

**GEOTHERMAL ENERGY
R&D
PROGRAM**

**ANNUAL PROGRESS REPORT
FOR
FISCAL YEAR 1991**

**GEOTHERMAL DIVISION
U.S. DEPARTMENT OF ENERGY**

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**GEOTHERMAL DIVISION
U.S. Department of Energy**

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EXECUTIVE SUMMARY

Research in Geothermal Energy organized on a national scale began in 1971 under the supervision and funding of the Department of Energy (DOE) and DOE's predecessors. DOE's Geothermal Division oversees the network of national laboratories and universities in developing the nation's vast geothermal resources. Geothermal Energy has reached the status of an environmentally and economically sound energy source.

The research program recognizes three major resource categories: Hydrothermal, Geopressured-Geothermal, and Hot Dry Rock.

Each category enjoys its own unique potential but has its own unique hurdles to overcome. Each category also has a different range of applications and different timelines for expected progress.

Briefly, the first category, hydrothermal energy, derives from liquid-dominated (hot-water) or vapor dominated (steam) reservoirs with temperatures for electric power production ranging from 150°-360°C (300°-680°F). The highest quality U.S. resource areas occur in the western states, where a thinning of the earth's crust yields many high-temperature sites. Research focuses on all aspects of development, from exploration to energy conversion, including the problem of reservoir management at productive fields.

The second category, geopressured-geothermal energy, consists of moderately hot brines containing dissolved methane, at high pressures approaching the load of overlying rock

(~ 1 psi/ft). The best known geopressured resource base lies along the Texas and Louisiana Gulf Coast area, although similar conditions may exist elsewhere in the United States. The current status of the technology successfully permits energy extraction, which will become cost-competitive depending on economic factors in the nation's energy mix. In Fiscal Year 1991, the Department concentrated on scaling down research efforts and summarizing its findings for transfer and further development by private industry.

The third category, energy from Hot Dry Rock, results from creating a man-made reservoir to bring the heat of dry (water-deficient) rock to the surface. Water, under great hydrostatic pressure, fractures the rock between two wells. Water, as a heat transfer medium, is then injected in one well, circulated through the man-made reservoir, and recovered through the production well. The most accessible hot dry rock of sufficient temperature to produce electricity occurs in the western states in young volcanic centers. Nevertheless, the resource is so widespread that successful commercialization may eventually occur throughout the country. Research concentrates principally on the Long Term Flow Test at the Fenton Hill test site. The test will provide baseline data for the further definition of the technology.

The Geothermal Division employs a system of research objectives for each resource category. The objectives all focus on bringing each geothermal category into commercial competitiveness. A hierarchy of objectives guides the research in each resource category.

Fiscal Year 1991 saw the following major research accomplishments:

HYDROTHERMAL RESEARCH

- Filed a patent application for the downhole cement injector to control loss of circulation.
- Completed advanced conceptual design of the drillable straddle packer to aid in controlling circulation loss and built two prototypes in early FY 92.
- Completed construction of a 6-liter downhole fluid sampler that can withstand the high temperatures and corrosive environment at The Geysers.
- Completed and released an improved reservoir model, "TOUGH2", and documented new features and their application in a user's manual.
- Completed validation studies of the reservoir simulator TETRAD; initiated sensitivity studies.
- Produced seismic velocity and attenuation images from microsignals provided by UNOCAL Geothermal and related those images to geological and reservoir conditions.
- Developed a new design for stripper rubbers in rotary head seals transferred to industry and introduced as a commercial product.
- Confirmed the hydrolytic stability of phosphate-modified calcium aluminate cements in 300°C brine and their resistance to chemical attack by CO₂.
- Achieved very promising results in the development of high-temperature, hydrolytically-stable chemical coupling

systems needed to bond elastomers to reinforcement using high melting point (>280°C) polyaromatic type adhesives.

- Constructed and tested a new generation of bench-scale bioreactors to optimize the efficiency of the clean-up process.
- Completed documentation of the brine chemistry model and held a training session for the geothermal community.

GEOPRESSURED-GEOTHERMAL RESEARCH

- Published a final report on the design and operation of the geopressured-geothermal hybrid power system, a first-of-a-kind demonstration power plant.
- Successfully flow tested the geopressured Pleasant Bayou No. 2 well in Texas throughout 1991 and analyzed reservoir production data.

HOT DRY ROCK RESEARCH

- Concluded from historic pressurization data that, below reservoir pressure of about 15 MPa (2175 psi), water storage is largely in reservoir rock microcracks; at higher pressures, storage is largely in the joints between the rock blocks.
- Achieved a very good fit of the FRACNET model to actual reservoir behavior over a period of 100 days of pressurization.
- Prepared Fenton Hill site for Long Term Flow Test by installing and testing last major system components.

SECTION I

INTRODUCTION

PURPOSE

The Geothermal Division of the Department of Energy has led the nation's geothermal research program since 1971 — at the Department itself or earlier at the Department's predecessor agencies. The geothermal program structure proceeds from law, which gives the program the mandate to provide the nation with a fully acceptable and economic energy source. Since 1971, geothermal technology to extract energy from hydrothermal resources has matured to a commercially competitive technology.

This Annual Progress Report presents the geothermal research and development (R&D) accomplishments funded and directed by the Department during Fiscal Year 1991.

Section I encapsulates the R&D program, its program budget, and management hierarchy. It also summarizes how the research objectives structure the program.

Section II details accomplishments for the three major geothermal technologies: Hydrothermal Energy, Geopressured-Geothermal Energy, and Hot Dry Rock. For each of these major technologies, the narratives proceed with Background — putting the R&D into technical and historical context, to Objectives — restating relevant measurable goals, to Approach — encapsulating the research methodology. For individual research programs, the narratives proceed with Findings — giving actual program accomplishments, and conclude, where appropriate, with Discussion — exploring the implications for future research directions.

The reader may request detailed progress reports from the R&D groups themselves listed in Appendix A, GEOTHERMAL R&D PROGRAM PARTICIPANTS. Published FY91 papers appear in Appendix B, GEOTHERMAL PUBLICATIONS BY RESEARCH CATEGORY.

OBJECTIVES HIERARCHY

The Geothermal Division administers the research program through the management-by-objectives (MBO) approach. The Division in fact measures progress by matching accomplishments against the research objectives set for each major technology, process, and component.

Level I objectives address *overall* cost targets for each of the three major geothermal technologies:

- Hydrothermal — Reduce the cost of electric power to 3-7 cents per kilowatt-hour (kWh) by the mid-term (1995-2005).
- Geopressured-Geothermal and Hot Dry Rock — Create a scientific

information base sufficient for industry to make rational energy investment decisions.

Level II objectives address improvements in the *major components* comprising a geothermal plant. Examples of major components are Resource Analysis and Energy Conversion, and these vary from technology to technology.

Level III objectives address *individual research targets*, such as specific materials, tools, and processes that impact the economics of the major components.

Figure 1 summarizes this hierarchy of objectives. These objectives — at all levels — are subject to review and revision.

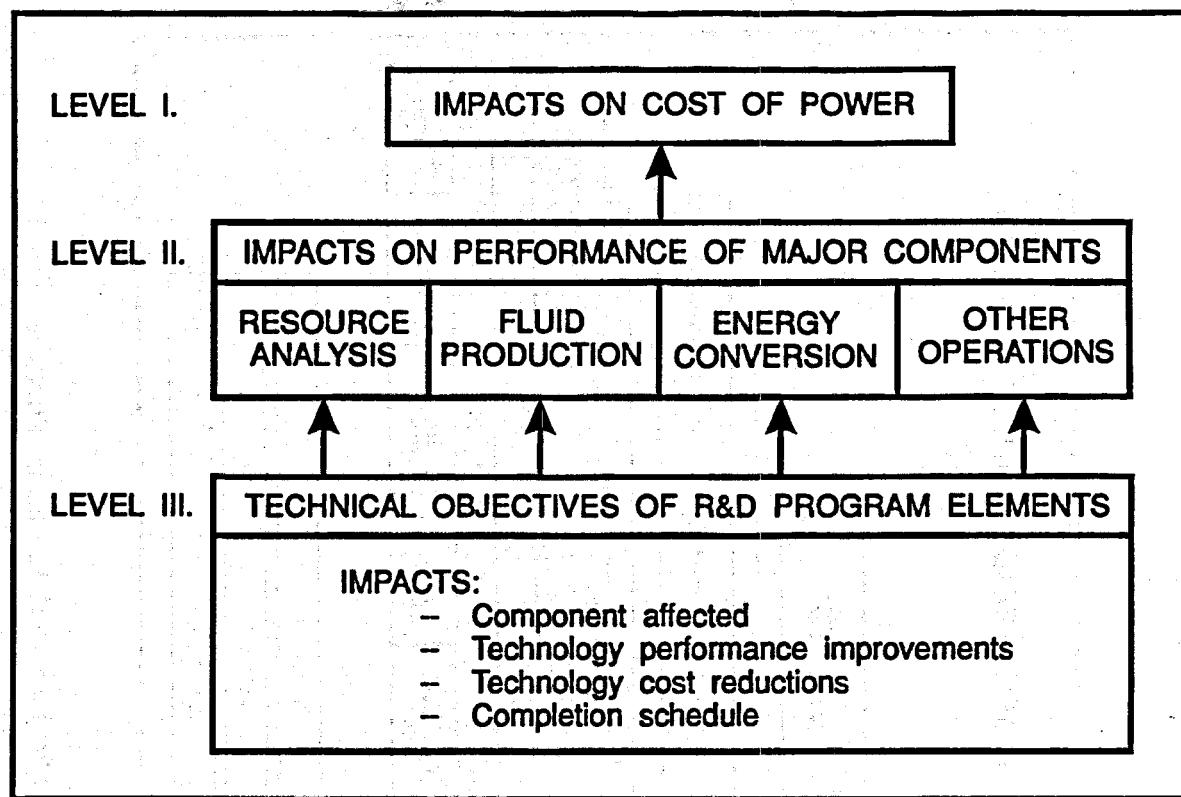


Figure 1
Geothermal Research Objectives Hierarchy

PROGRAM OVERVIEW

The FY92 Geothermal R&D Program concentrated on the three major technologies. (See Figure 2 for a breakdown of the entire research program):

Hydrothermal research explores the components affecting the economic viability of this liquid-dominated, moderate-temperature resource:

HARD ROCK PENETRATION focuses on new approaches to lost circulation, rock penetration, and downhole instrumentation. The Geothermal Drilling Organization (GDO), an association of industrial concerns, cost-shares high-priority research.

RESERVOIR TECHNOLOGY focuses on interpreting geophysical data, developing modeling techniques, the problems of production/injection, and extending well life. The Geothermal Technology Organization, a group patterned after the GDO, also cost-shares much of the industrial research.

CONVERSION TECHNOLOGY addresses the thermodynamic issues inherent in using geofluids: geothermal brine behavior, binary plant efficiency and special material needs, cooling water makeup requirements, and residual waste handling techniques.

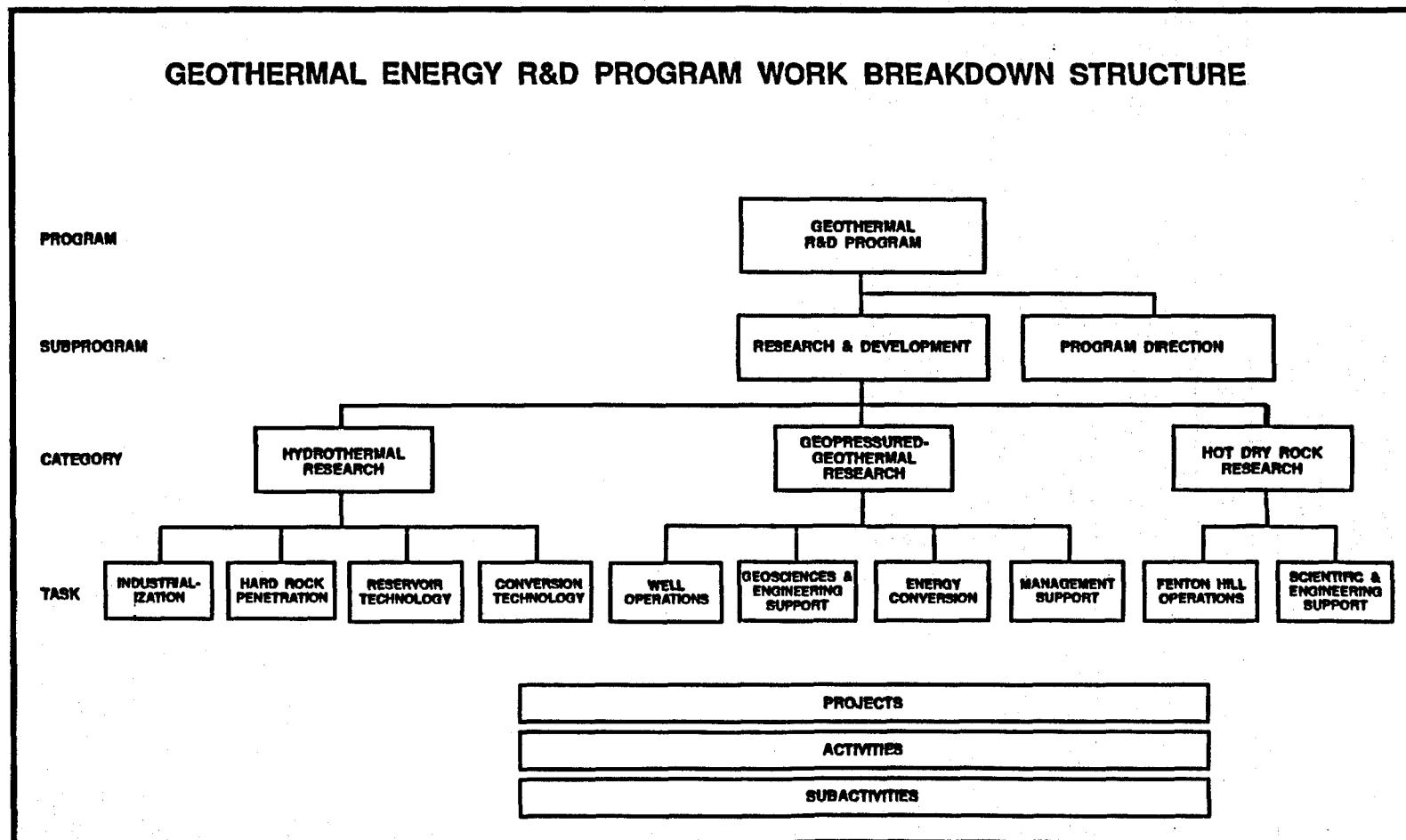


Figure 2
Geothermal Energy Research and Development Program Work Breakdown Structure

Geopressed-Geothermal research aims at improving energy conversion technology through four interrelated tasks:

WELL OPERATIONS focuses on field experiments, such as well testing to determine the power potential and to demonstrate the feasibility of commercial applications.

GEOSCIENCES AND ENGINEERING SUPPORT focuses on refining predictive models for reservoir performance, hydrocarbon studies, as well as rock mechanics and environmental monitoring.

