet.

A disposal well was drilled and completed to inject brine from the Willis Hulin No. 1 Well.

Future Plans
Planned activities include the preliminary short-term flow testing of the 20,000-foot reservoir and, potentially, the commencement of long-term testing.

GEOSCIENCES & ENGINEERING SUPPORT

This project provides geoscience and engineering support needed to complement well operations and adequately characterize geopressured-geothermal reservoirs. At present, the mechanisms driving the production of geopressured fluids are ill-defined. Without knowledge of how and when these mechanisms function, the reliability of geopressured reservoirs will remain uncertain. The Level II objectives for the Geosciences & Engineering Support project are designed to address these issues. These objectives are to:

Improve the understanding of how geopressured reservoirs behave over extended periods of time by decreasing uncertainty in reservoir performance to enable predictions of characteristics (i.e., reservoir size and longevity, hydrocarbon content, salinity) with 90 percent confidence over a 10-year operating period by 1992.

Determine environmental acceptability of production and disposal of fluids by 1995.

The research activities are conducted in five interrelated areas. The **Rock Mechanics** task investigates basic rock properties. Analyses of produced hydrocarbons to determine the source rock are conducted in the **Liquid Hydrocarbons** task. The **Reservoir Engineering** task synthesizes operational data and develops reservoir models to gain an understanding of the reservoir drive mechanisms. Improvements in wireline log interpretation methods to identify geopressured resources are being developed in the **Logging** task. The **Environmental Effects** task evaluates the ramifications of producing and injecting large volumes of brine.

Rock Mechanics

Task Description
The Rock Mechanics task addresses the effects of compaction and tension on geopressured-geothermal reservoir rocks, the wellbore stability, stress/strain relationships, and basic rock properties. This work provides basic data for future well development programs and is the source of data for use in reservoir modeling studies. The Rock Mechanics task supports the Level III objectives to:

> **Determine the drive mechanisms for the design well reservoirs by 1991.**
>
> **Develop a test procedure which has sufficient accuracy to predict the capability of any geopressured reservoir to be produced for a period of five times as long as the test period by 1992.**

The compaction and tension tests provide data which are specific to the geopressured test wells. These data are incorporated into the reservoir models to better define the most realistic reservoir drive mechanisms. Tensile measurements enhance the modeling of near-wellbore stability and aid in predicting near-wellbore rock failure.

Fiscal Year Accomplishments
Analyses of strength and moduli data on Gladys McCall and Pleasant Bayou samples were continued by the University of Texas Center for Energy Studies using uniaxial and triaxial compaction tests and pore pressure reduction tests. An apparatus for tensile testing of geothermal sandstone cores was developed and tensile tests were initiated during FY89.

A system for pore pressure loading and control was also designed.

Future Plans
A review of creep data and numerical data usable in modeling will be prepared.

Data on three-dimensional strength and stress-strain from well cores will be obtained and employed in a numerical model for addition to the geopressured reservoir simulator.

Liquid Hydrocarbons

Task Description
Geopressured brines contain cryocondensates (aromatic hydrocarbons), primarily benzene, toluene, and xylene, in small quantities. The gas streams from all the DOE design wells contain these compounds, and archival brine samples from the "wells of opportunity" contain the more soluble, lower molecular weight aromatic compounds. Laboratory analyses of the samples will be conducted to determine the composition of the hydrocarbons in the produced brine, the solubility of the aromatics and their distribution coefficients, and the relationship of hydrocarbon production and cryocondensate properties

to the geopressured reservoir. These activities will assist in achieving the Level III objective to:

> **Determine source and flow mechanisms for the liquid hydrocarbons and methane being obtained from producing geopressured reservoirs by 1991.**

Monthly sampling at the Gladys McCall well indicated variations in cryocondensate concentrations with time. Aliphatic hydrocarbons (heavy oil) were also produced at Gladys McCall. Researchers currently hypothesize that the oil is released from the shale when the reservoir pressure is reduced enough to cause oil migration from the shale to the sandstone. A low flow rate of 10,000 barrels of brine per day at Gladys McCall in 1987 allowed the reservoir pressure to recover partially, and oil production at the surface facilities ceased. Apparently, the pressure gradient across the sandstone (the producing formation) and shale interface was no longer large enough to allow the oil to migrate.

Fiscal Year Accomplishments

Monthly sampling of brine and cryocondensates at Pleasant Bayou was accomplished as scheduled by the University of Southern Louisiana (USL). Measurements of time-dependence and brine production-dependence of the cryocondensates were made and the correlation of cryocondensate yields with well operations was initiated. During FY89, the solubility of certain aromatic hydrocarbons was measured and the Pleasant Bayou well was monitored for aliphatic hydrocarbon production.

The design and installation of a benzene scrubbing system at the Pleasant Bayou well was successfully completed. The system measures daily variations in the benzene concentrations.

Future Plans

At the Pleasant Bayou site, the correlation of hydrocarbon production with well operating parameters, the measurement of distribution coefficients and solubilities of aromatic hydrocarbons, and the monitoring of any aliphatic hydrocarbon production will continue in FY90.

Sampling and analysis of aromatic hydrocarbons from the Hulin well will begin when flow testing commences.

Coring has been proposed as part of the final scientific testing program at the Gladys McCall well. If the confining shale is cored, it will be analyzed to determine whether it is the source rock for the hydrocarbons.

Reservoir Engineering

Task Description

The activities in the Reservoir Engineering task include the analysis and synthesis of operational test data from the design wells, synthesis and integration of geoscience data into the reservoir model, development of improved reservoir simulation techniques, site-specific geological research on geopressured-geothermal reservoirs, and evaluation of the interrelationships of well chemistry and corrosion. These efforts are aimed at achieving two Level III objectives. The objectives are to:

Determine the drive mechanisms for the design well reservoirs by 1991.

Develop a test procedure which has sufficient accuracy to predict the capability of any geopressured reservoir to be produced for a period of five times as long as the test period by 1992.

Among the possible drive mechanisms for geopressured reservoirs are:

(1) elastic compression of the fluid-rock matrix;
(2) irreversible rock compaction;
(3) long-term formation creep;
(4) cross flow from overlying/underlying sands;
(5) shale water recharge;
(6) leakage across boundary faults; and
(7) gas drive.

Elastic compression of the rock and fluid drives most gas and oil reservoirs that produce without pumping. While this force certainly contributes to the production of geopressured brines, models based on compression alone have been unable to predict the observed long-term production of geopressured brines. Parametric simulations of pressure testing of a geopressured well suggest that irreversible rock compaction is not a major pressure maintenance mechanism.

Shale water recharge as a pressure maintenance mechanism seems unlikely because the volume of shale immediately adjacent to the Gladys McCall sandstone reservoir is not large enough to account for pressure maintenance. Gas drive has been ruled out as well for the Gladys McCall reservoir. A 1987 drawdown test at Gladys McCall, in which the wellhead pressure was substantially decreased, did not detect any free gas in the reservoir.

Cross flow from other sands and leakage across boundary faults seem the most likely pressure maintenance mechanisms. They are consistent with reservoir drawdown data. Pressure testing of adjacent sands at the end of the long-term pressure buildup test may determine if cross flow is occurring.

The proposed scientific testing program at Gladys McCall includes measuring the pressure in adjacent geopressured brine zones and coring around the production zones to find evidence of the drive mechanisms. Compaction testing and tensile failure testing of geopressured rocks will supplement the field tests. The reservoir stress state for the design well reservoirs will be modeled using geologic, rock compressibility, and reservoir pressure data and the computer simulator will be updated to include the most likely pressure maintenance mechanisms. This should increase the accuracy of predicting long-term well performance on the basis of short-term tests which will decrease the risk of developing the resource.

Fiscal Year Accomplishments
Reservoir simulations of the Gladys McCall and Pleasant Bayou wells conducted by researchers at S-Cubed continued with the integration of additional geoscience and well operations data including geologic, rock mechanics, reprocessed seismic, and pressure and temperature data.

Compilation and mapping of chemical analyses of wells penetrating the Frio formation in the Pleasant Bayou fault block were completed by the University of Texas Bureau of Economic Geology (BEG).

Louisiana State University (LSU) initiated an effort to interpret the structural geology in the vicinity of the Hulin well using 22 miles of seismic line data.

An analysis of production data from the Pleasant Bayou well was conducted by BEG and the results corroborated earlier estimates that the reservoir may contain more than 6 billion barrels of brine.

Progress was made in the development of a three-dimensional, heterogeneous reservoir simulation model for the Pleasant Bayou reservoir.

Future Plans
The reservoir modeling effort will be enhanced by integrating additional geoscience and well operations data.

The analysis and interpretation of the structural geology from seismic lines around the Hulin well will be continued. This work will assist in estimating reservoir volume and characteristics.

Development of a three-dimensional simulation model for the Pleasant Bayou well will be continued and the code made available to DOE.

Logging

Task Description
Routine geological information (e.g., logs, geophysical surveys, cores, fluid samples) is available for most Gulf Coast wells. Methods are being developed to synthesize the information in such a way that geopressured resources may be identified and evaluated more readily. The techniques will be combined into a standard procedure that operators can use during or immediately after drilling operations to indicate resource potential. These efforts will assist in satisfying the Level III objective to:

> **Develop techniques to increase confidence in the ability to locate and evaluate geopressured resources by 1992 such that at least 90 percent of wells recompleted for geopressured-geothermal development are subsequently shown to be economic.**

DOE is co-sponsoring logging research with Phillips Research Center, Tenneco Oil Exploration & Production, Schlumberger Well Services, ResTech, Exxon Production Research Company, Mobil Research & Development Corporation, Schlumberger-Doll Research, and Sun. This research deals mainly with improving the interpretation of electric and neutron logs. Prior work has shown that large daily variations in mud resistivity and mud filtrate resistivity occur in many wells during drilling. Uncertainties in mud filtrate resistivity increase the error of several log interpretation procedures. Studies show that reducing the variation in resistivity of mud make-up water should reduce mud filtrate resistivity fluctuations.

Researchers at the University of Texas at Austin are currently studying the effect of shale content, wettability, and pore complexity on the cementation exponent and the saturation exponent in the Archie Equation. The saturation exponent is often assumed to be 2, in spite of the fact that considerable data, not obtained under reservoir conditions, show that values can range from 1.3 to greater than 3. Researchers will measure several different types of reservoir rock at in situ pressures to correlate rock type with changes in cementation and saturation.

Researchers also are evaluating the effect of 16 trace elements with very high thermal neutron capture cross-sections on the neutron log. These elements can mimic the hydrogen atom in neutron capturing ability and cause a misinterpretation of neutron logs. Boron, an element found in high concentrations in some Gulf Coast wells, is one of the principal trace elements being evaluated.

Fiscal Year Accomplishments
During FY89, researchers studied the effect of boron on the thermal neutron log. It was concluded that boron is present in amounts that seriously affect thermal neutron log interpretation in the Gulf Coast Frio and several West Texas formations. Boron is also present in some cement additives in amounts that are significant for thermal neutron log interpretation.

A "state-of-the-art" Elan log analysis on the Hulin well was performed. The results indicated an increase in anticipated gas production.

Future Plans
A reinterpretation of Hulin log analyses will be performed, if necessary.

During FY90, researchers will continue determining the effect of rock wettability, pore complexity, and shale content on rock resistivity.

Research activities to evaluate the effect of trace elements on the neutron log will continue.

Environmental Effects

Task Description

Potential environmental effects associated with the development of geopressured resources in the Gulf Coast region are land surface subsidence, growth-fault activation, and water quality changes. The Level III objective of this task is to:

> **Determine if fluids can be disposed of in an environmentally acceptable manner by 1995.**

Surface subsidence, induced seismicity, and water quality in fresh water aquifers above injection zones and in surface waters will be monitored both during and after site operations. A plan for monitoring impacts was developed before resource testing began and has since been implemented consistently at each of the test well sites. Regional first-order vertical surveys were used to determine baseline rates of subsidence in each prospect before well testing and to monitor changes in land surface elevation during and after testing. Networks of first-order elevation benchmarks were installed in the immediate vicinity of each test well.