ENERGY CONVERSION (now complete) focused on the construction and operation of the Pleasant Bayou Hybrid Power System in Texas. This plant used both geopressed brines and dissolved methane to generate electric power, and was the first of its kind in the world.

MANAGEMENT SUPPORT focuses on technology exchange and project administration.

Hot Dry Rock research aims principally at validating the HDR concept through the Long Term Flow Test, which will culminate years of research and is expected to answer a number of important technical and economic questions industry has posed. The research comprises two interrelated tasks:

FENTON HILL OPERATIONS focuses on the energy extraction system under construction at the Fenton Hill site in New Mexico.

SCIENTIFIC AND ENGINEERING involves designing tools and instrumentation, conducting tracer studies, reservoir engineering, and other technology support for the long-term flow test.

PROGRAM BUDGET AND MANAGEMENT

As Figure 3 depicts, the Geothermal Division reports to the Assistant Secretary for Conservation and Renewable Energy. The Division Director implements energy research policy and allocates resources for program activities. The Division Director also establishes policy for the Operations Offices and National

Laboratories and approves their annual plans in accordance with national energy policy. Table 1 presents the Geothermal Energy R&D budget from FY88 through FY92 by resource category. Figure 4 identifies the category, the managers, and team leaders for each research team.

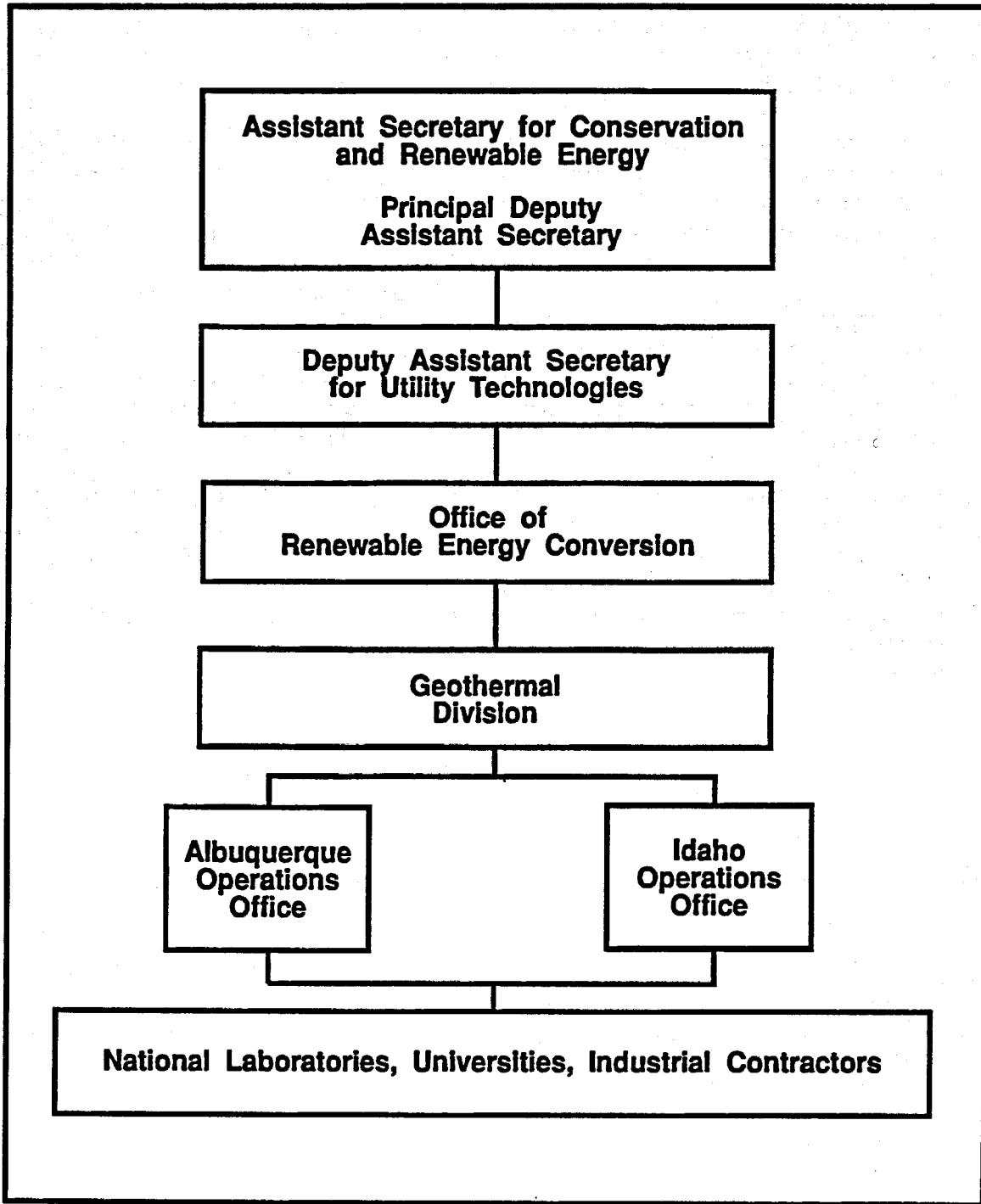


Figure 3
Geothermal Research and Development Program Participants

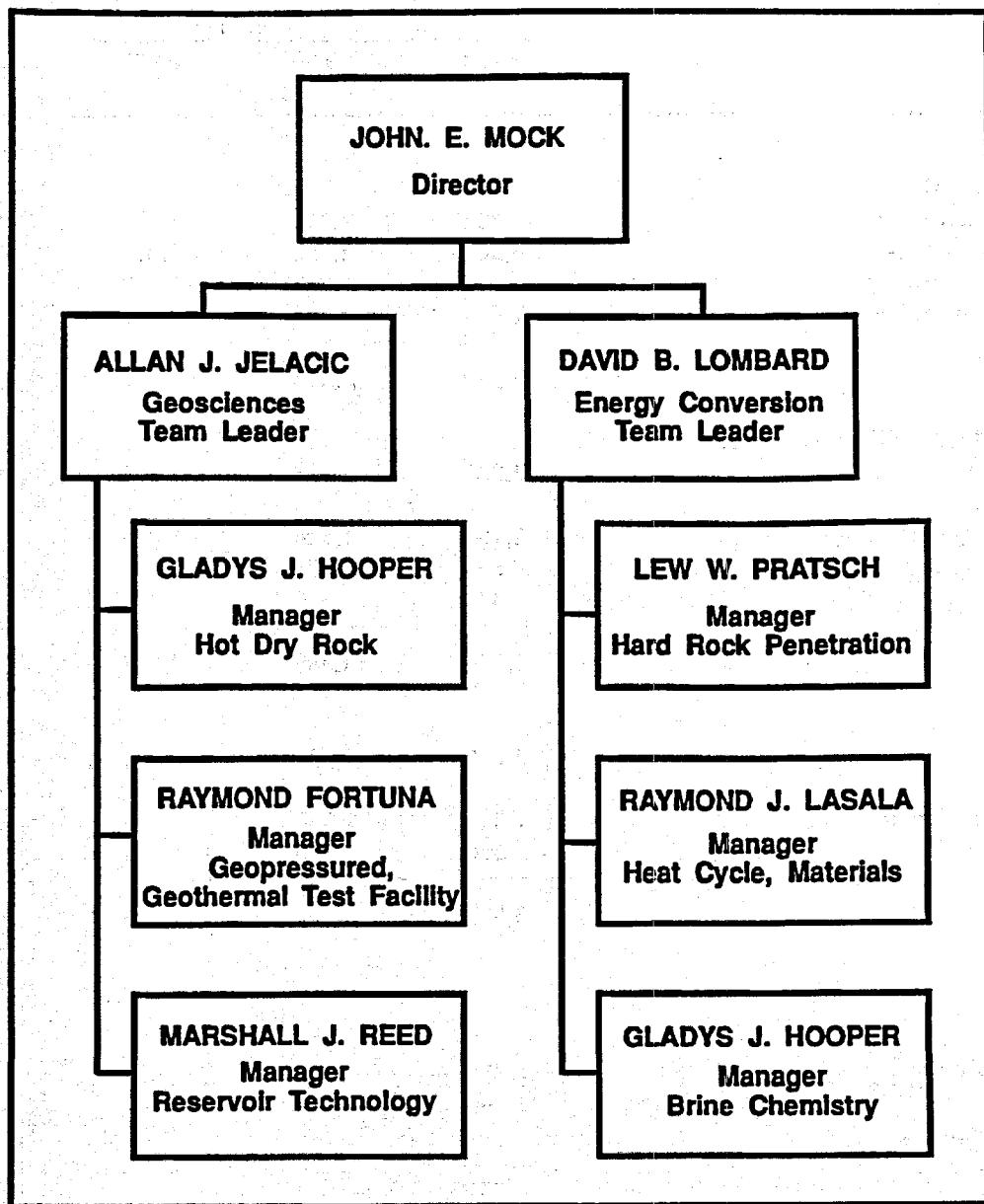


Figure 4
Management Structure of the Geothermal Research and Development Program

Table 1
Geothermal Research & Development Budget (\$1,000s)

	Actual			FY91	Est. FY92
	FY88	FY89	FY90		
HYDROTHERMAL:					
Hard Rock Penetration	1,800	2,250	2,205	2,435	2,555
Reservoir Technology	4,500	2,450	2,074	4,393	5,632
Conversion Technology	1,600	1,935	1,527	2,055	4,631
Long Valley Operations	1,400	1,635	1,663	1,150	662
TOTAL	9,300	8,270	7,469	10,033	13,440
GEOPRESSURED-GEOTHERMAL:					
Well Operations	2,921	6,698	2,898	3,746	2,950
Geosciences &					
Engineering Support	1,164	1,504	1,826	980	1,005
Energy Conversion	538	1678	644	593	0
Management Support	377	500	487	565	1,045
TOTAL	5,000	10,380	5,855	5,884	5,000
HOT DRY ROCK:					
Fenton Hill Operations	3,876	2,520	2,570	2,500	2,368
Scientific &					
Engineering Support	1,344	980	856	1,140	800
Reserve & Misc.	580	0	0	327	432
TOTAL	5,800	3,500	3,426	3,967	3,600
OTHER:					
Capital Equipment	0	795	444	402	821
Program Direction	835	826	814	889	893
Hawaii	—	—	—	4,440	0
Low-Temperature	—	—	—	2,485	1034
Res. Assist.					
GTF Clean-up	—	—	—	150	71
Support Activities	—	—	—	1,546	2,311
TOTAL:	835	1,621	1,258	9,912	5,130
TOTAL GEOTHERMAL R&D	20,935	23,771	18,077	29,796	27,170

SECTION II

GEOTHERMAL R&D ACHIEVEMENTS

Fiscal Year 1991

HYDROTHERMAL RESEARCH

The Geothermal Division's hydrothermal research program focuses on the geothermal industry's real-world needs. The program spans the entire geothermal project cycle: exploring for geothermal fields with more sensitive instrumentation, drilling into these resources more economically, predicting reservoir performance with greater certainty, tracking reinjected spent geothermal fluids with greater accuracy, and converting the geothermal heat into useful energy more efficiently.

This hydrothermal research effort breaks out into four interrelated tasks and 15 projects, all of which support the central objective to:

Reduce the life-cycle cost of producing electricity from liquid-dominated, hydrothermal resources to 3 to 7 cents/kWh by 1997.

The objectives for the entire hydrothermal program appear on the following page.

LEVEL II

LEVEL I

**HARD ROCK
PENETRATION**

**REDUCE LIFE-CYCLE
COST OF ELECTRICITY
BY 10-13% BY IMPROVING
FLUID PRODUCTION
TECHNOLOGY BY 1992**

**RESERVOIR
TECHNOLOGY**

**REDUCE LIFE-CYCLE
COST OF ELECTRICITY
BY 15-22% BY IMPROVED
EXPLORATION AND
RESERVOIR CONFIRMATION
TECHNOLOGY/PROCEDURES
BY 1992**

**CONVERSION
TECHNOLOGY**

**REDUCE LIFE-CYCLE COST OF
ELECTRICITY BY 10-13% BY
IMPROVED FLUID PRODUCTION
TECHNOLOGIES**

**REDUCE COST OF POWER BY
17-28% FOR BINARY PLANTS
(150°c-200°c) BY IMPROVED
EFFICIENCY AND O&M**

**REDUCE COST OF POWER BY
UP TO 4% FOR FLASH PLANTS
BY IMPROVED MATERIALS AND
EQUIPMENT**

**HYDROTHERMAL
RESEARCH**

**REDUCE LIFE-CYCLE COST OF PRODUCING
ELECTRICITY TO
3-7¢/kWh BY 1997**

LEVEL III

RESERVOIR ANALYSIS

REDUCE NUMBER OF WELLS TO DEFINE RESOURCES BY 33% BY 1995

BY INCREASING ACCURACY OF MODEL INPUTS DECREASE FORECASTING UNCERTAINTIES FOR RESERVOIR PARAMETER CHANGES AND CHEMISTRY BY 10% BY 1995

REDUCE UNCERTAINTIES IN RESERVOIR CAPACITY PREDICTIONS BY 15% BY 1995

BY IMPROVING RESERVOIR EVALUATION DECREASE FORECASTING UNCERTAINTIES BY 15% BY 1995

REDUCE NUMBER OF WELLS TO EVALUATE A RESERVOIR BY 10% BY 1995

IMPROVE MONITORING METHODS TO DECREASE FORECASTING UNCERTAINTIES IN RESERVOIR PARAMETERS AND CHEMISTRY BY 10% BY 1995

EXPLORATION TECHNOLOGY

INCREASE SUCCESS RATIO OF WILDCAT WELLS BY 20% BY 1992

DEVISE BETTER METHODS AND STRATEGIES TO FIND 3 HIDDEN RESERVOIRS BY 1992

INCREASE SUCCESS RATIO FOR IN-FILL WELLS BY 33% BY 1995

IMPROVE METHODS FOR POSITIONING/DESIGNING WELLS TO REDUCE COST BY 15% BY 1995

BRINE INJECTION

REDUCE NUMBER OF LOW-FLOW/SHORT-LIVED WELLS BY 15% IN 1995

IMPROVE EFFICIENCY OF PROD/INJECTION SCHEMES TO REDUCE NUMBER OF MAKE-UP WELLS BY 10% BY 1995

REDUCE UNCERTAINTIES TO LONG-TERM CHANGES IN FLUID TEMPERATURE AND INJECTION BREAKTHROUGH BY 10% BY 1995

REDUCE UNEXPECTED ENVIRONMENTAL PROBLEMS, ESPECIALLY RELATED TO SEISMICITY AND SUBSIDENCE

GEOTHERMAL TECHNOLOGY ORGANIZATION

COST-SHARE R&D WITH DOE TO ENCOURAGE INDUSTRY INVOLVEMENT

SALTON SEA DRILLING PROJECT

STUDY THE PHYSIOCHEMICAL PROPERTIES OF DEEPLY BURIED ROCKS AND FLUIDS

LONG VALLEY DRILLING PROJECT

DEEPEN WELL TO 14,000 FEET OR MORE AND BETTER DEFINE HYDROTHERMAL REGIME

USE WELL AS A TEST BED FOR NEW EQUIPMENT AND PROCESSES

LEVEL III

LOST CIRCULATION CONTROL

REDUCE COSTS ASSOCIATED WITH LOST CIRCULATION EPISODES BY 30% BY 1992

ROCK PENETRATION MECHANICS

REDUCE COSTS OF DEEP WELLS AND DIRECTIONALLY DRILLED WELLS BY 10% BY 1992

INSTRUMENTATION

DECREASE COST OF DRILLING BY 5% BY 1992 THROUGH BETTER IDENTIFICATION OF FRACTURES

DECREASE WELL MEASUREMENT UNCERTAINTY FOR MODERATE TEMPERATURE RESERVOIRS BY 25% AND BY 50% AT TEMPERATURES $>250^{\circ}\text{C}$ BY 1992

GEOTHERMAL DRILLING ORGANIZATION

DEVELOP AND TRANSFER RELATED TECHNOLOGY FOR A 5% REDUCTION IN WELL COST BY 1990 AND 10% BY 1992

HARD ROCK PENETRATION PROGRAM

Drilling and completion of wells for exploration, production and injection account for much of the cost of generating electricity from geothermal resources. Current drilling and completion technology derives primarily from the oil and gas industry. This technology is often unsuitable for the high temperatures, hard rock, and highly corrosive fluids found in the hostile geothermal environment. The Hard Rock Penetration task focuses on developing economic drilling and completion technology for geothermal wells. Specialized instrumentation is often needed to assess drilling operations and to describe and measure reservoir characteristics. Table 2, below, outlines the Hard Rock Penetration Program.