To determine the effects of fluid production and disposal on local growth fault activity, microseismic monitoring arrays were established in the vicinity of each test well. Each network consists of five to seven short-period vertical motion seismometers. The seismic signals are amplified and transmitted via phone lines to the Louisiana Geological Survey in Baton Rouge for analysis. Microseismic networks are located at the Gladys McCall, the Pleasant Bayou, and the Hulin wells.

Geopressured brines are high in total dissolved solids, principally sodium, chlorine, and calcium. These and other constituents could contaminate surface and ground water if not handled and disposed of properly. Surface and ground water at the well sites are sampled and analyzed quarterly to detect any possible contamination.

So far, no significant adverse environmental impact related to the well activities has been detected. Environmental monitoring will continue at the test sites until about two years after the completion of flow testing. A model for reservoir compression will evolve which should verify that no adverse environmental effects will occur from the planned production and disposal methods over a ten-year period of operation.

Fiscal Year Accomplishments

Louisiana State University (LSU) drilled a 400-foot water quality observation well near the Hulin Well and installed a first-order benchmark network and a microseismic monitoring station at the Hulin site. LSU also conducted leveling surveys at the Gladys McCall and Pleasant Bayou sites.

Periodic environmental monitoring of the Gladys McCall, Pleasant Bayou, and Hulin sites does not indicate any detrimental environmental effects, such as microseismic activity, water quality deterioration, and subsidence attributable to the long-term testing operations and other well site activities.

Future Plans
Subsidence, seismicity, and water quality monitoring around the Gladys McCall, Pleasant Bayou, and Hulin wells will be continued in FY90. Water quality monitoring will be handled by Eaton Operating Company, Inc., the well operations contractor. LSU will continue the subsidence and seismicity monitoring.

ENERGY CONVERSION

This project encompasses the **Pleasant Bayou Hybrid Power System** task. The Level II objective is to:

> **Improve methods for extracting commercially useful energy from geopressured fluids by 1993.**

Hybrid power systems that combine methane and geothermal heat for power generation will produce more electricity than separate power plants using the same amount of natural gas and geothermal heat. The heat and methane can be used to generate electricity, or the heat can be used separately for direct application or electric power production, and the methane sold to a pipeline.

Pleasant Bayou Hybrid Power System

Task Description
This task represents the first application of a hybrid energy conversion process in which both the thermal and chemical energy of geopressured brine are converted to electricity. The task activities include the construction and operation of a 1-MWe hybrid power system for up to one year at the Pleasant Bayou site and analysis of the operational data. The Level III objective is to:

> **Develop hybrid conversion technology with thermal efficiency at least 20 percent greater than that from separate combustion and geothermal power cycles by 1992.**

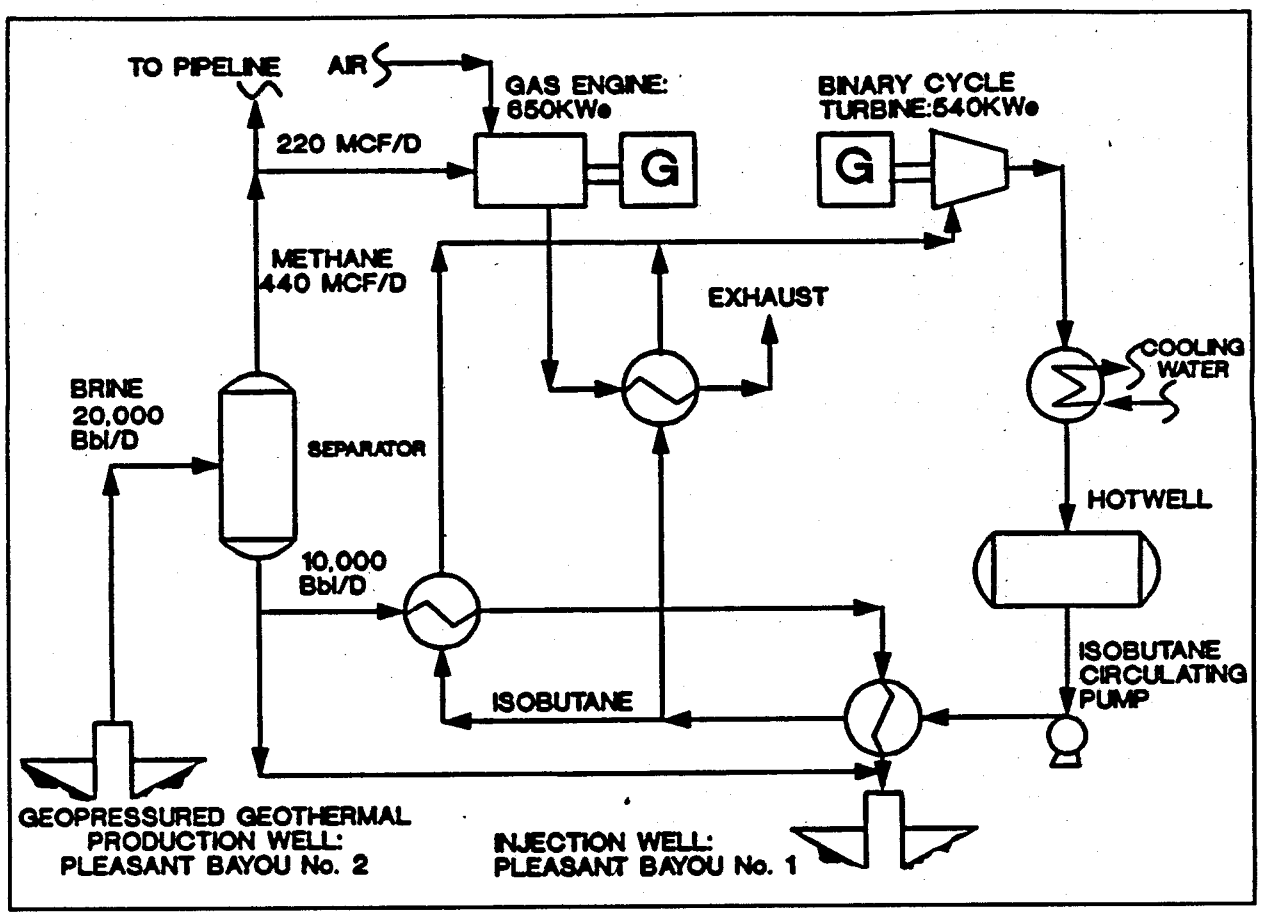
The strategy is to conduct cost-shared utilization experiments in order to establish the technical feasibility of efficient power conversion methods. They will provide a basis for industry to compare the advantages of electric power production versus straight sales of gas.

DOE is evaluating a 1-MWe power system employing hybrid conversion technology at the Pleasant Bayou site in Brazoria County, Texas. Figure 12 illustrates the hybrid process which burns the methane from the hot, geopressured brine in a gas engine to drive a generator and uses the heat from the combustion products and the brine to vaporize a working fluid. The vaporized isobutane is expanded through a turbine to drive another generator. Equipment from the DOE Geothermal Test Facility in the Imperial Valley of California was refurbished by the Electric Power Research Institute (EPRI) and delivered

FIGURE 12

SCHEMATIC OF GEOPRESSURED HYBRID POWER SYSTEM

BRAZORIA COUNTY, TEXAS



to the Pleasant Bayou site. Construction of the hybrid power system was completed in 1989, and the system will be operated for about one year. The Pleasant Bayou hybrid power system is the first geopressured-geothermal installation to generate electricity.

Fiscal Year Accomplishments
Construction of the 1-MWe hybrid power system was completed and operations were initiated in September 1989.

An operations checklist was developed for monitoring the performance, safety, quality assurance, and environmental aspects of the task.

Future Plans
The testing and evaluation of the hybrid power system at the Pleasant Bayou well in Texas will be concluded after nine months of operation. A final report on the results will be prepared for future reference.

MANAGEMENT SUPPORT

Activities in the Management Support project include long-range planning, preparation of various reports, management of the program budget, technical monitoring and support of university research efforts, review of testing operations for adherence to safety, health, and environmental regulations, organization of an Industrial Consortium to encourage the use of geopressured-geothermal resources, and day-to-day program management. The project is divided into two tasks: **General Administration** and **Technology Exchange.**

General Administration

Task Description
This task encompasses the administrative activities required to manage and support the research effort. The activities include overall planning and budget management, report preparation, and the monitoring of work being conducted by the various research organizations.

Fiscal Year Accomplishments
During FY89, long-range research plans were developed, various reports were prepared, and the overall program budget was analyzed. Review of quality assurance and safety procedures was continued.

Technical monitoring and support of university research and well operations continued and day-to-day management and technical assistance was provided.

Future Plans
Reports on the feasibility of hydraulic and thermal conversion, direct use, and the use of supercritical water in detoxification of pollutants will be completed.

Long-range planning, budget analyses, and preparation of required reports will continue and improvements in the reporting procedures will be made. Management and technical assistance will be provided in FY90 and environmental, quality, and safety reviews will be performed.

Technology Exchange

Task Description
This task supports the transfer of technical data to industry.

Fiscal Year Accomplishments
An Industrial Consortium which supports the utilization of geopressured-geothermal resources was initiated in September 1989. This activity begins the transition of geopressured-geothermal resources to commercialization.

Future Plans
Activities associated with the Industrial Consortium will continue and will include formulation of a charter and organization of the group.

HOT DRY ROCK RESEARCH

Estimates of the amount of potentially useful heat present in hot dry rock (HDR) at accessible depths beneath the United States vary widely with the assumptions made concerning minimum temperatures required, practical drilling depths, the characteristics of the subterranean environment, and the effectiveness of the heat recovery method. The USGS estimates that there are at least 430,000 quads of useful heat in hot dry rock at accessible drilling depths beneath the U.S. Economical recovery of even a very small fraction of that heat would contribute significantly to the nation's energy future. HDR in high thermal gradient areas is most easily accessed. As illustrated in Figure 13, there are many high thermal gradient areas in the western U.S., and scattered high gradient areas in the east.

A concept for recovering useful heat from this tremendous natural resource originated at Los Alamos National Laboratory (LANL). As shown in Figure 14, it involves drilling two holes down from the surface into the hot rock, connecting them through the rock by means of hydraulic fracturing, and circulating water through the fractures to extract heat from the rock and transport it to the surface. At the surface, the useful heat is recovered through heat exchangers and the cooled water is recirculated to recover more heat from the man-made reservoir.

The Phase I or "research" system at Fenton Hill accomplished the original goal of the HDR Program by demonstrating the technical feasibility of HDR energy systems. However, the Phase I system did not produce heat at a temperature or rate that would support economical operation of a power plant. Thus, the HDR Program was extended to meet those more demanding requirements. Currently, the Level I objective for the Hot Dry Rock Research program is to:

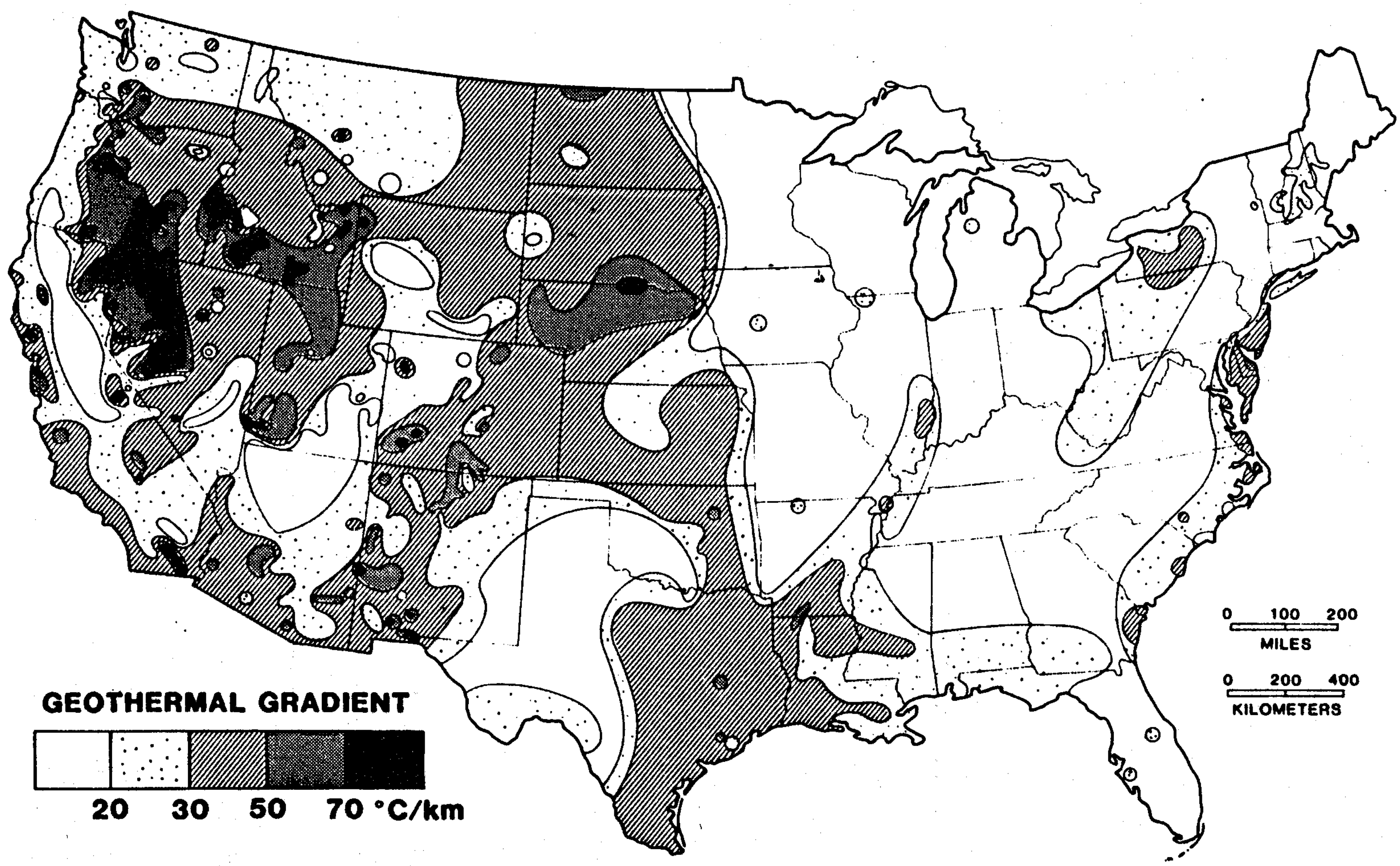
> **Provide the technology to enable industrial hot dry rock tasks to generate power at 5 to 8 cents/kWh by 1997.**

Construction of a larger, deeper, hotter Phase II or "engineering" HDR system began at Fenton Hill in 1979. Two new wells were drilled and the reservoir was hydraulically fractured in December 1983. Various short-term flow tests followed, along with reworking of both wells. Current efforts are almost exclusively focused on the preparation of the Long-Term Flow Test (LTFT) which will aid in estimating the thermal lifetime and determining the productivity of the reservoir.

The two principal projects under this category are Fenton Hill Operations and Scientific & Engineering Support, as shown in Figure 15. The site operations cover the drilling and completion operations at Fenton Hill, the performance and evaluation testing of the reservoir, and the supporting environmental monitoring and operations systems. The scientific effort of the Scientific & Engineering Support project entails reservoir engineering, seismic analyses, tracer development and application, and modeling of important reservoir characteristics, such as fracture patterns, fluid flow, and thermal

FIGURE 13

GEOTHERMAL GRADIENT MAP OF THE UNITED STATES



Adapted from: A. Kron and J. Stix, 1982, Geothermal Gradient Map of the United States, National Oceanic and Atmospheric Administration, and Los Alamos National Laboratory.

FIGURE 14
HOT DRY ROCK CONCEPT
BLOCK DIAGRAM

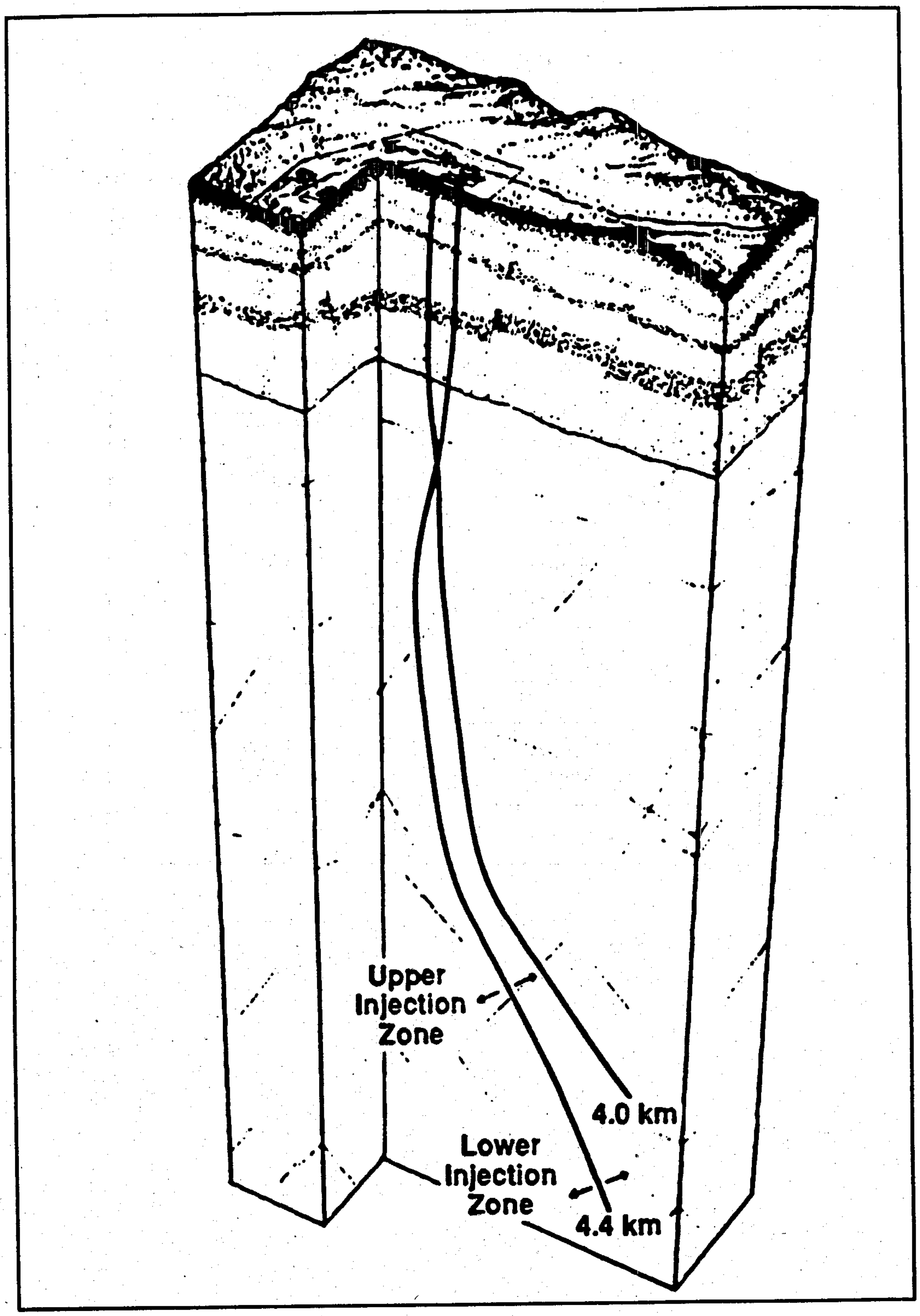
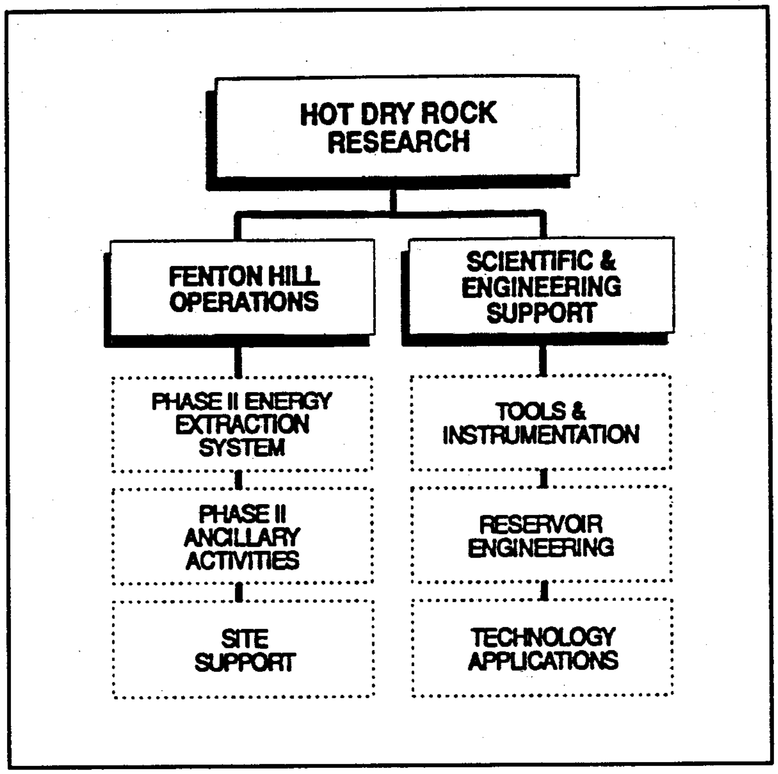


FIGURE 15
HOT DRY ROCK RESEARCH
WORK BREAKDOWN STRUCTURE



drawdown. Engineering support involves the design and construction of the surface loop for the LTFT to permit safe and reliable operation with maximum operating flexibility.

FENTON HILL OPERATIONS

There are three tasks under the Fenton Hill Operations project. The activities are involved with accomplishing the Level II objectives to:

> **Evaluate the performance of the Fenton Hill Phase II reservoir by 1993. That performance consists of system operating characteristics, including thermal drawdown, energy output, reservoir impedance, and water consumption.**
>
> **Determine the environmental acceptability of the technology.**

The **Phase II Energy Extraction System** task addresses wellbore completion and the surface system design, procurements, installation, and testing. **Phase II Ancillary Activities** includes diagnostic logging and environmental monitoring. The **Site Support** task pertains to water supply and site maintenance.

Phase II Energy Extraction System

Task Description
The Level III objective of the Phase II Energy Extraction System task is to:

> **Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics by 1993.**

Activities include short- and long-duration flow tests of the Phase II reservoir at Fenton Hill. During the period of thermal drawdown, parameters such as reservoir behavior, geochemical interactions, and fluid loss will be measured. Testing and modeling techniques to determine the effective energy production and longevity of fractured HDR reservoirs will be developed.

A long-duration flow test was conducted on the shallow, cooler, Phase I reservoir in 1979. In December 1983, a massive hydraulic fracturing operation created the man-made reservoir to be used as part of the HDR Phase II system. With the successful sidetracking operation in 1985, the flow loop was completed and available for open-loop testing. Since the completion of the Phase II reservoir, two short-duration flow tests have been conducted (a 7-day and 30-day test). Based in part on the results of those tests, a test plan is being developed for a long-duration flow test. Both Phase II tests were conducted open-loop, but the long-duration test will be closed-loop, i.e., after extracting the energy, the produced fluid will be reinjected. The surface equipment for the test is being procured and installed.

Fiscal Year Accomplishments
During FY89, comprehensive engineering and cost-benefit studies were conducted to address issues pertaining to the design of the surface installation for treating, cooling, and reinjecting reservoir production during the LTFT. The studies recommended plunger pumps over centrifugal pumps for the high-pressure injection pumps; diesel power over electrical for powering the pumps; and Nitronic steel over carbon steel for pump construction material on the basis of reliability, cost, and compatibility for the operation of the LTFT. A request for bids on the LTFT injection pumps having a total capacity of up to 8 barrels per minute at 4,500 psi was prepared and released.

Specifications were developed and design work initiated on the gas and particulate separator required for protection of the high-pressure injection pumps.

Fabrication and installation of an antifreeze system to prevent a shutdown of the heat exchangers during freezing weather was completed. Also completed were the installation of high-pressure suction piping from the pump house to the planned location of the high-pressure pumps and the installation of the Myers (system makeup) pumps.