Background

The overall system objectives of the Hard Rock Penetration Program are to:

- Develop a framework to assess the impact of new tools and procedures on drilling costs;
- Apply the framework to identify areas for future work.

To improve drilling cost models, the research team surveys current industrial problem areas. A recent survey identified industry concern in three primary research areas indicated in Table 3, on the following page.

HARD ROCK PENETRATION TASKS AND OBJECTIVES

PROJECT AREAS	OBJECTIVES
LOST CIRCULATION CONTROL	To identify the location and magnitude of loss zones and provide new materials and techniques for plugging them. To transfer to industry technology to reduce lost circulation costs by 30 percent.
ROCK PENETRATION MECHANICS	To investigate advanced drilling techniques for exploratory and production wells. To transfer to industry technology to reduce costs of deep wells and directionally drilled wells by 10 percent.
INSTRUMENTATION	To develop sophisticated tools and probes for operating in high temperature boreholes and for identifying fractures and formation boundaries. To decrease the cost of drilling wells by 5 percent through more accurate completion-zone siting.
GEOTHERMAL DRILLING ORGANIZATION	A nonprofit consortium whose members are from the geothermal and drilling industries. Sponsors activities with near-term commercialization potential to reduce well costs by an additional 5 percent.

Table 2.

HARD ROCK PENETRATION INDUSTRY SURVEY	
PRIMARY AREAS	SPECIFIC CONCERNS
LOST CIRCULATION AND CEMENTING	<ul style="list-style-type: none"> • Workable Staging Collar • Cement-to-Mud Interface Instrumentation
HIGH-TEMPERATURE TOOLS AND INSTRUMENTATION	<ul style="list-style-type: none"> • Casing-to-Cement and Cement-to-Formation Materials • Workable Sampler • Measurement Methods for Steam Quality and Enthalpy • Accurate High-Temperature Flow-Rate Instrumentation • Instrumentation and Materials Performance Specifications
EXPLORATION AND RESOURCE DEFINITION	<ul style="list-style-type: none"> • Slim-Hole Drilling Method • Small-Diameter Hole Instrumentation • Reservoir Characterization Models and Data Requirements

Table 3.

Instrumentation development continues for borehole radar and downhole memory tools. Researchers are evaluating advanced drilling systems, such as slim-hole coring, and updating overall systems analysis and drilling evaluation practices and costs. Analysts are assessing the

impact of new tools and procedures on well drilling cost by extending existing cost models, developing new common trouble models, and using the previously developed IMGEO cost-of-power model.

LOST CIRCULATION CONTROL

The most costly problem routinely encountered in geothermal drilling is lost circulation, i.e., drilling fluid used for cooling the bit and flushing rock chips out of the borehole is lost to the rock formation rather than circulated back to the surface. Besides fluid replacement costs, the loss of fluid also results in expensive loss of continuity and integrity of the cement used to bond the wellbore casing to the rock formation. The fluid loss also results in a discontinuous supply of cuttings.

Researchers have tested many potential lost circulation materials in past years under this

task. They have completed tests to identify materials with high temperature pressure durability, and fracture plugging capabilities. Recent tests indicate that lost circulation material performance often improves by using a mixture of different materials, sizes, and shapes. The task objective is to find materials to reduce lost circulation costs by addressing the following problem areas:

- Loss of Expensive Drilling Fluid,
- Unavailability of Rock Chips for Examination,

HARD ROCK PENETRATION PROGRAM

- Borehole Instability and Stuck Drillstrings,
- Loss of Well Control,
- Alteration of Logging Response From Drilling Fluid Invasion,
- Contamination of Fresh Water Aquifers, and
- Loss of Well From Poor Casing Cementing.

Approaches to controlling fluid circulation include development and placement of specialized materials, pumpable setting fluids, polyurethane foams, and special cements. Researchers are developing techniques for plugging major- and minor-fracture loss zones, and for measuring loss zone characteristics such as permeability, fracture thickness, and location in the wellbore. Researchers report significant progress in FY91 under the activity areas identified in Table 4, below.

LOST CIRCULATION CONTROL ACTIVITY	
ACTIVITY	SPECIFIC FY91 EFFORT
HIGH TEMPERATURE MATERIALS	<ul style="list-style-type: none">● High-Temperature Lost Circulation Material (LCM) Development● Particle Material Properties Tester (PMPT)
MAJOR-FRACTURE FLUID LOSS CONTROL	<ul style="list-style-type: none">● Development of Cementitious Muds● Development of Cementitious Mud Flow Models● Downhole Injector Development● Porous Packer Development● Drillable Straddle Packer Development● Packer Emplacement Feasibility Study
LOSS ZONE CHARACTERIZATION	<ul style="list-style-type: none">● Wellbore Hydraulics Model Development● Development of Wellbore Hydraulics Data Acquisition System● Borehole Televiewer - Formation Fracture Study

Table 4.

HIGH TEMPERATURE MATERIALS

High-Temperature Lost Circulation Material (LCM) Development - Sandia is evaluating materials, mixtures, and application procedures for high-temperature LCMs. Conoco had requested help in developing an LCM for oil and gas drilling. The team performed compression tests with the Sandia PMPT facility. Operating procedures and detailed design of a modified API slot tester were provided. (Conoco then built their own slot tester for further LCM testing.) Together with Conoco, Sandia performed mechanical properties tests on ground walnut shells including compressive strength and elastic modulus computation on water- and oil-soaked shells at room temperature and 200°F.

Particle Material Properties Tester (PMPT) - The research team refined and documented testing and analysis procedures for the PMPT. The team updated test software to improve control and automated data analysis. The PMPT testing program will stress major-fracture fluid loss control, but will continue with high-temperature LCMs for minor-fracture and porous-matrix fluid loss control.

MAJOR-FRACTURE FLUID LOSS CONTROL

Cementitious Muds - SNL and BNL are collaborating on the development of cementitious mud formulations: conversion of bentonite drilling mud to a fast-setting, temperature-activated cement to reduce setting for lost circulation control. Using BNL requirements for pumpability, setting time, and downhole temperature, SNL developed six techniques to apply the mud through:

1. Open-end drill pipe,
2. A drillable straddle packer,
3. The bit, using an encapsulated accelerator,
4. The downhole injector,
5. A wireless-deployed porous packer, and
6. A drill pipe-deployed porous packer.

BNL believes that these new less stringent requirements will improve workable formulations for several deployment methods.

Cementitious Mud Flow Modeling - Under contract to SNL, the University of Arizona developed mathematical models of the flow of a setting fluid into a loss zone, i.e., cementitious mud flow models. These models are useful to develop emplacement techniques for the muds and other fast-setting materials.

Downhole Injector - This concept proposes placing cementitious muds downhole while preventing the cement solidifying in the drillstring. A downhole sliding valve assembly is opened upon contact with a stinger on the end of a coiled tubing lowered into the drillpipe.

Workers pump a magnesium oxide slurry down the tubing, through the valve, and into the wellbore annulus, while simultaneously pumping a bentonite mud slurry containing other cement constituents (ammonium polyphosphate and borax) down the drillpipe and through the drill bit. The two streams mix in the wellbore and begin to harden as the cement flows into the loss zone.

During FY91, DOE filed a patent application for the downhole injector. Researchers estimate that the injector may be economically feasible if cementitious mud costs are reasonable.

Porous Packer - This concept proposes emplacing a fast-setting, expandable material, such as polyurethane foam, in a controlled manner. A wireline-deployed service module carries the setting material downhole, where it is injected into a porous fabric bag. Expansion of the bag provides temporary sealing against the flow of wellbore fluids into the loss zone. Internal pressurization of the bag causes the setting fluid to weep through the fabric, thereby flowing into the loss zone and bonding to the wellbore and fracture walls.

HARD ROCK PENETRATION PROGRAM

Researchers began testing the fabrics in FY91. Test software stressed compatibility with a new computer data acquisition system. Compatibility was confirmed and detailed testing will begin in FY92.

Drillable Straddle Packer Development - The low-cost, low-strength, drillable straddle packer helps emplacing cement in loss zones encountered in large-diameter wellbores. Major elements of the packer assembly appear in schematic form in Figure 5, on the following page. Two impermeable fabric bags, one above and one below the loss zone, insert into the wellbore. Operation involves three procedures:

- Flow of cement through the packer elements and out the exit ports creates a differential pressure that inflates the packer elements,
- Inflated packer elements direct the cement into the loss zone and provide partial sealing from other wellbore fluids, and
- Pumping a ball down the drillstring decouples the drillstring from the packer assembly.

The seal must be effective enough to:

- Prevent or retard the flow of wellbore fluids into the loss zone where cement dilution is a concern,
- Contain the cement in the vicinity of the loss zone to maximize cement flow into the loss zone and to minimize the volume of cement that remains in the wellbore.

The inflated bags press against the wellbore wall and prevent flow past the bags. The effectiveness of this seal depends on three characteristics:

1. The roughness of the wellbore,
2. The pliancy of the bag material, and
3. The pressures inside, above, and below the bag.

In FY91, researchers designed and fabricated two drillstring couplers and identified potential fabrics. The first prototype tested two characteristics of the system: (1) a means for clamping the fabric tubes to the bag bulkheads, and (2) the sealing capabilities of a flexible-fabric packer. Researchers completed testing a second prototype of the shroud extension mechanism. The Packer Test Facility was constructed and overpressure testing was begun in early November 1991. A technology transfer initiative will present testing results to industry and solicit a program plan for additional industry cost-shared field testing.

Packer Emplacement Feasibility Study - The goal is to develop concepts for lost circulation control based on the Science and Engineering Associates (SEA) Membrane Instrumentation and Sampling Technique (SEAMIST). In this technique, workers invert a fabric tube downhole for sampling fluids and for deploying borehole instruments used for waste-site evaluation. A contract was awarded to SEA for conceptual, advanced conceptual, and detailed designs for lost circulation concepts that use the SEAMIST technique to seal major-fracture loss zones at 4500 feet (250 degrees Fahrenheit).

During FY91, SEA completed two advanced conceptual designs:

1. A downhole packer that uses nested membranes to place a two-component setting material, and
2. A transparent-membrane camera system that can be deployed downhole to displace opaque drilling mud with water and allow optical logging of the borehole wall.

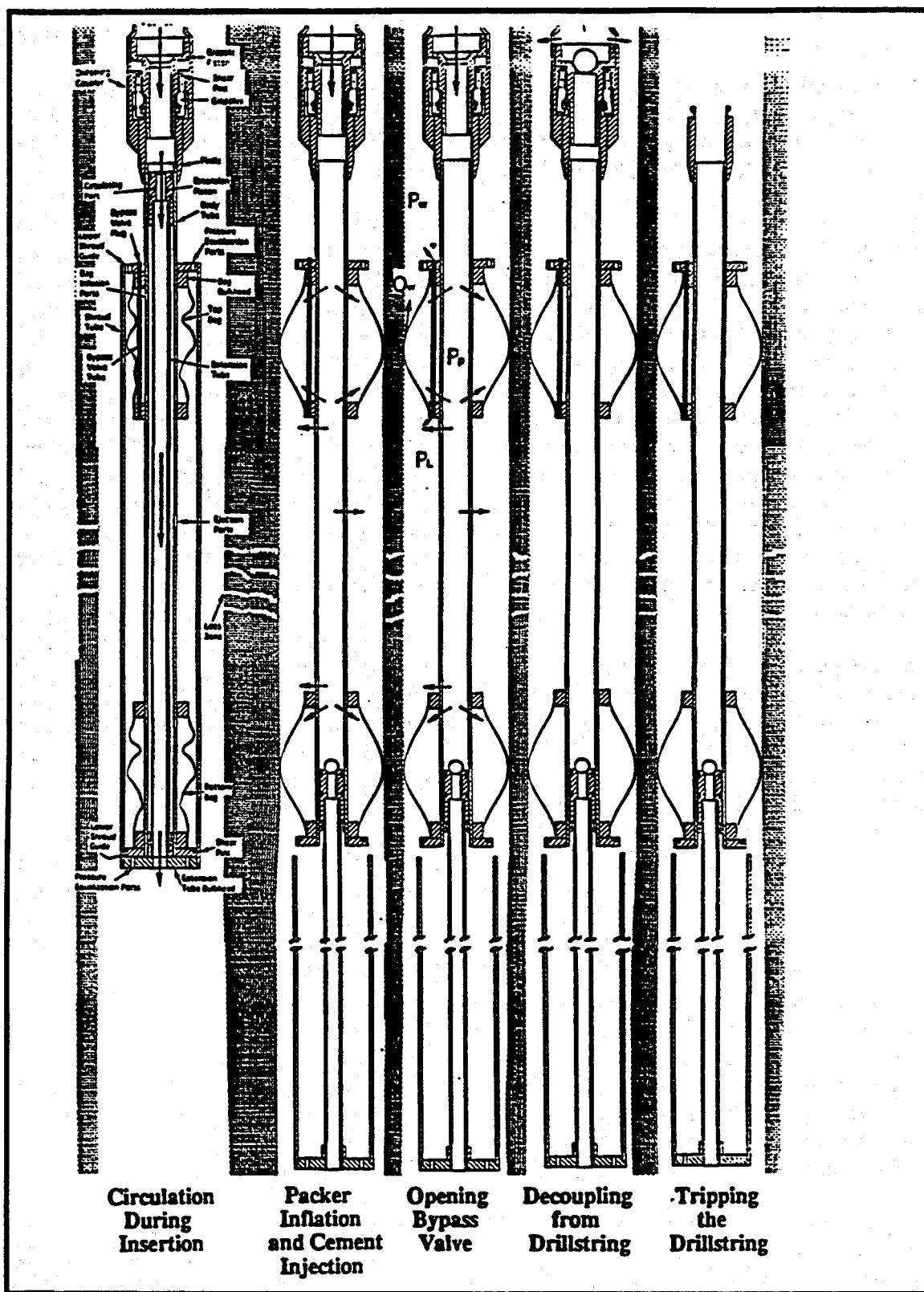


Figure 5
Sequence Showing Deployment of the Drillable Straddle Packer

HARD ROCK PENETRATION PROGRAM

Sandia researchers selected the transparent-membrane camera system for further detailed design. A follow-on contract is under consideration for FY92 to fabricate and test a prototype camera system in shallow, directionally-drilled boreholes.

Loss Zone Characterization

Development of Wellbore Hydraulics Data

Acquisition System - The goal of this effort is to develop a rugged, stand-alone instrumentation system for measuring, recording, and interpreting wellbore hydraulics data. In FY91, researchers developed a transducer for measuring the outflow rate of drilling fluid from the wellbore, i.e., a Rolling Float Meter consisting of a rolling float that rides on the surface of the fluid in the return flow line leading from the wellbore (see Figure 6, on the following page.) A pendulum potentiometer measures the angle of the pivot arm to determine the fluid height in the return line. This height is a monotonic function of the flow rate, which is then calculated from a calibration equation. Researchers developed the transducer with the Wellbore Hydraulics Flow Facility (WHFF). The WHFF, constructed in late FY90, provides a full-scale simulation of the return flow line and a test-bed for inflow and outflow transducers.

During FY91, researchers completed laboratory tests of the transducer which indicated that the float height was a monotonic and nearly linear function of the flow rate, thus, an accurate correlation for field conditions. Researchers conducted a field test program at the Long Valley Exploratory Well near Mammoth Lakes, California with three purposes:

1. To conduct a comprehensive comparative test of the performance and reliability of several techniques for measuring fluid inflow and outflow rates during drilling,

2. To determine the performance and reliability of the Sandia Rolling Float Meter (RFM), and
3. To determine the feasibility of using an Echo Meter to measure wellbore fluid levels under lost-circulation drilling conditions while rotating the drill string and pumping fluid.

Researchers comparatively measured inflow rates with two magnetic flow meters, conventional pump stroke counters, pump rotary speed transducers, and a Doppler flow meter. Outflow rates were measured with a conventional paddlemeter, an acoustic level flow meter, and the Sandia RFM.

Researchers found that the Sandia RFM measures outflow rates within an accuracy of 1/2 to 2 percent, compared with a measured accuracy of 2 to 8 percent for an acoustic level meter, and 5 to 15 percent for a paddlemeter. The rolling float meter also detects small quantities of lost circulation and wellbore fluid production undetected by the other meters.

Researchers did note some reliability problems due to float distortion at higher temperatures. A solid polyurethane foam float, expected to be stable at maximum drilling mud temperatures of 212°F, was developed and tested late in FY91. Once a reliable float material is available, Sandia will transfer this technology to industry.

Borehole Televiewer - Formation Fracture Study - This effort focuses on measuring fracture apertures downhole using the acoustic borehole televiewer (BHTV). Researchers are testing parameters such as rock type, mud density and viscosity, and tool eccentricity in the borehole. Field test data generally have been confirming laboratory results.

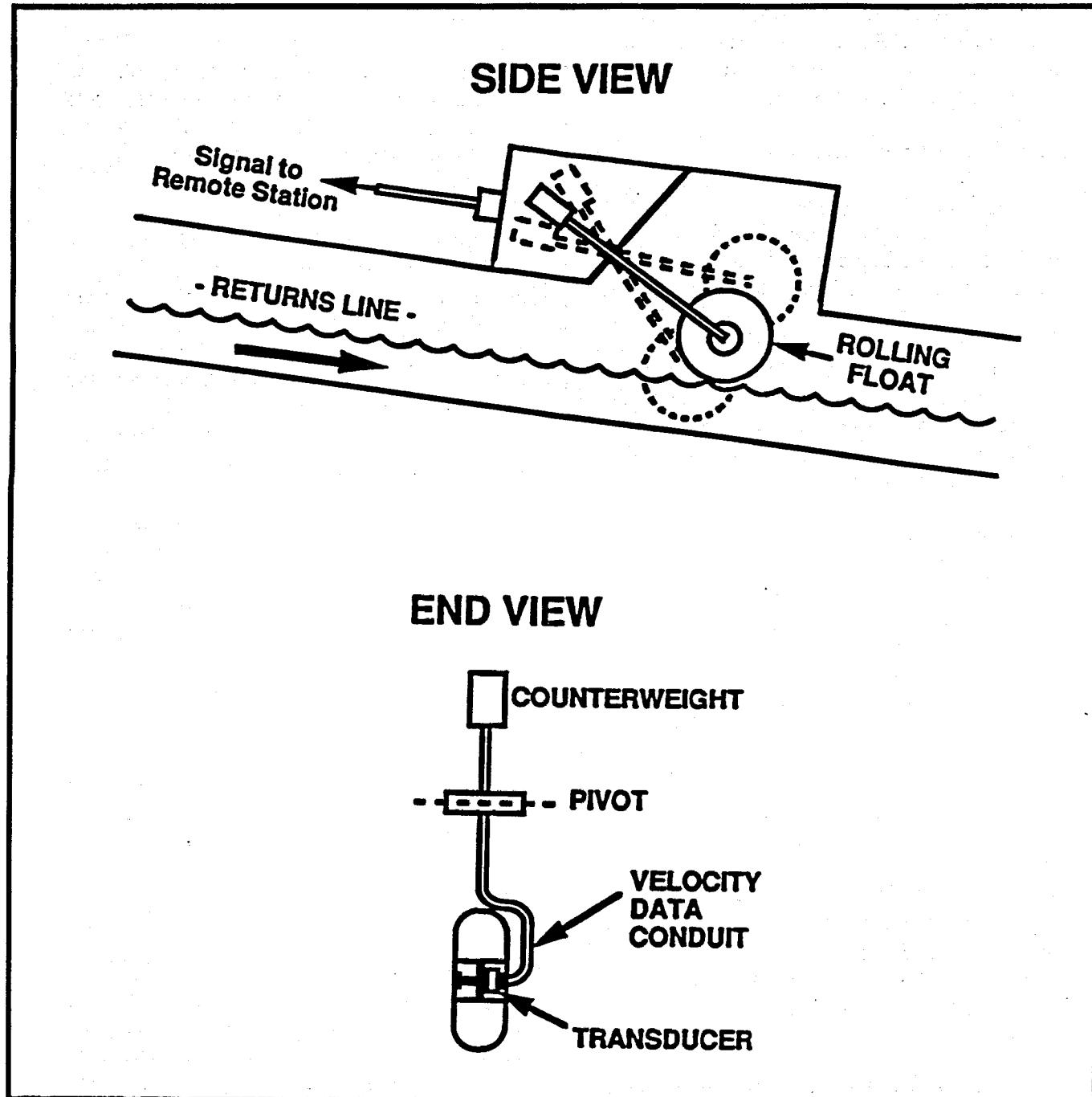


Figure 6
Schematic of Rolling Float Meter Developed and Field Tested in FY91

HARD ROCK PENETRATION PROGRAM

ROCK PENETRATION MECHANICS

Deep, hot formations are particularly detrimental to drilling fluids and drill strings, as well as to hole stability. Consequently, drilling in this environment is costly. The major objective of this task is to reduce the cost of deep wells and directionally drilled wells by 10 percent by the end of 1992.

The Rock Penetration Mechanics task focuses on four activities shown in Table 5, below. Initial work on geothermal heat pumps began in FY91 to identify areas for cost reduction for group loops installation.

Researchers use data collected from direct measurement of the environment and bottomhole

forces to improve tool design, enhance selection of drilling components and parameters, and improve trajectory predictions. Research efforts stress developing advanced data transmission methods for measurement-while-drilling (MWD) systems and incremental advancements in drilling and coring systems. MWD systems can significantly reduce drilling times and costs.

Researchers hope to improve this technology by increasing data transmission rates between the downhole transducers and the surface rig through acoustic telemetry techniques. Finally, researchers are becoming familiar with geothermal heat pump installation practices.

ROCK PENETRATION MECHANICS	
ACTIVITIES	OBJECTIVES
GEOTHERMAL DRILLING SYSTEMS ANALYSIS	Analyze geothermal drilling cost components and industry needs to identify most effective use of drilling R&D.
ACOUSTIC DATA TELEMETRY	Improve Measures-While-Drilling (MWD) data rates by a factor of 50.
ADVANCED DRILLING/CORING SYSTEMS	Develop new concepts and components for drilling deep, hot wells and for exploratory drilling using high-speed coring equipment.
GEOTHERMAL HEAT PUMP INSTALLATION	Evaluate technology and methods for installation of heat exchangers for geothermal heat pumps and identify areas for cost reduction.

Table 5.

ACOUSTIC TELEMETRY

The basic concept of acoustic telemetry is to produce an encoded sound wave at the bottom of a well, let it propagate up the steel drillpipe, and extract the data from the returned signal at the surface. The transmission characteristics of metal drill strings are not well understood and normal transducers have a low efficiency. These issues have hindered the development of acoustical telemetry systems. Previous efforts have enabled the design and fabrication of transducers with broad frequency bands which may be capable of transmitting data through drill strings at rates up to 50 times greater than conventional technology. Researchers are investigating new transducer designs which are more compatible with downhole power supplies. Researchers are analyzing field test data for transmission bandwidth and attenuation. Researchers are also assessing less expensive new methods of collecting data and improving transmission path quality.

GEOOTHERMAL HEAT PUMP INSTALLATION

Researchers, working with the National Rural Electric Cooperative Association, have identified a need to reduce drilling costs for installing geothermal heat pump ground loops. Space-saving drilling systems are required for both landscaped, small or treed residential lots and one day installation for retrofits. This will complement the trenched systems using the "slinky" technology to install ground loops, which in the past two years has reduced the trenching lengths by about 50% and loop installation costs by about 33%.

A direct spin-off of drilling R&D for geothermal heat pumps is utilization of Ditch Witch boring equipment for accessing regions beneath DOE waste sites. Sandia, in a joint effort with Charles Machine Works, is extending the use of monitoring strategies. This effort will expand existing capabilities to include a broader combination of soil/rock conditions.

INSTRUMENTATION

Two major instrumentation objectives are:

- To decrease the cost of drilling production-related geothermal wells through better identification of fractures, and
- To decrease the uncertainties in measurements of downhole and wellhead temperature, pressure, and flow measurements for reservoirs.

Research focuses on developing probes to operate in very high temperature environments and tools to map fractures and major boundaries of reservoirs. Conventional seismic techniques

do not provide sufficient resolution to accurately locate fractures, e.g., wells drilled within 100 to 300 feet of a commercial producer have failed to encounter productive fractures. Higher resolution fracture-mapping techniques using radar technology are required to locate fractures so that directional drilling can ensure a productive well.

Researchers are developing advanced downhole logging instruments capable of withstanding the extreme conditions of hydrothermal environments, that is, high temperatures, high flow rates, and severe erosion/corrosion. In the completed DOE Salton Sea Scientific Drilling

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Project, researchers developed a series of "slickline" tools to measure temperature, pressure, and flow at temperatures up to 400°C. This effort indicated that electronic tools with downhole memory offered the most promise for future development. Researchers will expand these efforts to develop a complete modular downhole instrumentation system capable of operation at temperatures up to 500°C. High temperature capabilities of fiber optic cables and sensors will also be investigated.

DOWNHOLE MEMORY TOOLS

Downhole logging for production information is routine in the hydrocarbon industry, but rare in the geothermal industry because of a lack of suitable tools, high development cost, and limited understanding of the relationship between measurable parameters and desired production parameters. The objectives of this activity are to:

- Develop tools using self-contained, data-storing computers for wireless measurements in extreme environments,
- Develop inversion algorithms relating the tool response to geothermal production parameters, and
- Transfer technology to industry.

Researchers will develop memory logging hardware in three programmatic components; (1) Dewar and Pressure Vessel, (2) Computer and Memory System, and (3) Sensors.

Dewar and Pressure Vessel - Dewars have evolved over the past decade for large-diameter, deep and warm (about 260°C) gas wells. The vessels need modifications to be applied to small, diamond-cored geothermal wells. The first slim (50 mm diameter), high temperature (400°C) logging tool built in 1988 was used extensively in DOE-sponsored operations. The

development program is addressing deficiencies in this prototype tool.

Computer and Memory System - Scientists have traditionally avoided memory logging systems since the tools do not provide real time data and diagnostic information during logging operations. This criticism may be overcome with more sophisticated, decision-making and mathematically rigorous capabilities to minimize data storage. Data logging systems with acceptable programmability are available, but untested in 150°C environments. Researchers completed some high temperature tests in FY91 which indicated that continued development is necessary.

Sensors - In FY91 a decision was made to develop a spectral gamma sensor. This decision was supported by the:

- Needs of the geothermal industry,
- Knowledge of the sensor's applicability from hydrocarbon operations,
- Utility of gamma measurements for depth control,
- Present capabilities of memory logging systems, and
- Simple extension to measurements of density and porosity, and into the fields of neutron activation analysis using radioactive sources.

A Request-for-Proposal was issued to logging tool companies for development and fabrication of the sensor. The tool will be ready in FY93.

Borehole Radar

Locating fluid-filled fractures is necessary to establish the economic feasibility of a reservoir. These fractures are often narrow vertical

HARD ROCK PENETRATION PROGRAM

structures missed by vertical exploratory drilling. These fractures will disturb an incident electric field, whereas an operating frequency of 10 megahertz or higher will provide a useful range resolution. A borehole radar may be suitable for this measurement.

The prototype pulse-type borehole Sandia developed experienced two types of problems:

dispersion in the geothermal media and limitations in digitization techniques.

In FY91, Sandia developed concepts for a lower-cost, more reliable continuous wave (CW) radar requiring less power than the pulse system, and greatly simplifying receiver electronics. (Signal processing is not required in the borehole.)

GEOTHERMAL DRILLING ORGANIZATION

The Geothermal Drilling Organization (GDO), a non-profit consortium of industrial firms, co-funds Geothermal Energy R&D Program elements designed to transfer technology to industry vendors. GDO's main objective is to enhance commercialization by reducing the cost of drilling. GDO members become involved with field test activities holding promise of early commercialization of the technology/products. For example, recent GDO activities include investigation and development of:

- Acoustic Borehole Televiwer
- High-Temperature Elastomer Products
- Downhole Air Turbines.

UNOCAL, will operate the acoustic borehole televiwers and provide technical direction and interpretation of data collected. Logging and maintenance will be separately contracted. UNOCAL is modifying the rotating mechanical section of the televiwer for extended operation.

The rotary head seal is the first high temperature elastomer product to become commercially available under the GDO program. The new design is used for both the geothermal & oil & gas industries.

Several independent operators have expressed an interest in downhole air turbines. Operator liability agreements are needed before implementing the technology.

RESERVOIR TECHNOLOGY PROGRAM

The Reservoir Technology Research Task focuses on exploration, fluid production and injection, and prediction of reservoir lifetime.