Measurement of irrecoverable water losses during operation of the reservoir began in March. By the end of FY89, analysis of the data indicated that the rate of water loss from the margins of the reservoir was 6 gallons per minute, and still decreasing, at the pressure at which the reservoir will be operated during the LTFT. This observation resulted in a large reduction in the estimate of the amount of water needed for the test; significant cost savings can be expected.

Future Plans
Task activities will continue to focus exclusively on the preparations for the LTFT. The procurement and installation of all of the major equipment items for the LTFT surface facilities will be accomplished, and the design and installation of the remaining piping runs will be completed.

The specification, procurement, and installation of the LTFT control and data acquisition systems will also be completed. Surface systems will be integrated and undergo a comprehensive set of operational acceptance checks. A comprehensive risk analysis will be completed, as well as a handbook for operation of the surface facilities.

Phase II Ancillary Activities

Task Description
The Phase II Ancillary Activities task primarily includes efforts such as surface and downhole seismic monitoring during and immediately following downhole pressure/flow operations, and sampling and chemical/biotic analysis of site water supplies. These efforts support the Level III objective to:

> **Verify that the environmental consequences of HDR development are acceptable by 1997.**

Monitoring provides environmental surveillance and documentation as required to satisfy state and federal environmental regulations and to establish an environmental baseline which may be used to assess environmental effects. Seismicity at Fenton Hill and in the surrounding vicinity is monitored continuously to determine any undesirable response from long-term operations. The environment at Fenton Hill has been monitored for over ten years. Geochemical analyses have been conducted on the fluids used for the Fenton Hill experiments. This has been especially important during the short- and long-duration flow tests. In addition, samples from the area's springs, streams, lakes, and water wells have been analyzed since 1975. Water from the on-site well is analyzed for organics on a monthly basis and a full chemical analysis is conducted annually. Seismic monitoring is conducted during injection and production experiments to detect any abnormal seismicity in the surrounding area and microseismic event monitoring is used to determine the presence of thermal stress cracking and the extent of the active reservoir. In addition, occasional noise level and illumination measurements are made during various types of site operations.

Fiscal Year Accomplishments
A digital event-recorder for environmental monitoring of natural background seismicity at Fenton Hill was purchased and installed during FY89. The instrument was triggered by several earthquakes; however, none of the events was determined to be associated with the activities at Fenton Hill.

The cleaning and surveying of the EE-1 one million gallon pond was completed during FY89 in order to provide an accurate measurement of its volume and to enable the design of a pond liner.

Future Plans
In FY90, the EE-1 pond will be lined in preparation for use in the high back-pressure tests later in the year and for the LTFT in 1992.

The seismic detection package in GT-1 will be pulled, reconditioned, and re-inserted in the well. The surface signal conditioning and transmission electronics from the three borehole precambrian stations will also be reconditioned and upgraded.

Site Support

Task Description
Activities encompassed by this task are directed at maintaining the site in the condition necessary to perform the planned experimental operations. Activities include access and on-site road grading, graveling and snow removal, building and utility maintenance, housekeeping, maintenance of the flow loop, uninterruptible power supply (UPS) system and freeze protection system, maintenance of emergency vehicle and facilities, maintenance of water storage and transfer facilities, multiple handling of workover towers, site security, handling of visitors, and site safety.

Fiscal Year Accomplishments
In FY89, tests of an exploratory water well were conducted to evaluate the aquifer from which Fenton Hill water is currently drawn. The tests showed that the well was suitable for providing all of the additional water needed for the LTFT and an application to obtain a permit to withdraw water from the well was filed with the New Mexico State Engineer's Office.

Future Plans
In November 1989, the inner casing in GT-2 parted and abruptly rose 3 feet. Subsequently, it was confirmed by a television inspection that the casing had failed at a collar at a depth of 1,020 feet. Because of the particular type of wellhead completion at wells EE-2A and EE-3, these wells are susceptible to similar failure. In FY90, a casing anchoring system will be designed and constructed at these wells so that spontaneous large vertical upward movements of casing will not be possible.

SCIENTIFIC & ENGINEERING SUPPORT

The Scientific & Engineering Support project consists of three tasks. The research activities support the Level II objectives to:

> **Evaluate the performance of the Fenton Hill Phase II reservoir by 1993. That performance consists of system operating characteristics, including thermal drawdown, energy output, reservoir impedance, and water consumption.**
>
> **Improve the performance of drilling and completion technology under conditions typical of hot dry rock environments by 1997.**
>
> **Evaluate the economics of the technology.**

The **Tools & Instrumentation** task covers downhole instrument improvements, and calibration and maintenance of existing system instrumentation. Modeling activities, analyses of microseismic, tracer and geochemical data, and the design and planning of the experimental program are conducted as part of the **Reservoir Engineering** task. The **Technology Application** task pertains to technology transfer, report preparation, and a comprehensive HDR Systems Study.

Tools & Instrumentation

Task Description
The Tools & Instrumentation task addresses downhole instrument improvements needed for fracture detection and the development of reservoir mapping techniques to locate production well sites. The Level III objectives for this task are to:

Improve instrumentation and hardware to control, locate, and measure fracture propagation in hot dry rock reservoirs by 1995.

Establish reservoir mapping techniques to locate drilling targets for production wells by 1995.

Variable-pressure flow tests of the Phase II reservoir at Fenton Hill are being investigated to detect fracture propagation and fluid entry and exit locations in the wellbores. Acoustic techniques, particularly the study of microseismic events, are the best means by which direct information can be obtained about reservoir changes away from the borehole.

Analyses of seismic data obtained during the massive hydraulic fracturing experiment conducted in 1983 are continuing and improved seismic systems will be tested for their fracture measuring abilities. Instrument requirements will be developed for measuring and locating seismic events using a single wellbore (injection well) during the fracturing operation and maybe a second wellbore (production well), which would be only partially completed. In order to accomplish this, new instruments, data evaluation systems/techniques, and software are needed. Using the results of the Long-Term Flow Test (LTFT) and the analysis of hydraulic fracturing activities, specifications will be developed and prototype hardware bench tested.

Fiscal Year Accomplishments
No activity associated with logging tool research and development was scheduled for FY89. Surface measurement instrumentation continued to be calibrated.

Future Plans
A pressurized entry system will be designed and built for insertion of LANL logging tools into EE-2A, which will be the production well during the LTFT.

Reservoir Engineering

Task Description
The Reservoir Engineering task supports research in modeling, microseismic, tracer, and geochemical analyses, and the design and planning of the experiments at Fenton Hill. The activities are aimed at achieving the Level III objectives to:

Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers by 1994.

Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system by 1995.

Determine means to locate accurately the intersection of fractures with the wellbore by 1997.

Complete studies on water-rock interactions and their effects on flow through a hot dry rock reservoir by 1993.

During the Phase I energy extraction experiment, several techniques were used to estimate the size and lifetime of the reservoir. Methods include monitoring the changes in the chemical makeup of the extracted fluids and the injection of chemically reacting tracers. Tracers were used during the Phase II 30-day, open-loop circulation test at Fenton Hill. The test helped to further the development of implementation techniques and to verify the tracer models designed to estimate the thermal lifetime of the reservoir. The fluid was filtered to reduce the number and concentration of its constituents and, because of the expected dilution of the fluid, laboratory measurement techniques were identified for measuring very low concentrations of tracer species -- parts per billion.

A prototype high-temperature televiewer to map irregularities and discontinuities in the wellbore has been built and field tested. Fractures have been identified in the openhole section of an HDR well and confirmed using data from other sources. The advancement of acoustic techniques, particularly the study of microseismic events, has provided a significant method by which information about changes in the reservoir can be obtained from locations away from the boreholes. Using the automated three-point method, the existence of planar structures within the reservoir has been postulated and the resulting information used to select targets for the redrilling of well EE-2A. Analytical techniques have been identified that may assist in estimating the orientation of the strike and dip of the native rock and its tectonic stress.

A single-well, seismic measurement technique, such as the hologram method, will be developed for minimizing the number of observation points required to locate and characterize the man-made reservoir. A technique of this type is required for commercial systems to complete the drilling of the production well and design the completion for the injection well.

Spectral analyses and fault plane solutions for seismic events generated during previous experiments have been carried out. The seismic data acquisition and analysis system will be improved. The results will be verified using data developed during the LTFT, such as gamma logs, temperature surveys, spinner surveys, caliper logs, televiewer surveys, geologic data, wellbore cuttings, geochemical analysis, and other relevant data. Discrete fracture planes will be identified by application of the recently developed "3-point" method. The approach will increase the chance of success of any given system and reduce the cost of drilling wells by minimizing the need for additional wells.

HDR reservoir fluids have been monitored since the first Phase I loop experiments at Fenton Hill. The constituents of the fluids have been used to determine reservoir contaminants, estimate the ambient temperature of the reservoir, evaluate the geology of the reservoir, and estimate the expected lifetime. Models have been constructed to fit the available data. Ongoing studies of the geochemistry at Fenton Hill provide assurance that the technology is environmentally acceptable. These studies also allow detailed reservoir analyses and modeling of hydraulic and thermal performance, aid in determining fracture locations, and provide information on water-rock interactions and their effects on flow through the reservoir. Assessments of the potential impact on the system from scale/corrosion/erosion will be made and procedures will be developed to protect the surface system and the reservoir, if needed.

Other models have been created to predict the behavior of the man-made system. As more knowledge is gained of the processes involved, the models have been modified to better represent the reservoir characteristics including heat content, lifetime, flow geometry, impedance, water loss, hydrochemistry, and mineral dissolution/opposition. Analyses to date have been sufficient to verify the HDR concept, but have not adequately reduced the technical and economic risks associated with a commercial system. It is anticipated that analysis of the Long-Term Flow Test data, when available, will verify the hydraulic and thermal models developed to represent the HDR system. As the models evolve, they will be used as design bases for commercial systems.

Fiscal Year Accomplishments

A temperature/collar-locator log was run in well EE-2A prior to reinitiation of Experiment 2077 which is measuring the reservoir leak-off rate as a function of time. The data indicated that the wellbore had essentially recovered to background temperatures, as shown in Figure 16. It also showed that a small region with depressed temperatures still exists below 11,300 feet. This depth corresponds to the injection zone depth for two previous experiments and the depth of the massive hydraulic fracture (MHF) of December 1983.

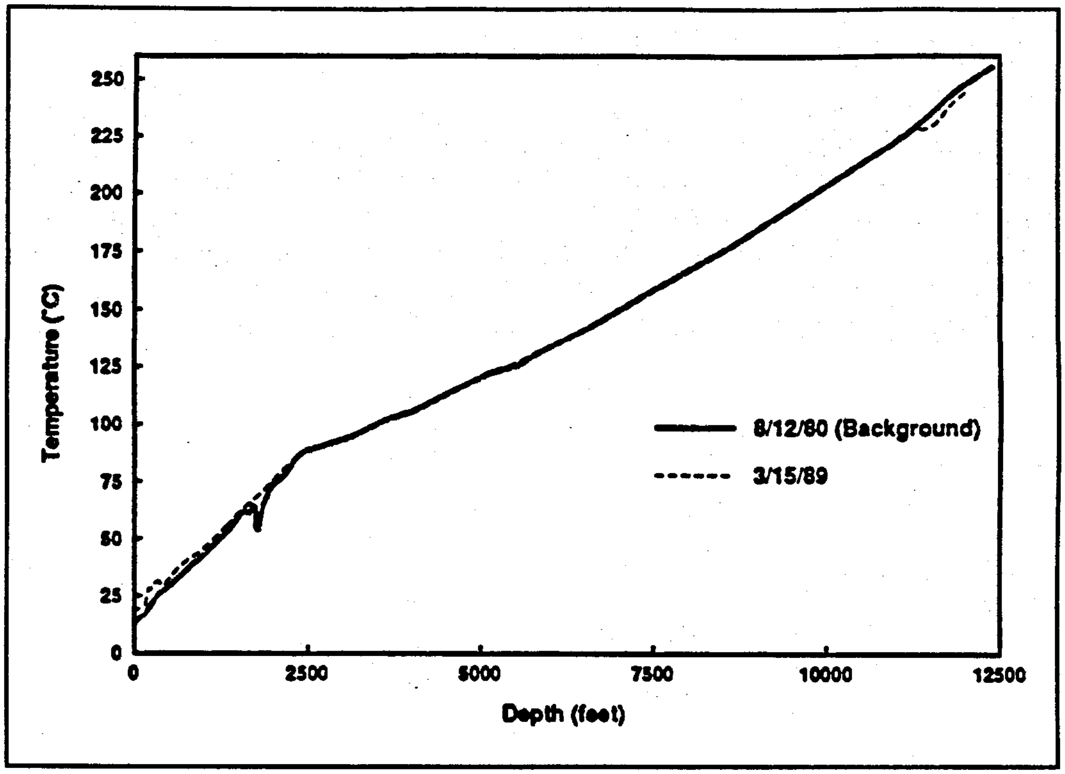
Automated processing of the seismicity data recorded during the construction of the reservoir was performed. The results furnished details of the reservoir geometry that were not previously available and provided further explanation for the collapse of the casing in the EE-2 well.