Background

The geothermal industry has recently made progress in the techniques of locating and developing hydrothermal reservoirs. Nevertheless, reservoir technology still suffers from several major uncertainties, such as those encountered in assessing reservoir productivity and in assessing the extent of field reserves. These uncertainties may lead to over-production in a field and premature pressure and production declines.

As geothermal developments mature, reservoirs change, and the lack of understanding about reservoir processes tends to compound costs and can lead to project abandonment. Additionally, problems arising from reservoir pressure changes and from chemical changes in relatively mature reservoirs, such as The Geysers, have created needs for supporting research. For example, changes in the chemistry may be a fundamental attribute of vapor-dominated fields or may instead result from pressure declines.

Industry needs research into the cause and control of such phenomenon to insure continued economic production at The Geysers. Conversely, many other reservoirs have yet to reach full production potential because they cannot be adequately characterized to allow effective exploitation.

Other geothermal systems have seen low drilling

success rates — leading to high drilling costs — because of the lack of techniques to:

- Locate and characterize fractures,
- Define reservoir boundaries,
- Assess fluid recharge, and
- Understand complex reservoirs.

Approach

This research task employs a two-fold strategy:

- (1) to conduct DOE-sponsored research to meet the high-risk and longer-term research needs of the geothermal industry; and
- (2) to fund cost-shared research with industry in areas of greatest current need.

The research combines laboratory and analytical investigations with equipment development and field testing to evaluate the usefulness of various analytical techniques. The program participants recognize that geological, geochemical, geophysical and reservoir engineering characteristics of geothermal resources are highly interrelated. The participants (See Table 6 on the next page) therefore maintain close coordination between all the geo-scientific aspects of the research.

The Tasks and Thrust of the Reservoir Technology Program appear in Table 7 on page 25.

RESERVOIR TECHNOLOGY PROGRAM

RESERVOIR TECHNOLOGY PROGRAM PARTICIPANTS	
PROGRAM RESPONSIBILITIES	ORGANIZATION
Conduct research into reservoir engineering and the physics of fluid flow.	IDaho NATIONAL ENGINEERING LABORATORY (INEL)
	LAWRENCE BERKELEY LABORATORY (LBL)
	STANFORD UNIVERSITY
Conduct innovative research into geophysics.	LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL)
	UNIVERSITY OF UTAH RESEARCH INSTITUTE (UURI)
	LBL
Conduct research into geochemistry and chemical thermodynamics.	OAK RIDGE NATIONAL LABORATORY (ORNL)
	UURI

Table 6.

The national laboratories and other DOE Geothermal Division contractors conduct cooperative research with industry through work at geothermal fields and through a program of cost-shared research. This cost-shared research focuses on reservoir exploration, and field performance.

Researchers adapt exploration and reservoir assessment techniques developed by the petroleum, mining, and groundwater industries for potential geothermal application and they build on this base to develop new exploration and analytical techniques specifically for geothermal application.

RESERVOIR TECHNOLOGY PROGRAM

RESERVOIR TECHNOLOGY PROGRAM TASKS AND OBJECTIVES	
TASK AREAS	THRUSTS
RESERVOIR ANALYSIS	Characterize geothermal reservoirs, i.e., develop techniques to: (1) detect and describe fracture systems responsible for fluid flow within the reservoir; (2) determine and describe the reservoir processes which influence the quality, quantity, and longevity of production; and (3) develop predictive models of the reservoir.
EXPLORATION TECHNOLOGY	Develop integrated models of the resource system to support exploration and reservoir analysis and to develop improved methods for exploration and reservoir characterization for industry use.
BRINE INJECTION	Provide industry with new geothermal tracers; develop techniques to follow the flow of injected fluids in the reservoir; and develop computer codes that model fluid and solute migration and heat transfer associated with injection into a reservoir.
GEOHERMAL TECHNOLOGY ORGANIZATION	Support industry through short-term cooperative research to develop technology useful in reservoir performance assessment and energy conversion.

Table 7.

RESERVOIR ANALYSIS

This task will provide analytical and interpretive tools to more clearly determine reservoir characteristics and reservoir performance. The task objectives are to:

- Reduce the number of wells needed to define a resource and to evaluate a reservoir;
- Decrease uncertainties in forecasting reservoir changes in fluid temperature, flow rate, and chemistry; and

- Reduce uncertainties in predicting reservoir capacity.

GEOTHERMAL RESERVOIR MODELS

The research team refines computer models by analyzing field test data from individual production well and interference tests. These refined models help to identify reservoir processes and to evaluate the response of hydrothermal systems to development. In

RESERVOIR TECHNOLOGY PROGRAM

addition, the development of computer models to predict reservoir performance from combined well testing and production history data will continue.

- Idaho National Engineering Laboratory (INEL) published a study evaluating the TETRAD model's ability to simulate geothermal systems. INEL used Stanford University's reservoir test problems, as well as other problems with known solutions, to test the simulator.
- Lawrence Berkeley Laboratory (LBL) identified and described several conceptual models of the high-temperature zone at the NW Geysers. LBL also began simulation studies of this zone to establish its origin and compared it with the shallow "typical" vapor-dominated system.
- Stanford University wrote a computer simulation program of flow processes in the presence of adsorption. Stanford is documenting this program, which should be available soon.

GEOPHYSICAL METHODS TO CHARACTERIZE AND LOCATE FRACTURES

Testing will continue on vertical seismic profiling and microseismic monitoring to detect and map fractures. The research team will continue to collect and interpret high-quality seismic data to determine locations of steam and two-phase zones.

Findings

- LLNL developed and evaluated seismic imaging methods for geothermal reservoirs, using recordings made by UNOCAL Geothermal. LLNL monitored small earthquakes at The Geysers to produce a low-resolution seismic and

attenuation image. By comparing this image with known locations of steam and water-saturated rocks in the northeastern Geysers area, LLNL hopes to demonstrate that the images can be used to delineate steam and two-phase regions.

- UURI measured the orientations of fractures within the oriented core from just above The Geysers reservoir. UURI concluded that different structural zones exist, giving rise to the observation that the reservoir controls in one part of the geothermal system may have orientations different from those in other parts of the system.

CONCEPTUAL GEOLOGIC MODELS

The research team will develop and field test new equipment for downhole measurement of the borehole environment. Studies of fluid inclusions at various geothermal fields will assist in predicting fluid circulation in hydrothermal systems.

Findings

LBL began investigating the effects of capillarity, vapor adsorption, and vapor pressure lowering in vapor-dominated systems. The Laboratory also issued the users' manual for LBL's multi-feedzone wellbore model.

UURI completed the following tasks:

- Documented the development of reservoir porosity at The Geysers through dissolution of metamorphic calcite coupled with prograde formation of calc-silicates. These calc-silicates develop remarkably intricate textures which may have a large influence on liquid water storage in the vapor-dominated reservoir.

RESERVOIR TECHNOLOGY PROGRAM

- Characterized the flow patterns and physical processes occurring in the granite-hosted geothermal reservoir at Coso prior to production.
- Determined the distribution of CO₂ in two volcanic-hosted geothermal systems (Los Azufres, Mexico and Zunil, Guatemala) and the conditions that lead to the formation of CO₂-rich fluid inclusions in near-surface environments.
- Completed more than a thousand fluid inclusion measurements on cores and cuttings from The Geysers. UURI is currently interpreting this data.
- Established pre-production chemical values for many of the wells from the Coso geothermal field, California and documented and mapped some changes in the chemistry of the produced fluids at Coso.

NUMERICAL METHODS

The research team will use improvements in numerical models to better interpret well measurements and laboratory data. The team will interpret field data from geology, geophysics, geochemistry, and hydrology of specific systems and will attempt to synthesize knowledge about general reservoir processes. Researchers will also complete laboratory studies to evaluate tracer and multiphase flow in fractures.

The team will then use laboratory physical models to develop techniques for simulating geothermal systems response to different reservoir management programs and for estimating the generation capacity as well as for estimating the longevity of these systems.

Findings

- INEL began studying the sensitivity of TETRAD to various reservoir parameters. Such information is important to the geothermal industry for planning reservoir studies.
- LBL numerically modeled the grid orientation effects of liquid injection into vapor-dominated geothermal reservoirs. The Laboratory also released the numerical code TOUGH2, now available through DOE's National Energy Software Center.
- Stanford University installed two sets of experimental apparatus to measure steam adsorption in geothermal rocks. The first is a steady state (BET) apparatus, and the second measures adsorption in a transient flow experiment.
- Stanford measured adsorption characteristics of geothermal rocks from several operating fields in different parts of the world. Samples from the Geysers spanned a variety of depths and reservoir locations, and showed that the amount of steam adsorbed is considerable. A report is in preparation.
- Stanford University also developed an analytical solution for the pressure transient response of a finite conductivity fracture and derived a mathematical expression for the skin factor of this kind of fracture. Stanford developed these analytical techniques to solve a problem whose only solution up to now had involved a laborious, numerical procedure. This type of fracture flow is probably one of the more common in actual geothermal wells.

HCl SOURCES AND DEVELOPMENT OF CHEMICAL DATA AND MODELS

The research team will investigate the source of HCl in vapor-dominated geothermal systems and will develop a deeper understanding of geothermal chemical systems. Laboratory studies will continue on central issues such as reservoir porosity, volatility of HCl from brines, isotopic distributions, and thermodynamics of aqueous fluids and synthetic granitic melts.

From these investigations, the team will develop geochemical codes that emphasize the origin and behavior of fluids and changes from varying reservoir parameters.

Findings

Oak Ridge National Laboratory showed progress on several fronts:

- ORNL submitted publications on aluminum hydroxide (gibbsite) solubility to 100°C in concentrated NaCl brines. The thermodynamic properties of Al^{3+} , $\text{Al}(\text{OH})^{2+}$ and $\text{Al}(\text{OH})_4^-$ in water and their activity coefficients in NaCl brines are now available for input to geochemical models. Also, acetate ions were found to form strong complexes with Al^{3+} .
- ORNL published definitive EMF measurements on the ionization constant for bisulfate to 250°C and 5 molal. ORNL also determined ion interaction parameters for $\text{NaSO}_4(\text{aq})$ from osmotic measurements in the ORNL apparatus to 250°C and derived the parameters using the new EMF results on the ionization of bisulfate.

- ORNL is addressing the origin of the acidity in the steam at The Geysers in laboratory studies of the volatility of HCl from brines. The distribution constant is now available to 350°C from studies in platinum-lined vessels.

Results indicate that at the highest temperatures (300°-350°C) the predicted level of HCl is relatively independent of salinity and temperature. Under these conditions a pH of less than 4 is required to obtain a level of HCl near 100 ppm in the steam from NaCl brines.

- New results from laboratory studies on hydrogen and oxygen isotopic distributions between liquid and vapor show important salinity effects. Results to 100°C show that isotope effects for mixtures are additive functions of the individual electrolytes.

These studies demonstrate that very significant errors would result from the neglect of these effects in the interpretation of isotopic data from geothermal systems.

- LBL built a 6-liter downhole fluid sampler designed to obtain condensate from the high-temperature and the "typical" zones at The Geysers. LBL continued fracture flow visualization experiments and the measurement of relative permeabilities and capillary pressures.
- UURI initiated a sampling program of two superheated wells at Coso to monitor for the development of HCl-bearing steam and has detected its presence.

EXPLORATION TECHNOLOGY

Most of the obvious hydrothermal systems have been explored. New hydrothermal discoveries will require exploration in frontier areas where the reservoirs are either concealed or at greater depths. Some potentially promising reservoirs may occur adjacent to presently uneconomic systems.

The Exploration Technology task focuses on developing techniques to locate and characterize geothermal resources in young siliceous volcanic environments.

The Specific Exploration Technology task objectives are to:

- Increase the success ratio of wildcat exploration wells, especially in frontier areas; and
- Devise better methods to discover hidden hydrothermal systems, and to explore the deep portions of known systems.

Research will improve current exploration techniques through a program to:

- Solicit industry participation to determine characteristics of deep geothermal reservoirs, particularly in areas with deep circulation of ground water;
- Develop reservoir models that integrate geological, geophysical, and geochemical data; and
- Identify exploration techniques particularly suited to deep geothermal reservoirs.

INTEGRATED MODELS FOR DEEP GEOLOGIC RESERVOIRS

Researchers will collect existing data from geothermal exploration projects and integrated with geological, geophysical, and geochemical data from field and laboratory investigations. Results will lead to conceptual exploration models as well as case studies of resource exploration for the geothermal industry.

Findings

- As part of the effort to transfer technology to industry, LBL organized and hosted the September 23-24, 1991 Geothermal Exploration Technology Workshop. About 40 researchers from industry, academia and state and federal agencies participated.
- LLNL began evaluating existing laboratory data on velocity-attenuation systematics to provide a basis for interpreting combined images in geothermal areas. LLNL also began developing and testing an artificial-intelligence-based system for teaching the computer to pick P-arrivals from recordings of earthquakes.
- UURI developed advanced algorithms for modeling 2-D and 3-D MT. The 2-D finite element code in particular is probably the most accurate and versatile of its class and currently is being used in state-of-the-art regularized inversion. The 3-D integral equations code now can produce accurate responses for outcropping structures which transect host layer interfaces. Such interfaces extend indefinitely in one or more dimensions.

GEOPHYSICAL METHODS FOR EXPLORATION

The research team will determine theoretical geophysical responses from fluid-filled fractures through numerical analysis. Field testing of surface geophysical techniques will verify expected responses. The team will also investigate new interpretation methods for using these techniques. The team will then combine observed geophysical data with laboratory measurement of physical properties and existing geologic data to develop exploration plans for specific regions.

LBL operated a high-resolution seismic borehole array at Long Valley. The research team used MEQ data to image the resurgent dome area and to investigate P- and S- velocity structure to determine the presence of hydrothermal activity and shallow magma bodies.

Findings

UURI's accomplishments include:

- Studies at Valles Caldera that determined that structural zones established during the

earliest phases of volcanism control hydrothermal circulation.

- A field system was deployed for acquiring electrical geophysical data using borehole-to-borehole, borehole-to-surface and surface-to-borehole electrode arrays; to be field tested in the spring of 1992.
- SP data was acquired over about half a dozen shallow, low- and moderate-temperature hydrothermal systems in Utah and New Mexico. In each case, UURI detected positive SP anomalies over areas where other data, including drilling, indicated zones of upwelling of hydrothermal fluids.
- UURI redesigned and field tested the magnetotelluric field system employing digital FM telemetry to achieve full remote referencing. Multitasking at the recording truck provides concurrent acquisition and processing capability to achieve a fully processed sounding on-site. In-field processing includes sophisticated data coherence sorting which greatly improves response quality.

BRINE INJECTION

The project addresses three specific areas: fluid migration, fluid-rock are chemical interactions, and injection well placement. Specific brine injection objectives are to:

- Increase the success ratio of fill-in wells for production and injection;

- Improve methods for positioning and designing production and injection wells;
- Improve reservoir monitoring methods to decrease uncertainties in forecasting changes in key reservoir parameters;
- Reduce the number of low-flow and short-lived production and injection wells;

RESERVOIR TECHNOLOGY PROGRAM

- Reduce uncertainties related to long-term reservoir changes in fluid temperature and injection breakthrough; and
- Reduce the number and severity of unexpected environmental problems related to potential seismicity and subsidence.

The Injection Technology project addresses industry needs for effective and environmentally acceptable injection systems. Techniques to predict the intensity and timing of the thermal, chemical, and hydrologic effects of injection should reduce adverse impacts on geothermal reservoirs.

TRACER TESTING

Researchers will evaluate potential geothermal tracers through laboratory experiments simulating natural geothermal systems. Industry will participate in developing field operations techniques for tracer injection, sampling, and interpretation to track injected fluid. The research team will investigate the effectiveness of injection methodologies at The Geysers.

Findings

- Stanford University completed the project on optimizing reinjection scheduling at the Palinpinon geothermal field in the Philippines and prepared a report for circulation. Stanford developed techniques to make use of optimization algorithms (developed earlier in the project) originally intended for use with tracer return data. Since sufficient tracer data is usually difficult and expensive to obtain, the project made use of more commonly available data from routine chloride monitoring. Stanford showed that, by proper selection and correlation

of data, it is possible to obtain "breakthrough indices" from the chloride data that are in good agreement with the few tracer test results available.

- UURI identified a class of compounds that appear to be suitable as vapor-phase tracers. Industry tested two of the potential vapor-phase tracers at the Southeast Geysers. The tracer was injected into one well, and was successfully detected in 38 production wells. Although the tracer functioned suitably well, more research is needed to define the stability-composition relationships.

NUMERICAL ANALYTICAL CODES DEVELOPMENT

Researchers will determine if injection of spent geothermal fluids can generate detectable signals. If necessary, they will design equipment capable of detecting the theoretically determined signals.

Findings

Under a joint industry/DOE project, LBL brought high-resolution seismic monitoring array in NW Geysers into fully operational status. LBL then developed a detailed 3-D velocity model of the area. LBL also installed a second microearthquake monitoring array in the SE part of the Geysers to more fully understand the mechanisms associated with liquid injection into vapor-dominated systems. LBL researchers obtained baseline seismic velocity model for the SE Geysers. Finally, LBL initiated a cooperative effort with industry to analyze the effects of liquid injection in the SE Geysers and initiated an analysis of the spatial variation in noncondensable gases and isotopes at The Geysers.

RESERVOIR TECHNOLOGY PROGRAM

ANALYTICAL METHODS

The research team will continue developing computer models used to analyze and predict the flow of injected fluids through reservoirs. The team will also investigate the potential for coupling the fluid flow model with models of chemical interactions between rocks and the injected fluid well.

Findings

INEL performed reservoir studies of historical injection in two areas at The Geysers. INEL developed and calibrated a detailed reservoir model. The model is being used to model historical injection response and to develop injection strategies.

GEOTHERMAL TECHNOLOGY ORGANIZATION

Members of the Geothermal Technology Organization (GTO) jointly select research projects with emphasis on high priority near-term industry needs. GTO shares the costs of geothermal research and development with DOE. Included in this project area are technology transfer activities of the Reservoir Technology Program, such as the Lawrence Berkeley Laboratory Industry Advisory Committee and the coordinated research program concerning The Geysers.

INEL acts as DOE representative to the industry's Geothermal Technology Organization

to sponsor cooperatively-funded technological development. The geothermal industry works with DOE through a cooperative research agreement between the DOE Idaho Field Office and the GTO. LBL will continue coordinating research activities with Geysers operators and the researchers.

In FY91, GTO reached an agreement for joint interpretation of data from an impending tracer test conducted by operators at The Geysers. Data from the test was received and preliminary results of the stability determinations of the tracers were published.

LONG VALLEY DRILLING PROJECT

The general objective of the Long Valley Drilling project is to test and improve technology for locating and describing deep thermal resources. The research team is drilling near a well-studied thermal anomaly in the Long Valley caldera. The near term objective is to deepen the existing well to 14,000 feet or more and to use it as a test bed for new geothermal equipment and processes.

The Interagency Coordinating Group of the Continental Scientific Drilling Program has designated the Long Valley exploratory well as a "hole of opportunity." The Group regards the well as a means to obtain important new data about active calderas relating earthquake and volcanic processes. In FY89, Phase I saw the drilling of a well to 2,568 feet. Following this well completion, a small scientific hole was

RESERVOIR TECHNOLOGY PROGRAM

cored for an additional depth of 186 feet. Phase II was completed in late FY91 with the extension of the hole to a depth of 6,825 feet. Two research efforts are the project (1) Long Valley Operations, and (2) Laboratory and Engineering Support.

LONG VALLEY OPERATIONS

The operations at Long Valley comprise two areas; (1) Drilling and Engineering, and (2) Supporting Science. The research team hopes to confirm the existence of a large thermal resource in the caldera through exploratory drilling. Emphasis is on the acquisition of data useful to the hydrothermal industry.

The research team will perform Wellbore measurements to:

- Confirm a significant thermal resource at drillable depths;
- Evaluate drilling problems and materials compatibility; and
- Assess hydrothermal productivity.

Findings

The Phase II 6,825 - foot well consisted of a 17-1/2 inch diameter hole with a 13-3/8 inch casing. The scientific coring of the well will

take place early in FY92. Funding for the drilling was shared by the California Energy Commission and the U.S. Department of Energy. Although not an explicit part of the Long Valley exploration program, the Lost Circulation Project Group used Phase II data for field evaluation of prototype instrumentation.

The broad research goal is to design any technology needed to drill and complete wells into the deep, hot regimes typified by the Long Valley Exploratory Well. This goal includes design and development of engineering materials compatible with the Long Valley well chemical environment.

PROVIDE LABORATORY AND ENGINEERING SUPPORT

Activities focus on three areas; (1) Drilling Technology, (2) Geochemistry and Materials, and (3) Energy Extraction.

Findings

No activities were planned specifically as Supporting Science in FY91. Nevertheless, many of the results from Phase II drilling contribute to future activities, such as temperature logs, sidewall cores, and a borehole televiwer log of the complete 17-1/2 inch hole.

CONVERSION TECHNOLOGY PROGRAM

Because geothermal resources have varied characteristics, a variety of technologies are used to convert geothermal heat to electricity. Three technologies in current use are:

- Dry steam conversion technology, such as that used at The Geysers in California (in commercial use since 1960);
- Flash steam plants, favored when the resource temperature is over 180°C (360° Fahrenheit); and
- Binary cycles, favored when the resource temperature is under 180°C.

Dry steam conversion and flash steam plants are mature technologies that are generating cost competitive electricity.

Binary cycle power plant technology is less mature, but these plants are more thermodynamically efficient than flash steam systems at more moderate geothermal resource temperatures. However, economic disadvantages of binary cycle power plants caused by higher costs for conversion equipment have inhibited the use of binary systems.

Background

Of major concern to geothermal developers are problems associated with chemically aggressive geofluids. Special muds and cements are needed to drill into hydrothermal reservoirs. Equipment (such as wells, brine gathering systems, steam separators, and heat exchangers) must withstand high levels of corrosion and scaling if the availability, lifetime, power output, and conversion efficiency of geothermal installations are to be economically competitive.

Conversion Technology activities focus on alleviating these concerns by permitting a greater use of the more abundant moderate-temperature geothermal resources and by reducing the life-cycle cost-of-electricity for the power generated. The program has two major thrusts:

- (1) to advance binary technology to develop other surface systems, and
- (2) to develop new materials and methods to reduce capital cost, unscheduled downtime, and the need to replace equipment.

The Conversion Technology program addresses these thrusts by focusing on the task areas and objectives in Table 8, on the following page.

HEAT CYCLE RESEARCH

Heat Cycle Research focuses on using liquid-dominated, moderate-temperature hydrothermal

resources to generate electricity. The intent is to extend commercial, cost-competitive geothermal

CONVERSION TECHNOLOGY PROGRAM

CONVERSION TECHNOLOGY PROGRAM TASKS AND OBJECTIVES	
TASK AREAS	OBJECTIVES
HEAT CYCLE RESEARCH	Seeks to improve conversion cycle efficiency and focuses on binary cycle technology
MATERIALS DEVELOPMENT	Directed toward finding materials capable of simultaneously withstanding high temperatures and highly saline brine
ADVANCED BRINE CHEMISTRY	Addresses problems associated with the production, use, and disposal of highly saline brines

Table 8.

power generation to the more abundant lower temperature resources not suitable for flash steam technology, and to provide a more efficient alternative for some of the resources developed with flash steam technology. The specific intent of heat cycle research is:

- to improve the efficiency of binary cycle technology, and
- to expand the resource base to include marginal resources not being developed because of technical or institutional barriers.

Current major project research activities are:

- Supercritical cycle investigations (nearing completion);
- Investigations of the condensation behavior of supersaturated turbine expansions;
- Support to the development of non-fouling heat exchanger tubes;

- Advanced heat rejection; and
- System studies.

The above activities are conducted at the Idaho National Engineering Laboratory (INEL) and the Heat Cycle Research Facility (HCRF) which INEL operates in the Imperial Valley of California. The HCRF contains all of the major components in a typical binary cycle power plant, but at a reduced scale (an electrical power output of 50 kilowatts). In Fiscal Year 1989, the facility moved from its original DOE site to a commercial facility, the B.C. McCabe binary power plant. The compliance of the HCRF operations to safety, environmental, and health regulations is also a major project activity. The following paragraphs describe research in FY91.

ADVANCED PLANT - SUPERCRITICAL CYCLE INVESTIGATIONS

This activity addresses the Level III objective of improving the binary cycle performance by 20%. The Heat Cycle Research Facility

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(HCRF) serves as the principal facility to generate data to achieve this objective.

Findings

The investigations at the HCRF have thus far shown that the assumptions used in making the Level III projections are valid. Current property and design codes adequately characterize the supercritical vaporization of working fluid mixtures; however, existing design methods are not adequate for sizing the heat exchangers.

With the existing tools, the condenser heat exchange area would be under-predicted, leading to higher turbine exhaust pressures and lower power output than desired. Though the projected 20% improvement in performance can be achieved with the technology being developed in the project, there is uncertainty associated with the amount of improvement and impact on the cost of power.

The uncertainty comes primarily from the condenser design. This activity is currently 80% to 90% complete. Specific FY91 progress includes:

- Both the HCRF brine preheater and vaporizer heat exchangers were retubed after repeated failures of the tube material in the geothermal service.
- The final phase of the supercritical cycle investigations at the HCRF began using the isobutane/hexane working fluid mixtures.
- The data acquisition system was upgraded; the new system will facilitate the evaluation of the data collected.
- Researchers completed the re-tubing of

the HCRF brine heat exchangers and resumed operations.

Discussion

The suspension of operations at the McCabe plant hindered the initial HCRF operations at the new location (adjacent to the B.C. McCabe binary power plant). Modifications were necessary to provide both brine and cooling water to the HCRF. Excessive amounts of sand suspended in the brine also required modification to the facility to allow operations to continue. Difficulties associated with the age of the facility also hindered operations. It was necessary in FY91 to replace or repair many of the facility components (particularly those exposed to the brine). This location also presents extreme ambient operating conditions for electrical equipment and instrumentation. Maintaining an adequate supply of spare materials in the event of equipment failure has also been a problem.

Data reduction efforts were minimal during FY91. The data acquisition system was upgraded using a personal computer (PC) and recorder from the INEL. The upgrade allows the operating conditions for the facility to be recorded as data files used directly in the data analysis software. This modification should expedite the data reduction and reduce the associated cost.

INVESTIGATION OF CONDENSATION BEHAVIOR OF SUPERSATURATED EXPANSIONS

This activity addresses the Level III objective of increasing binary cycle performance an additional 8 percent by using supersaturated turbine expansions. Investigations at the Heat Cycle Research Facility (HCRF) will determine whether these expansions avoid the formation of condensation droplets and, if not, whether these

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droplets are sufficiently large to damage the turbine or adversely affect performance.

Findings

- Researchers completed the engineering design to install the two-dimensional expansion nozzle, purchased materials, and sent them to the HCRF.
- Researchers completed the engineering and procurement of the laser data acquisition system to detect the presence of condensate in the expansions. This data acquisition system was installed at the HCRF.

Discussion

Previously, a two-dimensional expansion nozzle was obtained to simulate and monitor the turbine expansions. Researchers at North Carolina State A&T University also developed a laser droplet illumination system to detect the presence of condensate in these expansion streams. During the second half of FY91, INEL engineering initiated the design of the two-dimensional nozzle and the laser detection system. Compliance with safety requirements for the installation and operation of the laser required a significant engineering effort. The definition of the specific requirements for the laser installation and operations will be available during the first quarter of FY92.

Researchers completed the design and installation of the output monitoring equipment for the laser detection system. This system used a PC from INEL and a software package to allow the PC to emulate a digital oscilloscope. Researchers completed preliminary checkout of this system at the HCRF; the final checkout cannot be completed until the installation of the laser system is completed.

Researchers also completed the design modifications to the HCRF for the installation of the two-dimensional nozzle. This design included an enclosure for the nozzle which provides for: (1) the mounting of the optical equipment at the nozzle, (2) protection for personnel, and (3) minimization of background light, which could cause erroneous data from scattering of the laser by condensation droplets. This enclosure was fabricated and shipped to the HCRF.

This project activity suffered from delayed receipt of funding for FY91. Because of the uncertain funding, work initiated during FY90 was suspended, and personnel were assigned to activities outside of the project. These people were not immediately available when funding was approved. Work on the design of the laser had to be suspended, pending the definition of the safety-related requirements for the laser installation and operation. The field investigations to validate the analytical projections should begin in FY91. At present, this activity is approximately 20% completed.

PCL HEAT EXCHANGER TUBE FOULING INVESTIGATIONS

The polymer-concrete lined (PCL) heat exchanger tube is used to investigate the technical barriers to developing geothermal resources with aggressive, highly saline brines.

The lining provides corrosion protection to a relatively inexpensive base material, at a cost less than an exotic material. If the lining can also resist fouling of surfaces and have a thermal performance comparable to conventional heat exchanger tube materials, PCL tubes could reduce heat exchanger costs, as well as maintenance costs (for cleaning).

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Findings

Installation of the test unit for conducting the investigation of the PCL heat exchanger tube resistance to fouling was completed at the Del Ranch power plant. Preliminary results indicated the PCL tube does not have the quoted thermal performance, and that its surfaces did scale when exposed to the brines at the Del Ranch plant. Initial examination of the tubes after the completion of the testing indicate a thicker than anticipated lining. This heavier lining could account for some of the degraded thermal performance.

In FY92, researchers will examine the tubes some more, to further evaluate the uniformity of the lining thickness and to determine if any noticeable difference exists in the scale formation on the lined and unlined tubes.

To evaluate the potential application of this material, the researchers must obtain accurate cost data and identify a means to make tube-to-tube sheet joints. They must examine and revise the methods for applying the lining to the base tube material to produce a more uniform and consistent application.

Discussion

INEL built an earlier test unit at the heat cycle research facility (HCRF) to investigate the performance of the PCL tube and its resistance to fouling of heat exchange surfaces. During the summer of 1990, INEL moved the test unit to the Del Ranch plant near the Salton Sea to conduct these investigations. Because of the delayed receipt of FY91 funding, the test unit installation was delayed until the spring of 1991.