During FY89, laboratory measurements of the reactive tracer p-bromonitrobenzene showed that adsorption of the chemical in the reservoir will be sufficiently small so that it can be used in estimating the growth of the cooled volume surrounding the injection well during the LTFT. In addition, the threshold for the detection of the tracer in reservoir fluids was reduced to 0.2 ppb allowing for improved measurement of the tracer at low levels.

Evaluation of simulations of reservoir performance using the FRACNET model were made and the results suggested that operation of the reservoir at high production back-pressures may reduce flow impedance, and hence reduce the hydraulic horsepower required to operate HDR systems. Other simulations, which incorporate the geochemistry of silica, suggested that removal of silica from production fluids would effectively remove silica from the region surrounding EE-2 where high impedance to flow now exists. Both silica removal and higher production pressures are currently under study for incorporation into the LTFT. Also during FY89, the computer model FRACNET was expanded to account for changes in the aperture of reservoir fractures due to pressure. The FRACNET model evaluates seismic events during pressurization tests and flow tests.

FIGURE 16

COMPARISON OF BACKGROUND VS. RECENT TEMPERATURE SURVEYS



Future Plans
The measurement of water loss as a function of reservoir pressure and time will continue (Experiment 2077). The measurement of reservoir impedance under high back-pressure (Experiment 2078) will also take place during FY90. Taken collectively, the results of these experiments will define the optimum operating conditions for the LTFT. The FRACNET model will continue to be used to explore means for improvement in the performance of the reservoir.

Technology Applications

Task Description
The activities comprising the Technology Applications task are technology exchange, report preparation, and a comprehensive HDR systems study. Efforts are directed at accomplishing the Level III objective to:

> **Determine if the performance of the Fenton Hill Phase II reservoir, when considered as a unit reservoir in a commercial-scale project, could support production of electricity at an economical busbar cost by 1995.**

A preliminary economic assessment of electric generation applications has been conducted by EPRI from the utility viewpoint and several HDR economic studies have been performed by other organizations (i.e., the Los Alamos National Laboratory; Bechtel National, Inc.; and the United Kingdom Department of Energy).

A continuing effort is devoted to promulgating system engineering and resource information, as well as hardware developments, from the HDR Program to the energy-producing and other interested industries and to cognizant government and educational institutions. Reciprocally, such liaison affords access to current industrial technology for application in the HDR Program.

Fiscal Year Accomplishments
The transfer of knowledge and developed technology in such areas as drilling, well completion, and hydraulic fracturing continues.

LANL personnel applied the experience gained at Fenton Hill to the identification of potential hot dry rock locations for the siting of a power plant for the municipality of Clearlake, California. This study was completed.

LANL personnel are also participating in activities aimed at mitigating the pressure decline at The Geysers. In particular, contributions are being made pertaining to the mechanical properties of fractured reservoirs.

Future Plans
The planning for a comprehensive systems study will begin in FY 1991. Results from flow tests (the LTFT is critical) will be combined with data on the cost of wells and cost/performance of binary power plants to estimate overall cost of power from

commercial-scale projects. Other important inputs will be the results of the HDR experiments conducted by other countries, i.e., Japan, United Kingdom, USSR, Sweden, France, and West Germany. An important outcome is the transfer of the system engineering and resource information, as well as hardware developments, from the HDR program to the geothermal industry. Reciprocally, such exchange affords access to current industrial technology for application to HDR technology.

Work with the Clearlake, California, municipal authorities to establish the feasibility of implementing hot dry rock technology for electric power applications at Clearlake will continue. The possibility of using hot dry rock technology in an integrated treated-waste water disposal/power generation facility for the Clearlake region will be explored.

MAGMA ENERGY RESEARCH

Thermal energy contained in magmatic systems represents a huge potential resource. In the U.S., useful energy contained in molten and partially molten magma within the upper 10 km of the crust has been estimated by the USGS to be approximately 500,000 quads. The Magma Energy program is focused on determining the engineering and economic feasibility of locating, accessing, and utilizing magma as a viable energy resource. The feasibility is dependent on the size and depth of the magma body, drilling costs, problems encountered in completing the wells, energy extraction rates, and material lifetimes. The research activities are conducted to accomplish the Level I objective to:

> **Create a technology by which energy could be produced experimentally from magma at an equivalent cost of 10 to 20 cents/kWh by the year 2000.**

As shown in Figure 17, two projects have been organized to address the issues associated with this objective. The Long Valley Operations project encompasses the activities required to drill an exploratory well. Laboratory and Engineering Support pertains to the development of drilling techniques for use in hot, magmatic environments and the investigation of various energy extraction processes.

LONG VALLEY OPERATIONS

The Long Valley Operations project seeks to confirm the existence of a magma body at a known depth near the resurgent dome of the Long Valley caldera. An independent DOE review panel finalized the location of the Long Valley, California, drill site in January 1988. Since that time, a drilling permit has been issued by the Bureau of Land Management (BLM) and well design specifications have been completed for all drilling phases. This project will assist in refining the geophysical description of the caldera, verifying methods to locate magma bodies, and developing drilling technology applicable to very high temperature environments. The activities strive to accomplish the Level II objective to:

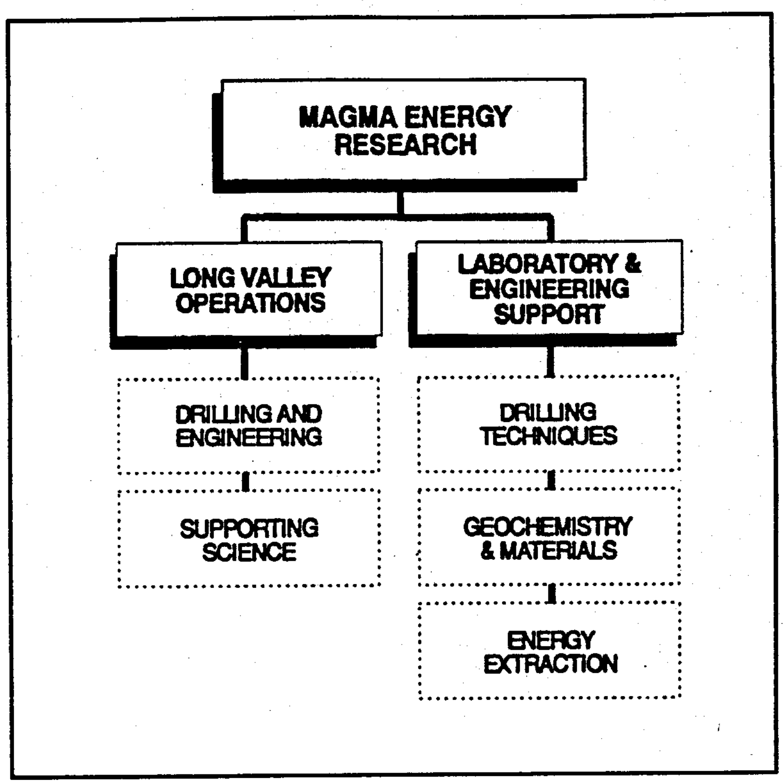
> **Improve the technology for locating and characterizing magma bodies with 90 percent confidence by 1994.**

The **Drilling and Engineering** task supports operations at the exploratory well site. The **Supporting Science** task includes activities such as analyses of well measurements and evaluations of fluid and core samples.

Drilling and Engineering

Task Description
The Drilling and Engineering task includes activities related to the drilling of an exploratory well at Long Valley, California. The caldera is a large silicic volcanic center typical of the resource base. An exploratory well deep into the caldera system, as depicted

FIGURE 17
MAGMA RESEARCH
WORK BREAKDOWN STRUCTURE



in Figure 18, will provide important new information about the current state of magma at this location as well as provide a test of existing geophysical models that predict magma at depths of 5 to 7 km beneath Long Valley. These activities will assist in achieving the Level II objective to:

> **Confirm the existence of a shallow magma body with the drilling of an exploratory well by 1992.**

An exploration well is the only sure means to confirm the existence of a magma body. Observations from the well should enable precise measurements of the body's size, shape, and location. The well should also enable the testing of first generation drilling techniques and materials required to enter into a magma body.

The magma energy exploratory well is planned to be drilled in four phases, as shown in Figure 19. The aim is to drill toward, but not into, the magma body that is believed to underlie Long Valley caldera. The target is a depth of 20,000 feet or a bottomhole temperature of 500°C, whichever comes first.

Fiscal Year Accomplishments
Phase I drilling of the Magma Energy exploratory well was conducted over a 35-day period beginning in August 1989. Figure 20 shows the Loffland Brothers Rig No. 202, with a 30,000-foot depth capacity that was used in Phase I drilling. The target depth for this phase was 2,500 feet -- the 20-inch casing point. The well was successfully drilled to a total depth of 2,568 feet, and had less than 3/4° deviation. It provides an excellent foundation for deeper drilling.

Massive lost circulation was encountered between 70 and 1000 feet and 29 cement plugs were placed in order to restore circulation. During these episodes, fluid losses were generally extreme (hundreds of barrels within a few minutes). Conventional lost circulation material proved to be ineffective and therefore, new techniques (i.e., ground tires) were explored.

Upon reaching total depth, a small suite of wireline logs was run and the 20-inch casing was set. A 186-foot core of Bishop Tuff was recovered for scientific evaluation below the 20-inch casing using a wireline-retrievable core barrel adapted from the Ocean Drilling Program. Installation and testing of the wellhead completed the major part of the Phase I operations.

Future Plans
Phase I drilling of the well was successfully completed during FY89. Additional drilling (Phases II-IV) of the exploratory well to a depth of 20,000 feet or a bottomhole temperature of 500°C is under review.