After completing the installation, the HCRF operators made several unsuccessful attempts to

initiate operation of the test unit for an extended test period (50 to 100 days). The brine being used was supersaturated with silica. It was also "seeded" by the plant operator to promote silica formation, since any cooling of the brine would result in silica precipitation. Researchers made modifications to remove the silica precipitation, or keep it suspended, to prevent "plugging" and to extend the operating period of the unit.

The modifications extended operating time from a little over an hour to more than 70 hours. In August 1991, they ended the testing. They removed sections of the PCL tube and sent them to Brookhaven National Laboratory for examination.

Although it was possible to significantly extend the period of time during which the test unit could operate without plugging, it could not operate for the desired 50 to 100 days. Despite the limited operational time, the surfaces of the unlined tubes were significantly fouled.

Because of the difficulties encountered in attempting to operate with the brines at the Del Ranch plant, the operating costs for the test unit were considerably less than anticipated. Because of the FY91 funding delay, this activity did not begin as scheduled. Test results will now be reported in FY92.

ADVANCED PLANT - SYSTEMS STUDIES

Researchers are focusing on improving geothermal power cycle performance and reducing the cost of power generated. This work parallels field investigations in other projects. Investigators are evaluating advanced concepts under a common set of assumptions to evaluate their relative merit.

During FY91, researchers concluded a study to determine potential further improvements in performance of binary power cycles. They

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considered limits of binary cycle performance based on practical constraints of rotating equipment efficiencies and heat exchanger approach temperatures (without imposing site-specific constraints). These limits on component performance then define the maximum performance (according to a thermodynamic second law analysis) of a cycle using an "idealized" working fluid. Researchers then evaluated the concepts currently investigated in the Heat Cycle Research project with the same set of constraints. This analysis showed the performance of a cycle incorporating these concepts approached the performance of an idealized cycle operating under practical component limits. They evaluated other advanced power cycles, including the Kalina cycle and the Trilateral cycle, according to the same approach and with the same constraints. These cycles approached the performance of the supercritical cycles using the mixed hydrocarbon working fluids under investigation at the HCRF.

Findings

A summary of FY91 reports included other studies on binary power cycles. In two studies, researchers employed the value analysis to evaluate the economic impact of both supersaturated turbine expansions and heat exchanger pinch points in power cycles using both "wet" and "dry" heat rejection systems. The evaluation of the heat exchanger pinch points suggested that the economic optimum occurred at approach temperatures less than the 10°F typically used as a component limit in power cycle performance. The studies also indicated that the economic benefit of supersaturated turbine expansions varied from

4% to 8% reduction in the cost of power, depending upon the type ("dry" or "wet") of heat rejection system utilized.

A third study considered the impact of outlet temperature limits imposed on brines leaving geothermal power plants on the performance of the plant. The researchers considered both liquid (pumped) and flashed (two-phase) supply streams and binary and flash-steam power cycles.

INEL also sought industry's thoughts on the direction of the research. Initial meetings at the DOE Program Review in the spring of 1991 established a preliminary industrial advisory group. Further discussions were held during the summer, and an organizational meeting for the advisory group was scheduled for the annual Geothermal Resources Council meeting in the first quarter of FY92.

In FY91, INEL drafted a scope of work for a solicitation for projects to demonstrate the economic benefits of improved electrical generating systems for geothermal applications.

Discussion

The work accomplished in this activity suggests that the technology under consideration in other HCRF activities will allow industry to achieve performance levels approaching practical limits.

Reports soon to be published will address: (1) the impact of the limit on the effluent brine temperature from a binary plant on the cycle performance, (2) the optimization of heat exchanger and condenser pinch points, and (3) the economic impact from allowing supersaturated turbine expansions.

MATERIALS DEVELOPMENT

The materials development task provides information to industry designed to reduce costs of geothermal well field design and as well as power plant design, construction, and operation by:

- Extending equipment operating temperature limits and tolerance to chemically aggressive fluids;
- Extending equipment life;
- Reducing maintenance and replacement costs; and
- The use of lower cost materials.

Near-term goals are to:

- Reduce costs associated with lost circulation episodes by 30 percent;
- Reduce the costs of deep wells and directionally drilled wells by 10 percent;
- Reduce well-cementing problems for typical hydrothermal wells by 20 percent.

Advanced technology is needed during drilling, well completion and test development, heat extraction, power production, and reinjection of spent brines to develop improved materials and methods to withstand:

- (1) extremely high temperatures encountered in power production and energy conversion processes; and,
- (2) severe corrosion and scaling by geothermal brines.

The activities that take place at the Brookhaven National Laboratory (BNL) provide technical and managerial support of high risk/high payoff materials research and development (R&D).

Because of the uncertain geothermal market, industry will not develop these special materials. Current major research task activities at BNL are:

- Advanced High Temperature Lightweight Cements;
- Thermally Conductive Polymer Cement Liners;
- Chemical Systems for Lost Circulation Control;
- Corrosion Mitigation at The Geysers;
- High Temperature Chemical Coupling Systems; and,
- Geothermal Drilling Organization Elastomer Activities.

ADVANCED HIGH-TEMPERATURE LIGHTWEIGHT CEMENTS

The service life of a geothermal well depends on the quality of the well cementing operation. As drilling environments become more hostile, the lack of high performance, lightweight cements will cause operational constraints. The R&D strategy for this task is to improve well completion procedure effectiveness and to minimize lost circulation problems by the development of CO₂-resistant lightweight high temperature cements. A cooperative BNL/New Zealand Department of Scientific Research (DSIR) research effort is in place to develop cement formulations, to perform physical and chemical/mechanical evaluations (at BNL), and to conduct downhole tests in wells at the Mokai and Rotokawa geothermal fields (at DSIR). Planned activities are to:

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- Identify the best candidate cement and retarding admixtures;
- Complete pumpability tests;
- Perform long-term durability testing in autoclaves;
- Complete downhole testing at DSIR; and,
- Conduct peer review of publications.

Findings

BNL researchers attained planned milestones for these activities in FY91, except for downhole testing at DSIR. Collapse of a well casing prevented removal of test specimens. The following was achieved:

- (1) BNL initiated planning for a Cooperative Research and Development Agreement (CRADA) with a geothermal firm for work on lightweight cements;
- (2) BNL continued work on phosphate-modified calcium aluminate cements, identified as promising CO₂-resistant binders in FY90. They published results of compressive strength based on curing time and reservoir temperature in the journal of the American Ceramic Society; and,
- (3) BNL completed tests to measure the rate of carbonation of various cements.

THERMALLY CONDUCTIVE POLYMER CEMENT LINERS

Corrosion of the brine side of tubing in shell and tube heat exchangers can be a major problem in binary cycle plants. A very expensive high

alloy steel (AL-29-4C) must be used, and even then, excessive fouling prevents the economic use of binary processes with hypersaline brine reservoirs.

Under this research activity, BNL:

- Determined the effects of composition and processing variables on the thermal and scale-resistance characteristics of the composite; and
- Measured the physical and mechanical properties of the composite after exposure to hot brine under laboratory and field conditions.

Findings

Idaho National Engineering Laboratory (INEL) completed "baseline" testing at the Heat Cycle Research Facility (HCRF) of a prototype shell and tube heat exchanger containing thermally conductive polymer concrete lined carbon steel (PCL) tubing. The system was then assembled and tested at the Del Ranch geothermal power plant.

The plant operator had considerable difficulty operating the heat exchanger and a conventional high alloy steel (AL-6XN) tubed unit over an extended period of time because of the supersaturation of the brine with silica. A scaling and silica deposition rate of 5 inches per year was estimated.

The high alloy steel tube fouled to the point where its overall thermal resistance doubled during 250 hours of operation. A doubling of thermal resistance also occurred in the test loop containing the PCL tubes. DOE/ID approved INEL's recommendation to terminate the experiment because of its high labor intensity and the scaling problems.

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The used PCL tubing was sectioned and returned to BNL in October 1991 for examination. A joint INEL/BNL report will be prepared and published in FY92 summarizing the thermal and hydraulic performance results from these tests at the HCRF and the Del Ranch plant.

CHEMICAL SYSTEMS FOR LOST CIRCULATION CONTROL

Correcting lost circulation problems during well drilling and completion operations is about 20% to 30% of the cost of a well. Significant cost reductions (on the order of 47% to 78%) accrue if advanced high temperature chemical formulations for cementitious materials can be used to rapidly plug lost circulation zones without removal of the drillbit. The objective of this research activity is to develop cementitious materials that meet the following criteria:

- Pumpability for up to 4 hours at temperatures to 200°C;
- Curing times to 4 hours at formation temperatures to 300°C;
- Compressive strength at 2 hours greater than 500 PSI;
- Permeability less than 0.10 Darcy; and,
- Cost of material less than \$10.00 per bag.

In addition, the material must be compatible with a variety of particulate filler systems, have a reasonable storage life, be environmentally benign, and be capable of placement by use of conventional or slightly modified techniques.

Findings

BNL and Sandia National Laboratories (SNL) performed cooperative experiments with a bentonite-ammonium polyphosphate-borax-

magnesium oxide system to determine methods for controlling curing rates and, therefore, pumpability. They are optimizing the formulations for placement, formation temperatures, and the resultant mechanical properties of the cured cements.

BNL and SNL began exploratory experiments with three other cement systems. In FY92, they will optimize the most promising formulations to provide suppliers and users with a choice based on existing field conditions and cost.

SNL identified six potential pumping methods for placement of the advanced chemical systems into fractured zones, i.e. through:

- (1) Open drillpipe;
- (2) Drillable straddle packer;
- (3) Bit using encapsulated accelerator;
- (4) Bit using downhole injector;
- (5) Wireline-deployed porous packer; and,
- (6) Drillstring-deployed porous packer.

Advanced high temperature MgO-based rapid setting materials suitable for placement using the above pumping methods 1,2, and 6 appear to be ready for demonstration. Materials for use with methods 3,4, and 5 should be ready for prototype testing late in FY92 or in FY93.

CORROSION MITIGATION AT THE GEYSERS

Increased HC1 concentrations in the steam produced at The Geysers have caused severe corrosion problems in the upper regions of the well casing (where some condensation occurs) and in the steam collection piping. Wells have

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been shut down, reducing steam supply and, consequently, causing decreases in power generation, increased operating costs, and concerns over safety and environmental impact. In FY91, BNL planned a cost-shared test program with steam producers at The Geysers to complete preliminary tests to establish technical feasibility of corrosion mitigation methods.

Findings

The operator company at The Geysers continued cost-shared testing with BNL to optimize the polymer cement (PC) composite systems identified in FY90 with respect to the exposure conditions. Four test samples were exposed in autoclaves to various HC1 solutions, steam conditions, temperatures, and durations. All systems performed well, exhibiting little or no degradation and minimal loss of strength.

In an additional test, the company evaluated the effectiveness of polyphenylene sulfide (PPS) polymer used as an acid resistant coating when applied to mild steel surfaces. After 3 months autoclave exposure to pH 2 HCL at 90°C, this system also displayed good durability.

Researchers fitted several carbon steel nipples with two PC liners at BNL and field tested them at the geysers. The nipples were inserted perpendicular to the wellhead fluid stream (177°C at 200 ft/s). Preliminary visual inspections at BNL indicated little erosion or chemical attack on the samples. Some polymer had been removed, probably because of abrasion by particulates in the fluid stream. Researchers plan additional field tests for FY92.

HIGH TEMPERATURE CHEMICAL COUPLING SYSTEMS

Brookhaven National Laboratories (BNL) supported SNL and the geothermal drilling organization (GDO) in FY91 to develop

advanced coupling systems. The effort was divided into three elements:

- Elemental alteration and transformation of zinc-phosphate crystal coatings for use as high temperature protective coatings on steel and to enhance bonding with the coupling system;
- Coupling adhesives that produce hydrothermally stable polymer-metal interfaces; and,
- Characteristics of polymer-elastomer interfaces after exposure to hydrothermal environments.

BNL researchers used two polyaromatic-type adhesives, polyphenyletheretherketone (PEEK) and polyphenylethersulfone (PES), and copolymers made from mixtures of them. Results were promising, but peel strength was 3 to 8 times lower than required for drillpipe protectors.

More importantly, researchers found that the bonding systems composed of copolymers made from PEEK-PES mixtures underwent no disbondment or loss of bond strength after 5 weeks, a factor of 35 better than the best commercially available systems.

BNL is attempting to increase the magnitude of the bond by chemically modifying the metal surface. Recent test results have been promising: modified coatings increase bond strength by 30%, and, more importantly, the interface remains stable upon exposure to high-temperature low-pH acid environments or electrochemical attack. The measured delamination rate was about 150 times lower than that of the agent-steel control seals using corporate funds. These seals are now advertised as commercially available.

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GEOTHERMAL DRILLING ORGANIZATION ELASTOMER ACTIVITIES

BNL provides liaison services to SNL and the Geothermal Drilling Organization (GDO) for transfer of high temperature elastomer technology to industry. Technical assistance covers drillpipe protectors, rotary head seals, blow-out protectors, and Moineau stators for downhole drillmotors.

In FY90, BNL researchers identified and laboratory - tested two promising elastomers and a bonding system, designed a sealing configuration, and fabricated full-scale seal units.

DOE support for field tests of these units

scheduled for FY91 was delayed due to contractual uncertainties. During FY91, however, the private GDO sector contractor fabricated and field tested advanced rotary head seals using corporate funds. They now commercially advertise these seals as available.

TECHNOLOGY TRANSFER

BNL made several initiatives with private industry in FY91. BNL initiated negotiations with a leading geothermal energy producer for a CRADA titled, "Advanced Cements for Geothermal Well Completions."

BNL implemented full-cost recovery programs for the applications indicated in Table 9, below.

FULL-COST RECOVERY PROGRAMS AT BNL	
ORGANIZATION	TECHNICAL EMPHASIS
Gas Research Institute	Condensing heat exchangers for high efficiency gas furnaces
Consolidated Edison of New York	Utility vaults for steam district-heating systems
Long Island Lighting Company	Corrosion resistant coatings for heat exchange applications

Table 9.

ADVANCED BRINE CHEMISTRY

Many of the most significant problems limiting the development of geothermal power relate to the chemical properties of the high-temperature, high-pressure formation fluids. When the temperature and pressure of the formation fluids change and return to chemical equilibrium under the new conditions, the chemical equilibrium of

the brine is disturbed, causing dissolved minerals to precipitate and form scale, which then restricts flow throughout the system. Handling of spent geothermal brines may also introduce additional chemical problems. Current strategies to control these problems increase operational and capital cost. The Advanced

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- Gas breakout in production wells.

Specifically, researchers at UCSD engaged in:

- Computer Modeling.