FIGURE 18

LONG VALLEY EXPLORATORY WELL

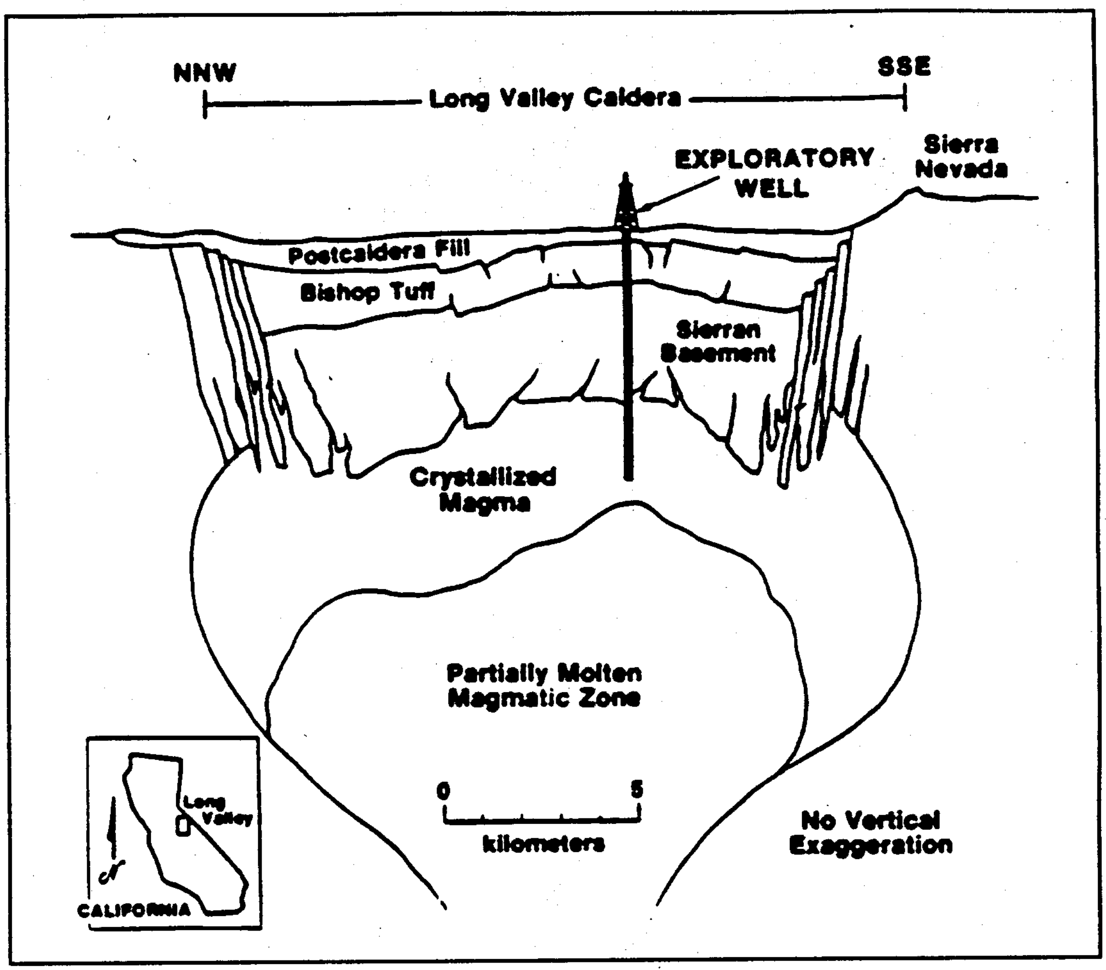


FIGURE 19

WELL DESIGN FOR LONG VALLEY EXPLORATORY WELL

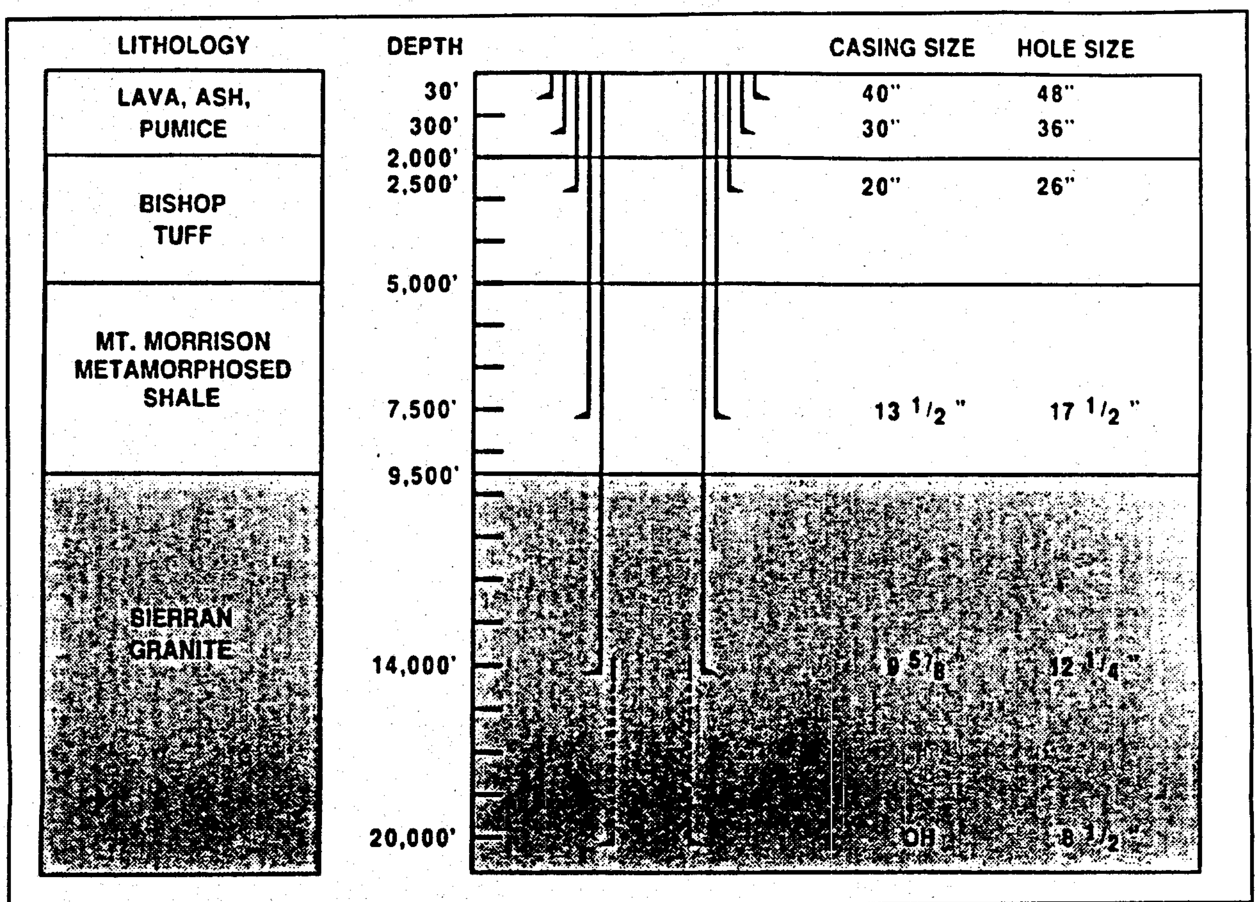
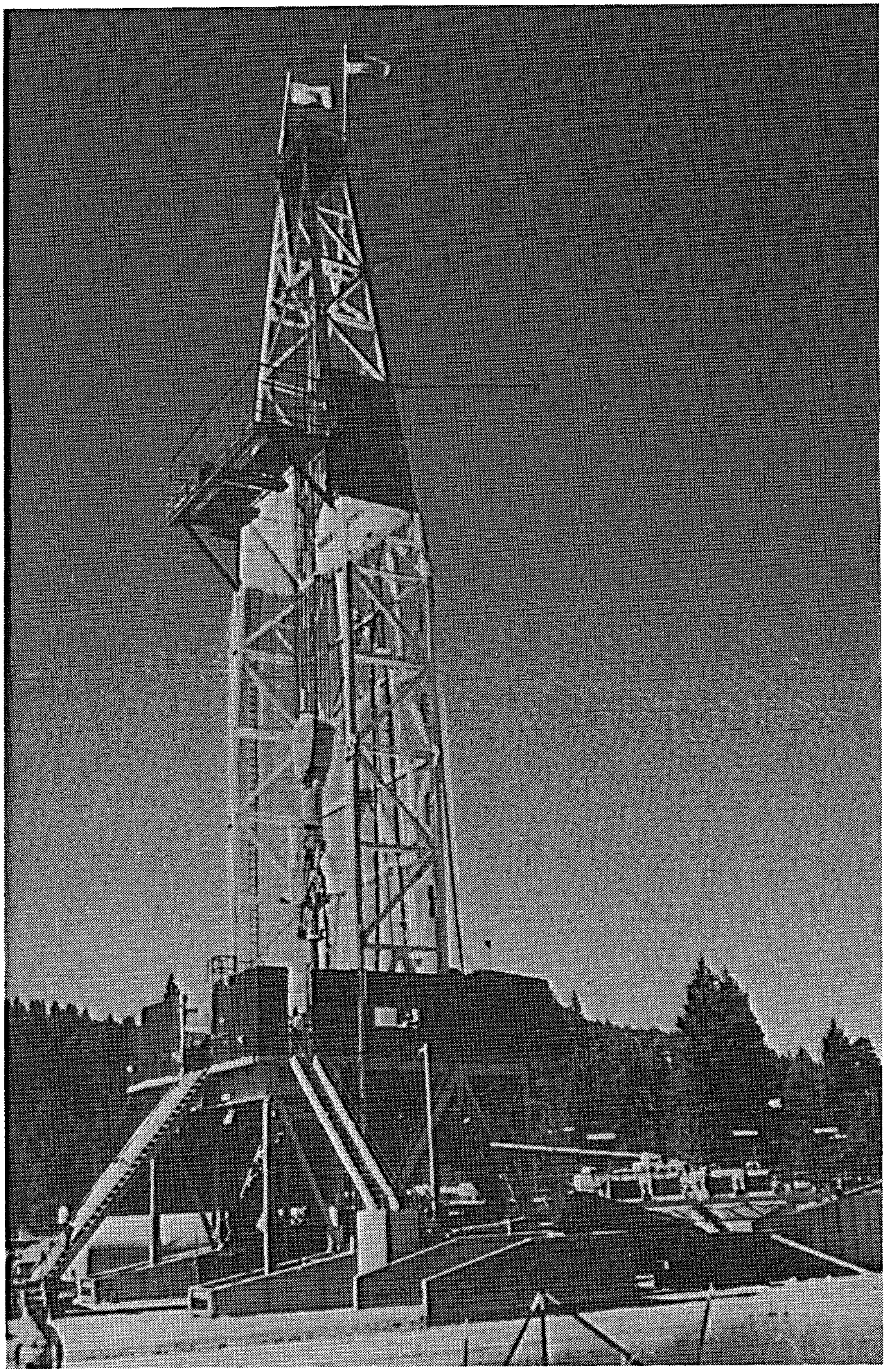


FIGURE 20

DRILLING RIG AT LONG VALLEY SITE



Supporting Science

Task Description
This task pursues the basic research required to confirm the presence of a magma body beneath the Long Valley caldera. The activities include analysis of core samples, thermal measurements, downhole fluid samples, seismic data, and stress measurements, and the establishment of baseline conditions for future comparisons with data obtained at progressively greater depths. The Level III objective for the Supporting Science task is to:

> **Understand the nature of geophysical anomalies at the Long Valley caldera using well observations data by 1992.**

Geophysical methods have proven successful in identifying likely magma targets. Twenty-one potential sites were evaluated in terms of suitability for conducting a long-term energy extraction experiment. Long Valley ultimately was selected as the primary site based on the extensive geophysical, geological, and geochemical studies completed in the area. Dynamic evidence indicates that the caldera has undergone exceptionally large, time-dependent deformations since 1980, as well as intense local seismicity both within the caldera and regionally. However, the many studies have not resulted in any conclusive evidence regarding the best site to drill in the caldera. Geodetic and other data show anomalies in the basement beneath the resurgent dome and beneath Mammoth Mountain. In addition, some data support a possible magma source in the western portion of the caldera based largely on a high-temperature hydrothermal system.

Until a magma exploratory well is drilled, there is no way to determine the nature of identified geophysical anomalies at the Long Valley caldera. The well, planned in the south-central portion of the caldera, will allow downhole measurements without the attenuation and structural complications introduced by caldera fill. Once the well is beyond a depth of 7,000 feet, geophysical measurements will be made. Results from these measurements will be correlated with the abundant surface data available on the caldera.

A Magma Science Panel has been established to coordinate the scientific experiments in the well. Other groups, besides GTD, are participating in the scientific aspects of the Long Valley operations and include the National Science Foundation, the U.S. Geological Survey (USGS), and the DOE's Office of Basic Energy Science (DOE/OBES). The overall plans for the supporting science activities have been developed and are described in the Long Valley Science Guide.

Fiscal Year Accomplishments
The first phase of drilling a magma exploratory hole did not explore new territory in terms of depth since a number of holes within the caldera have penetrated as deep or deeper. However, the hole did provide the first core from a central caldera location including significant intervals of post-caldera intrusives. Thus, even at this early stage, the hole has added significant insight to understanding the structure and history of the Long Valley caldera.

The new hole indicates that there is considerable local relief on the Bishop Tuff surface (700 feet [200 m] over a horizontal distance of 3,000 feet [1,000 m]). Because this relief is not expressed in surface topography and is at too low an elevation to have resulted from erosion, it must have resulted from faulting before much of the post-caldera volcanic sequence had developed. Apparently, post Bishop-eruption collapse and resurgence was irregular, breaking the Bishop surface. The new hole also shows that the post-caldera eruptive sequence is exceptionally tephra-rich at this central location compared to sites on the flanks of the resurgent dome where lavas predominate. The reason for this distribution of lithologies is not known.

Although there are insufficient data at this early stage of drilling to generalize, it is speculated that the central caldera location of the exploratory hole is one of intense intrusive activity. The hole may encounter many more such features as it advances toward the central pluton beneath the caldera. It is entirely possible that the accepted models are incorrect and that no basement exists under the site, having been displaced downward by the rising, long-lived pool of magma. When linked chemically to their dated eruptive equivalents, these intrusions will provide a valuable history of activity of the Long Valley magma chamber.

A comprehensive reobservation of the network of gravity stations established 8 years ago was conducted. These data will be processed and analyzed for changes in gravity indicating crustal distortion.

During FY89, an agreement to designate the Long Valley exploratory well as a part of the Continental Scientific Drilling Program (CSDP) was finalized by DOE, the National Science Foundation, and the USGS. A Magma Energy Science Panel was established under the CSDP Management Agreement Guidelines and the Science Guide was completed for all four phases. The Science Guide identifies important scientific issues and downhole measurements in hydrothermal systems, geology/petrology, geophysics, and stress and mechanics.

The Magma Energy Science Panel also prepared a post-Phase I science proposal which was submitted to DOE/OBES for funding consideration. This proposal resulted in DOE/OBES funding a major portion of the post-Phase I scientific corehole.

Future Plans
Borehole seismology studies, electromagnetic evaluations, stress measurements, and thermal analyses will be conducted. Data from the gravity stations will be processed and analyzed for indications of crustal distortion. Detailed analyses of the recovered core will be conducted to determine the history of the caldera, to identify intrusive events, and to describe the stratigraphy.

LABORATORY & ENGINEERING SUPPORT

Investigations of various drilling techniques, geochemistry, materials compatibility, and energy extraction processes are conducted within the Laboratory & Engineering Support project. The activities support the Level II objectives to:

Design the first-generation technology needed to extract energy from a magma body by 1997.

Drill, complete, and test a magma energy extraction well capable of producing 30 MWt by 1997.

Determine design specifications of required energy conversion equipment by 1996.

Determine the engineering feasibility of extracting thermal energy from a magma chamber by 1999.

Research in the **Drilling Techniques** task includes the development of insulated drill pipe. The evaluation of commercially available materials for resistance to corrosion in rhyolitic magma is the focus of the **Geochemistry & Materials** task. The **Energy Extraction** task addresses concepts for demonstrating the feasibility of magma energy extraction.

Drilling Techniques

Task Description

For a prospective magma extraction process to succeed, there must be drilling technology and materials available to withstand the higher temperatures, pressures, and volumes of dissolved gases expected in a magma environment. The Drilling Techniques task focuses on research associated with drilling a deep hole into magma and supports the Level III objective to:

Design and develop technology capable of drilling into molten magma at temperatures of at least 900°C and total depths of at least 5 km by 1992.

One area of research involves investigations of creep in viscous rock that could cause the wellbore to squeeze in behind the bit during drilling. The Hard Rock Penetration task is addressing the problem of extreme heat by examining the use of an insulated drill string to control drilling fluid temperatures. Drilling fluid temperature affects the performance of additives and the strength and corrosion rate of tubulars, bit life, and borehole stability. For these reasons, the design of insulated drill string has become a crucial need for magma research.

Other research activities pertain to general wellbore stability and the problems of creep of the surrounding hot rock and reheating of the surrounding rock after circulation is lost. Studies of high-temperature weighting materials for the drilling fluid and materials for casing support are being performed.

Fiscal Year Accomplishments

Drilling technology development for the magma program is funded through the Hard Rock Penetration task. Activities have focused on development of insulated drill pipe for drilling in deep, hot environments. Proposed designs for insulated drill pipe (IDP) were received from two companies which presently make insulated tubulars for steam injection. Further analysis at Sandia National Laboratories showed that insulation in the tool joints is essential to achieve adequate performance by an insulated drill string. Since the industry designs did not address the question of tool joint insulation, the Sandia effort focused on generating a conceptual design for an insulated tool joint. The most promising candidate was one that included ceramic insulating sleeves at the inside diameter of the joint, providing enough insulation to bring the total drill string conductivity down to that used in the theoretical model.

Requests for Quotation were sent to tubular manufacturers for the pipe bodies and to ceramics companies for the tool joints with ceramic liners installed. Satisfactory responses for both items were received and coordinated purchase requisitions that would provide assembled sections of IDP were prepared. After preparation of the purchase requisitions, budget uncertainties prevented their placement and the requisitions were cancelled.

Future Plans
Near-term activities for this task are reported in the Hard Rock Penetration section of this document.

Geochemistry & Materials

Task Description
The emphasis of the Geochemistry & Materials task is on the characterization of the magma and the determination of materials capable of withstanding the hot and corrosive magmatic environment. The Level III objectives to be accomplished by this task are to:

> **Evaluate performance of materials in the corrosive and volatile-rich magma environment for use in drilling tools by 1992.**
>
> **Predict rates for dissolution of silicate minerals and the composition of fluid in rock-to-water heat exchanger system, and evaluate the potential for loss of permeability due to precipitation of secondary minerals by 1995.**
>
> **Evaluate magma degassing hazards associated with drilling and energy extraction at Long Valley, California.**

Research efforts involve the performance of materials, including high-temperature casing support and weighting materials. The work addresses the characterization of commercial metals that are compatible with a rhyolitic magma environment.

Thus far, 17 commercially available alloys have been evaluated. Research results indicate that the corrosion problem for most alloys tends to be oxidation. Extensive testing of metals using simulated magma believed to be similar to the mineral composition and volatile concentrations of crustal bodies in the Long Valley caldera area was conducted. The test metal specimen, sealed with volatile-bearing rhyolite glass in a gold tube, was subjected to the desired pressure and temperature conditions to study selected parameters.

Research is being pursued on nickel-based materials which have proven to be the most promising alloys. Reaction rates between alloys and silicates are also being investigated.

Other activities strive to understand dissolution/transport kinetics by predicting silicate dissolution rates and solution composition in a direct-contact heat exchanger, and by evaluating the potential for loss of permeability due to precipitation of secondary minerals. An experimental facility has been built to study leaching and precipitation of minerals, specifically feldspars and quartz. These two minerals are expected to be prevalent in a magmatic system. Research focuses on determining the importance of several variables, such as pH, solution composition, and mineral defects on feldspar dissolution in aqueous solutions, and measuring quartz dissolution as a function of temperature, pressure, and orientation using a rotating disc autoclave. In addition, the physical processes involved in heat transfer from magma bodies will be studied and appropriate mathematical models developed.

Since drilling into a magma chamber has never been done, it is critical from a safety viewpoint to understand the hazards of a volatile-rich rhyolitic magma chamber. The degassing hazards of penetrating a magma chamber believed to contain silicate-rich minerals and free gases, particularly pressurized water vapor, will be studied. The geochemistry of magma (with emphasis on fluid inclusions) will be characterized in order to understand compositional variations and phase relationships, and flow and cooling patterns in simulated magma will be analyzed to provide an understanding of the dynamics of an erupting magma body.

Fiscal Year Accomplishments

In laboratory fluid-metal compatibility tests, hydrothermal solutions span the range of fluids in contact with the heat exchanger from pumped-in water to exsolved magmatic volatiles. A few Fe-based superalloys exhibited some evidence of corrosion; the Ni-rich alloys were only slightly tarnished, even after 45 days in a simulated magmatic brine. No other forms of corrosion were noted.

Results from the hydrothermal corrosion tests showed that the hydrous rhyolitic glass undergoes degassing and crystallization after a few days at normal heat exchanger operating conditions. Vapor bubbles were found within the hydrous glass and at the advancing crystallization front, and are the result of exsolution of magmatic volatiles from the glass. There was extensive alteration of the glassy rhyolite rubble to a cristobalite-feldspar-biotite crystalline assemblage and precipitation of silica and feldspar in the voids of the rubble. This is probably the result of fluid phase dissolution and transport of the reactive silicate rubble.

Silicate mineral dissolution in a downhole fractured magma heat exchanger is being studied to avoid problems of scaling or permeability reduction. Results obtained during FY89 have shown that minor amounts of iron in the hydrothermal fluid can effectively prevent quartz dissolution by precipitation of magnetite on the exposed quartz surface. This mechanism may be used to limit silica scaling in the heat extraction system.

Rates of magmatic vapor exsolution were measured during isothermal decompression and will be used in fluid flow and well control models to evaluate hazards associated with drilling into a magma body at pressures up to lithostatic.

Downhole heat extraction involves direct contact between an aqueous solution and a hot, fractured rubble of silicate minerals. Compatibility tests have demonstrated that the rhyolite rubble is susceptible to extensive dissolution and recrystallization in the presence of a fluid phase. Because flow characteristics in the rhyolite rubble could change as minerals dissolve and recrystallize, it is necessary to quantify the kinetics of mineral dissolution in hydrothermal fluids. Toward this goal, dissolution rates of quartz have been measured at 40 MPa in a boric acid solution (buffer @ pH=9) using a Hastaloy C-276 rotating disc autoclave system. Measured solubilities were found to be as high as 350 ppm Si at 300°C and results suggest that the dissolution mechanism for quartz should not change at the slightly higher temperatures and pressures expected in the severe hydrothermal environment of a downhole heat exchanger. Preliminary results in an acid solution (pH=3, HCl) indicate very low solubilities because of a protective coating of precipitated magnetite on the surface of the quartz sample.

Efforts to measure and characterize the dissolution of feldspar at low temperatures and pressures (25°-50°C and 0.1 MPa) in order to understand the mechanism of aqueous dissolution are being pursued. This study includes the entire plagioclase solid solution series, from albite (NaAlSi0) to anorthite (CaAlSiO). Initial results indicate that the rate of dissolution in acidic solutions is strongly dependent upon mineral composition.

Extraction of energy from a downhole heat exchanger will result in the cooling of the magma body, saturation of the magma with respect to volatiles (especially water), and exsolution of an aqueous fluid. Rapid, uncontrolled vapor exsolution of the hydrous rhyolite magma could lead to unwanted transport up the well. The extent of vapor exsolution was experimentally measured in hydrous rhyolite magma after a pressure drop from 150 MPa to 50 MPa in 1-600 minutes at 850°C. Ion microprobe analyses of these samples confirmed the results of bulk water analyses. The results indicated that the magma did not completely degas to the low pressure saturation level, but was limited by the diffusion of water through the melt. Analyses of experimental glasses which experienced isobaric crystallization also showed that degassing is incomplete (diffusion limited) even at cooling rates as low as 1°C per hour.

Future Plans
TBD

Energy Extraction

Task Description
The Energy Extraction task provides the research needed to demonstrate the engineering feasibility of magma energy extraction. The activities strive to achieve the Level III objective to:

Evaluate heat transfer effectiveness between a magma body and water circulating in the energy extraction wellbore.

By appropriate cooling during drilling, a borehole protruding into a body of molten magma will become surrounded by solidified magma. The volume of this solidified magma is expected to be highly fractured due to thermal stress. Energy extraction will be accomplished by circulating water from the bottom of the borehole through the fractured volume of solidified magma. Under steady-state operation, the extracted energy is balanced by the convective transport of energy from the molten magma to the solidified volume. The energy extracted is then converted into useful work at a surface plant. The Energy Extraction task includes studies of the fundamental mechanisms of solidifying and thermally fracturing magma, convective heat transfer within the fractured, solidified material, convective flow in the molten magma and heat transfer from the magma to the cooled heat exchanger protruding into it, numerical simulation of the overall energy extraction process, and the thermodynamics of energy conversion in a magma power plant at the surface.

A number of bench-scale magma energy extraction experiments have been completed. For example, experiments were carried out using a low-temperature simulant (plastic) to show that a magma-like material when solidified will produce a three-dimensional network of interconnected fractures. Also, a series of magma convection experiments -- using simulant material (corn syrup) with a viscosity of rhyolitic magma -- were conducted to provide additional insight for modeling the impact of magmatic convection. Research results from these experiments are producing needed guidelines for tasking energy extraction calculations from a magma body.

Ongoing research is directed at developing a fundamental understanding of an open, direct-contact heat exchanger in a crustal magma body. The energy extraction rate has a direct influence on the economic viability of the magma extraction concept. An open heat exchanger, in which fluid is circulated through the interconnecting fissures and fractures in the solidified region around the well, offers the promise of very high rates of heat transfer.

Fiscal Year Accomplishments

The extremely large magma viscosity variation with temperature was examined by performing an enclosed convection experiment using corn syrup as a magma simulant. The apparatus consisted of a lexan enclosure with horizontal dimensions of 0.56 m x 0.56 m. A 0.14-m-thick layer of syrup was heated from below by a centered strip heater, 0.14 m x 0.56 m, and cooled from above by a constant temperature plate. The experiments covered top-to-bottom viscosity ratios ranging from 3 to 1400. From the heat transfer data, a viscosity correction factor that can be applied to standard constant property heat transfer correlations was derived. This result is important because it enables the use of a large body of literature dealing with constant property flows. In addition to measuring the overall heat transfer between the heated strip and the top surface, velocity and temperature distributions were obtained.

The viscosity experiment was numerically simulated through the use of a state-of-the-art finite element computer program. The flow is characterized by two counter-rotating cells driven by a plume rising from the heated strip. The agreement between prediction and experiment is very good over the entire range of viscosity variations. With this experiment, the capability to calculate convective transport in magma was established.

In addition to the studies detailed above, the heat transfer process in the direct-contact heat exchanger was examined. The heat exchanger was modeled as an annulus filled with a porous material that was heated on the outside and cooled by a vertical flow of water through the porous bed. The use of a porous body to represent a fracture body is permissible since the fracture spacing (~1 cm) is much less than the overall dimension of the fractured body (~ tens of meters). Both numerical modeling and experiments were performed. Good agreement was obtained when the numerical model was compared to the experiment.

A numerical code called MAGMAXT was developed to simulate the flow of compressible, homogenous water/vapor within the well and the heat exchanger with heat transfer to and from the convecting magma and the overlying formation. The code allows arbitrary specification of a contiguous flow path through regions such as tubing, concentric pipe annulus, or the heat exchanger. Heat transfer between the injected water and the fractured body of magma comprising the direct-contact heat exchanger occurs in the radial direction only and is modeled as flow through a porous annulus. As the fluid is heated in the heat exchange region, its density decreases, resulting in a density imbalance between the injection and return flow paths. The flow loop has the capacity for natural thermosyphoning.

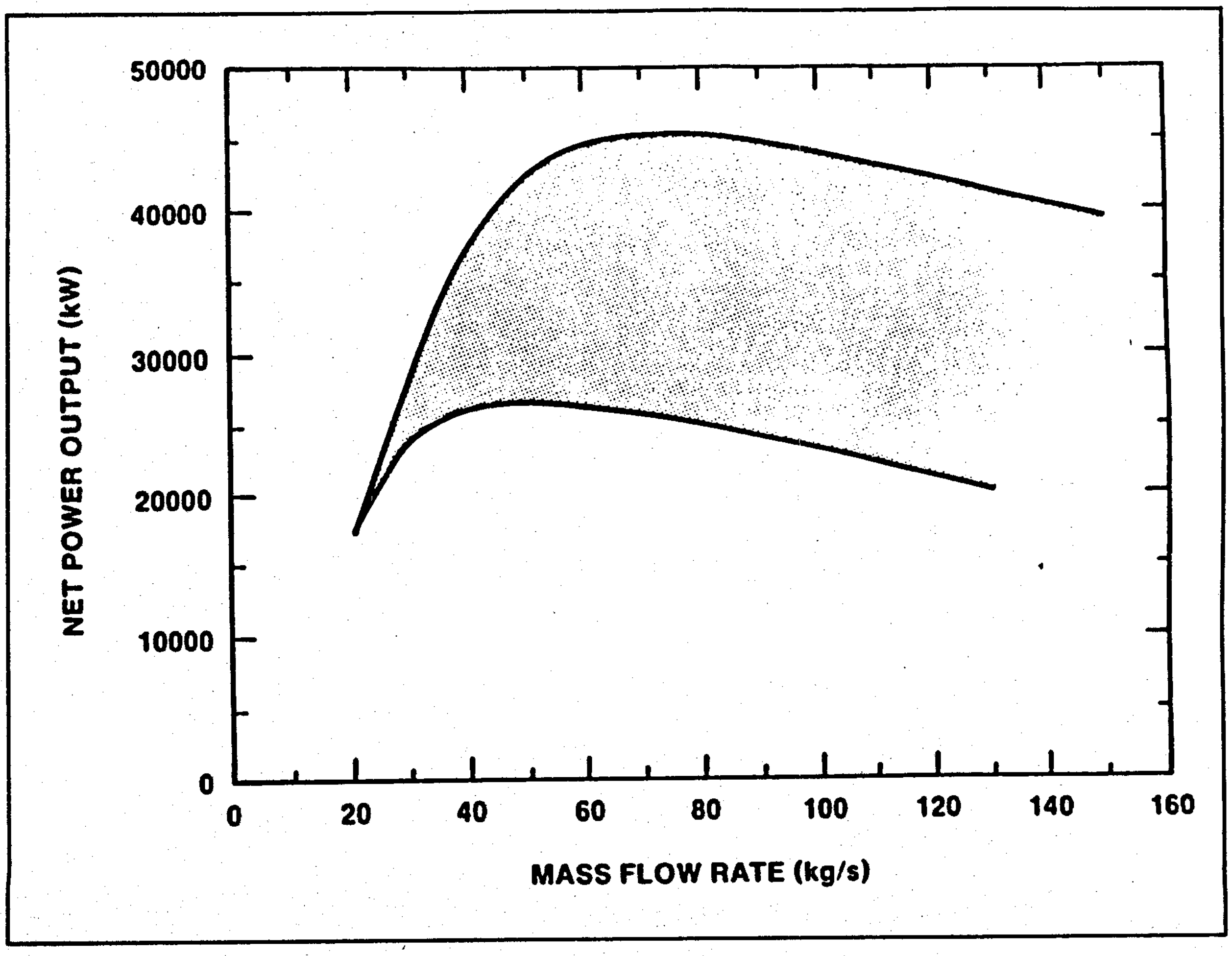
The overall thermodynamic performance of conceptual systems to convert the thermal energy from a magma well to electrical energy has been evaluated for a power plant utilizing a closed-loop Rankine cycle. In this cycle, a heat exchanger is used between the water circulating through the well and the power plant water. The closed-loop Rankine cycle is likely to be most practical in terms of corrosion and well control considerations because the well loop and the power loop are isolated from each other. Furthermore, in a closed-loop design, it is possible to exercise control over the cycle operating pressure for optimum performance.

The results of the closed-loop cycle analysis were obtained by stepping through different operating pressures for each flow rate. The net power output initially increases with mass flow rate because of increased energy extraction. However, the output temperature of the well decreases with flow rate, and the second efficiency decreases. As a result, an optimum flow rate exists for maximum net energy extraction, which is in the range of 50 kg/s with a corresponding net power output of 25 MWe to 45 MWe. Figure 21 depicts the most recent energy extraction projections for magma energy production from a single well.

Future Plans
TBD

FIGURE 21

MAGMA ENERGY EXTRACTION PROJECTIONS



APPENDIX A

GEOTHERMAL R&D PROGRAM

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- University of Texas at Austin (UTA)
- North Carolina Agricultural and Technical State University (NCA&T)
- University of California at San Diego (UCSD)
- University of Utah Research Institute (UURI)

Private Contractors

- Meridian Corporation
- Oregon Institute of Technology (OIT)

APPENDIX B

MANDATES FOR A

GEOTHERMAL RESEARCH PROGRAM

The Federal government has been actively involved in the development of geothermal energy since 1970, when the **Geothermal Steam Act** (P.L. 91-581) was passed. The Act provided for the leasing of federal lands for geothermal exploration and development. In 1974, the enactment of the **Geothermal Research, Development, and Demonstration Act** granted a continuance of research and development activities in geothermal energy technology and demonstrations in the utilization of geothermal resources, the creation of a Geothermal Energy Coordination and Management Task, and the establishment of a loan guaranty program for the financing of geothermal energy development and for other purposes.

The National Energy Policy Plan (NEPP) in 1978 and subsequent plans developed the strategies for implementing the Congressional mandates. The 1985 version of the NEPP reiterated the Nation's policy that "... Americans should have an adequate supply of energy, available at reasonable cost. The basic strategies for holding to this goal are to ... promote a balanced and mixed energy resource system." In its plan, DOE explained that this includes renewable energy, for which research should "... address key, high risk, technical issues that will provide a scientific and engineering knowledge for industry ...."

In 1980, the **Energy Security Act** was passed. It aimed to increase the Nation's energy security by promoting the development of alternative energy sources and reducing dependence on energy imports. This Act authorized the Secretary of Energy to grant loans to geothermal producers, to assess the need for a reservoir insurance program, and to establish an assistance program to hasten the development of geothermal resources for nonelectric applications.

Other legislation that may significantly affect the development of geothermal energy includes:

- **Clean Air Act** (P.L. 98-616), as amended. This Act has some major provisions which are of particular interest to the geothermal industry. The New Source Performance Standards (NSPS) provision establishes a primary control mechanism that is set on an industry-by-industry basis and requires the application of the best available technology to reduce emissions. The Prevention of Significant Deterioration (PSD) provision restricts emissions of major pollution sources outside of nonattainment areas, i.e., those areas not in compliance with the National Ambient Air Quality Standards of the Clean Air Act. For geothermal applications, the only air pollutants presently requiring control are H_2S and particulate emissions from drilling.

- **Resource Conservation and Recovery Act** of 1976 (RCRA). This Act provides technical and financial assistance for the safe disposal of discarded materials and regulates hazardous wastes. Geothermal wastes are exempt from the federal RCRA hazardous waste regulations, but are subject to the California Hazardous Waste Control Law and other similar state statutes. These statutes, as of May 8, 1990, preclude the land disposal of hazardous wastes, including injection, without (1) pretreatment or (2) designation as a "special waste." (California Administrative Code, Title 22, Sections 66740 and 66742).

The major costs of this legislation will be borne by operations at The Geysers because of the chemicals used in H_2S abatement. The impact on hot water plants will not be substantial since drilling wastes are typically non-hazardous and are disposed of on-site. The number of hazardous waste treatment facilities licensed within the country is restricted, and transportation and handling costs can be high for materials that must be transported to these facilities.

- **Toxic Substances Control Act** (TSCA). This Act was established "to regulate commerce and protect human health in the environment by requiring testing and necessary use restrictions on certain chemical substances, and for other purposes." The EPA administrator is authorized to determine the environmental, economic, and social impacts of the sale of any such material. If these by-products are determined to be toxic, regulations for their control, flow, and use must be developed. TSCA would only impact geothermal energy development if by-products recovered from either liquid or solid waste streams presented "an unreasonable risk of injury to health or the environment."

- **Noise Control Act** of 1972. This Act gave primary control of noise to the state and local governments. Under this Act, the Federal government retains regulatory authority over low-level noises produced by construction equipment, transportation equipment, and motor or engine, and electrical or electronic equipment. When a new class of products is regulated by the EPA, state and local noise emission levels for that product must be identical to those established by the EPA. Primary control of noise from geothermal energy development fall under the Occupational Health and Safety Act administered by OSHA and Geothermal Resources Operational Order (GRO) No. 4 issued by the U.S. Geological Survey (USGS) and currently implemented by the Bureau of Land Management (BLM).

- **Renewable Energy & Energy Efficient Technology Competitiveness Act** (P.L. 101-218) of 1989. This Act authorizes and directs the Secretary of Energy to pursue a program of research, development, and demonstration -- including the use of joint ventures with the private sector -- in the areas of wind energy, PV, solar thermal, biofuels, hydrogen, solar buildings, ocean energy, and geothermal energy. At least 50 percent of the costs directly related to any joint venture are to be provided from non-Federal sources. The Act also directs the Committee on Renewable Energy Commerce and Trade (CORECT) to establish a program to inform other countries of the benefits of policies that would allow small facilities which produce renewable energy to compete effectively with producers of energy from "non-renewable" resources. CORECT shall also assist in establishing administrative guidelines to simplify application by firms seeking export assistance for renewable technologies.

APPENDIX C

GEOTHERMAL PUBLICATIONS

BY CATEGORY

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