- 1) High temperature (to 250°C) seawater brine models now include new species interactions and solid phases. The research team collected and validated solubility data under a variety of pressure-volume-temperature conditions.
- 2) The current calcium carbonate scale model now calculates the amount of scale formation in NaCl and CaCl₂ brines and the dissolution-solution characteristics of rock-water systems containing Na-K-Ca-Mg-Cl-SO₄ from 0°C to 250°C. An amorphous silica solubility model for seawater-type brines is also available over the same temperature range.
- 3) Modelers extended parameters of the Mg-Cl interactions in brines containing Na⁺ and K⁺ to 250°C using quaternary data in the NaCl-KCl-MgCl₂-H₂O system. They also extended parameters of the Mg-SO₄ interactions in brines containing Na⁺ and K⁺ from 100°C to 250°C, but further testing is required.
- 4) Modelers developed a new technology (equation of state and mixing rules) to model gas-liquid systems of geothermal operations as a function of temperature and pressure. The model predicts reservoir characteristics (researchers have confirmed that the model has the necessary accuracy for fluid inclusion studies), carbonate scale formation, and gas breakout. This model has been included in the EQUIL software package. Another brine-gas model for the CO₂-CH₄-NaCl-H₂O system is available for gas breakout calculations.

Brine Chemistry project explores low-cost strategies to alleviate these problems in two major areas, (1) brine modeling, and (2) advanced biochemical processes.

The brine modeling effort develops computer models that reliably characterize the equilibrium chemistry of geothermal brines (solution, solid, and gas phases) under variable thermodynamic conditions. Such modeling can predict chemical behavior during resource recovery stages, i.e., exploration, production, plant energy extraction and reinjection. The modeling can also help in mineral recovery programs. The flexible model framework incorporates new species and extended temperature and pressure ranges for use in expanded chemical problems.

The advanced biochemical effort centers on removing toxic metals by biochemical processes. Bacteria interact with metal salts by various mechanisms to dissolve or settle salts out of the brine. Besides rendering the brines fit for reinjection, the process produces useful products and enables recovery of valuable metals.

UCSD GEOTHERMAL CHEMISTRY PROGRAM

The long-range goal of the University of California at San Diego (UCSD) computer modeling program is to construct models to accurately describe equilibrium chemistry of complicated brine systems as a function of ionic strength, pH, P_{CO₂}, temperature (to 250°C), and pressure. Throughout brine flow and heat exchange systems and during reinjection procedures, these models predict:

- Saturation ratios;
- Scaling behavior, i.e., gypsum-anhydrite, carbonate, silica, and metal sulfide scales;
- pH and acid-base characteristics; and

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- Technology Transfer
 - 1) Modelers adapted versions of the modeling codes for MacIntosh and IBM personal computers and published a manual for their use. An industry workshop in September 1991 demonstrated modeling applications and promoted the exchange of information.
 - 2) Researchers are applying models to other energy technologies (e.g., oil production, solar ponds thermodynamics, waste cleanup, etc.), to industrial process chemistry, and in nuclear waste isolation. They incorporate the models in other codes (e.g., EQ3/6, PHREEQ, SOLMINEQ, GMIN), and other agencies (e.g., LLL, LBL, Battelle, and USGS) support and distribute them. These models are therefore undergoing validation by comparison with many types of laboratory and field data from a variety of geochemical studies of both natural and industrial brines.

ADVANCED BIOCHEMICAL PROCESSES FOR GEOTHERMAL BRINES

A low-cost environmentally safe method for the removal of toxic materials from geothermal wastes is being developed by Brookhaven National Laboratory researchers. The method has been shown to be economically and technically feasible. Toxic material removal is accomplished by means of biochemical processes that take place when bacteria interact with geothermal sludges. The biochemical researchers have investigated bioreactor designs and key process variables for optimization of efficiency and low costs. The research and development team also performed multielement analyses (70 elements at a time) to determine the removal efficacy for each element and the time variation of the removal. An 80% or better

removal of toxic metals has been achieved. Thus, a new biotechnology is being developed that has global application in geothermal, as well as other, industries.

Difficulties in disposing of toxic leachable solid wastes in an economical manner which is also safe to the environment could be a major impediment to large-scale geothermal development. For example, the disposal of such wastes can cost over \$1 million per year for a 50-MW geothermal power plant operating in the Salton Sea known geothermal resource area. Increasingly high disposal costs and the long-term liability incurred with hazardous waste disposal make it imperative to find a low-cost solution that is environmentally safe. For this purpose, Brookhaven National Laboratory (BNL) researchers have identified and selected biochemical processes that fit these requirements.

Microorganisms interact with metals by several mechanisms, such as surface adsorption, oxidization, reduction, or some combination of solubilization and precipitation. These mechanisms serve as a basis for a biotechnology that employs biochemical processes to remove and concentrate toxic metals in geothermal waste or solubilize the waste.

At BNL, researchers have identified and adapted microorganisms that remove toxic metals from geothermal brines. The BNL researchers have also developed methods to recover the metals. The liquids can then be reinjected and the solids disposed of as nonhazardous waste.

The major thrust of the research program in Advanced Biochemical Processes for Geothermal Brines is to develop low-cost processes for concentrating and removing toxic materials and valuable metals from geothermal residues. Specifically, the overall objective of this project is to reduce the costs of the surface disposal of residual sludges from geothermal brines by 25%

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or more. It is anticipated that, with adequate funding, this task will be accomplished by Fiscal Year 1995 or 1996.

During Fiscal Year 1991, the BNL research staff addressed:

- Bioreactor design;
- Kinetic studies of biochemical detoxification processes and multielement analyses, including trace radionuclides; and
- Metal recovery

Bioreactor Design - In search of an optimum combination of bioreactor cost reduction and mixing efficacy, BNL researchers investigated several types of bioreactors. For each, they sought the optimum values of the bioreactor and bioprocess parameters and made cost/efficiency estimates. They sought various approaches for mixing the bacteria with the sludge.

Nine variables are essential in the process development and scaling up:

- Reactor size
- Effects of agitation
- Mixed cultures
- Biomass addition at maximum growth
- pH
- Microorganism growth
- Sludge concentration
- Salts involved
- Temperature

A working model for a biochemical process is shown in Figure 7, on page 49. This process is versatile and can use different bioreactors.

Multielement Studies - With the induced coupled plasma mass spectrometer and according to three frequently used sludge digestion methods, the researchers made simultaneous, comparative studies of the removal of several elements and their isotopes.

For each element considered, researchers measured the amount of the element removed from the sludge versus time for 80 hours. They made additional studies on a finer time scale (4-10 hours) for metals with less soluble salts: uranium, lead, bismuth, and thorium.

Metal Recovery - Researchers explored several chemical and biochemical processes for recovering metals from geothermal sludge.

Findings

Bioreactor Design - The bioreactor design studies showed that loading, residence time, and bioreactor type play a decisive role in the cost of the bioprocess. The cost may vary from \$150,000 to several million dollars.

Multielement Studies - Figure 8, on the top of page 50, shows an example of results that the BNL researchers obtained. At 55°C, the bacteria remove about 80% of most metals rapidly and then reach a plateau. (See, for example, Figure 9, on page 50) For the metals whose salts are less soluble, the measurements on the finer time scale revealed that solubility of 30%-60% occurs very quickly. The results indicate the need to investigate finer time scales and shorter residence times. The small levels of activity of radionuclides in

CONVERSION TECHNOLOGY PROGRAM

geothermal brines— $9 \cdot 10^{-11}$ to $2 \cdot 10^{-10}$ curies per gram (Ci/g)—require very careful sample preparation and calibration. This is particularly important if levels of 10^{-12} are to be attained.

Metal Recovery - The BNL researchers have achieved high chemical coprecipitation of several metals. They are exploring the technology further.

Discussion

The findings in this work form the basis of a new biotechnology for removing toxic materials from geothermal brine sludges. The benefits that result will be both environmental and economical. Not only will the detoxification be less expensive, but the end products will be useful. Recovered metals will have market value. The detoxified sludges can have such uses as land fills. The emerging biotechnology could find applications in other industries, for detoxifying wastes or recovering metals.

CONVERSION TECHNOLOGY PROGRAM

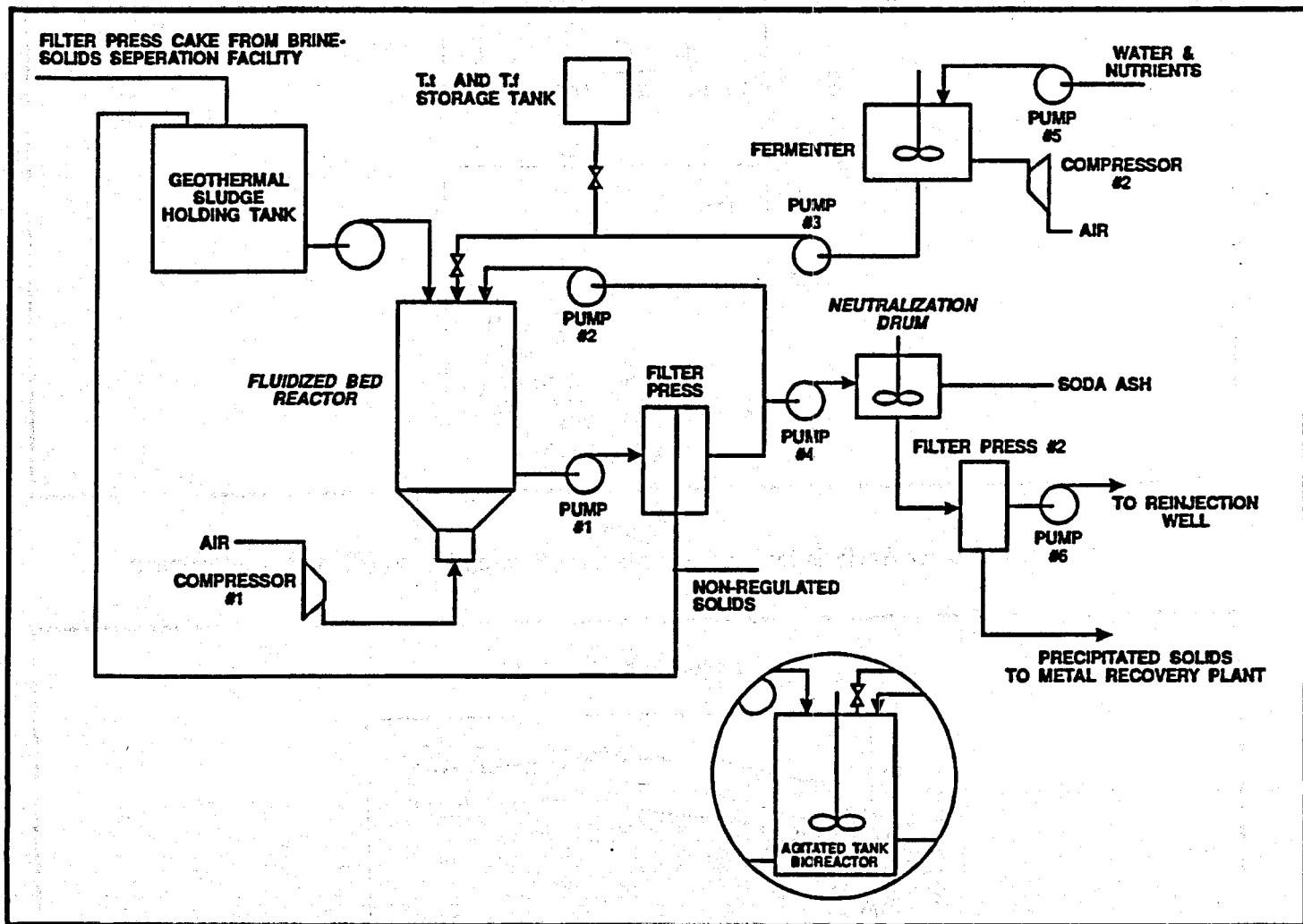


Figure 7.
Biochemical Waste Treatment Plant

CONVERSION TECHNOLOGY PROGRAM

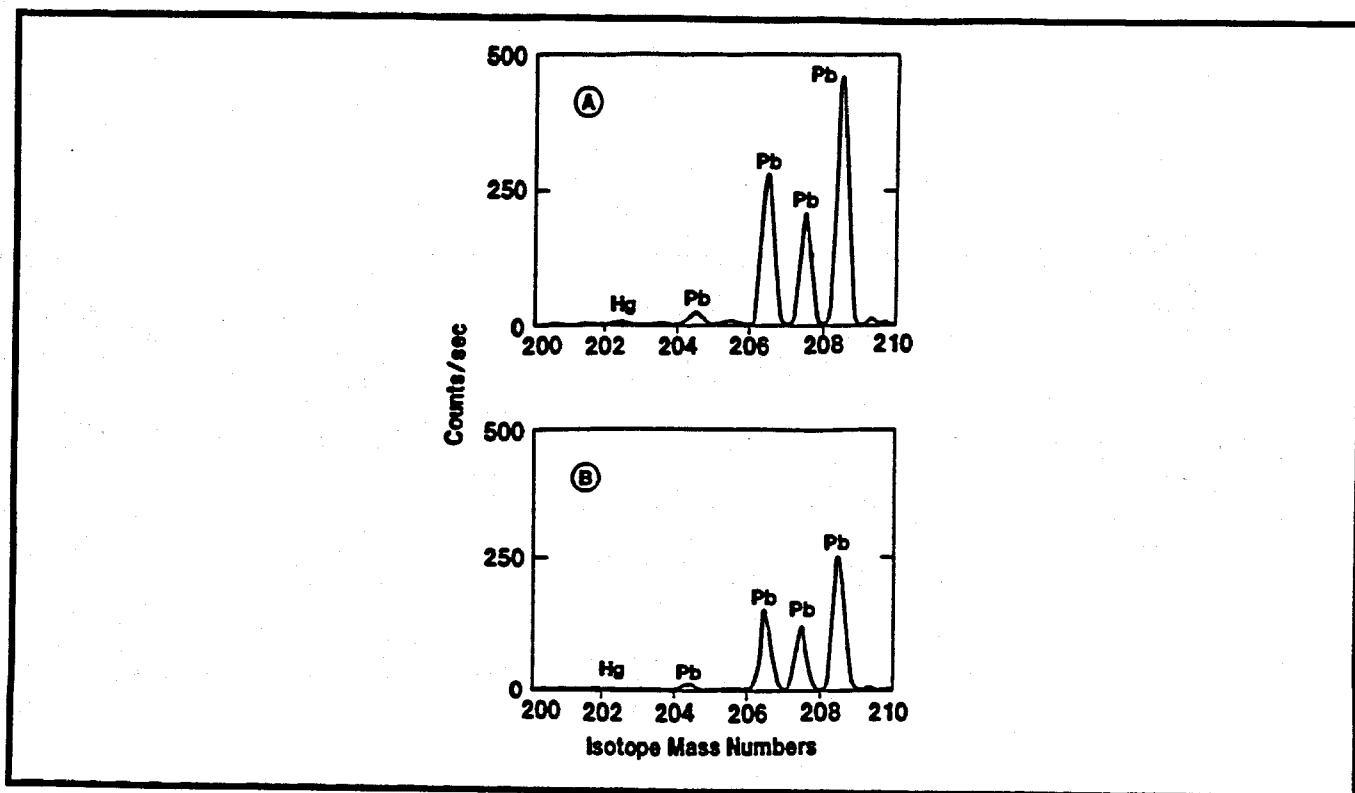


Figure 8.
Mass Spectrometer Analysis for Lead and Mercury Before (A) and (B) After Biotreatment

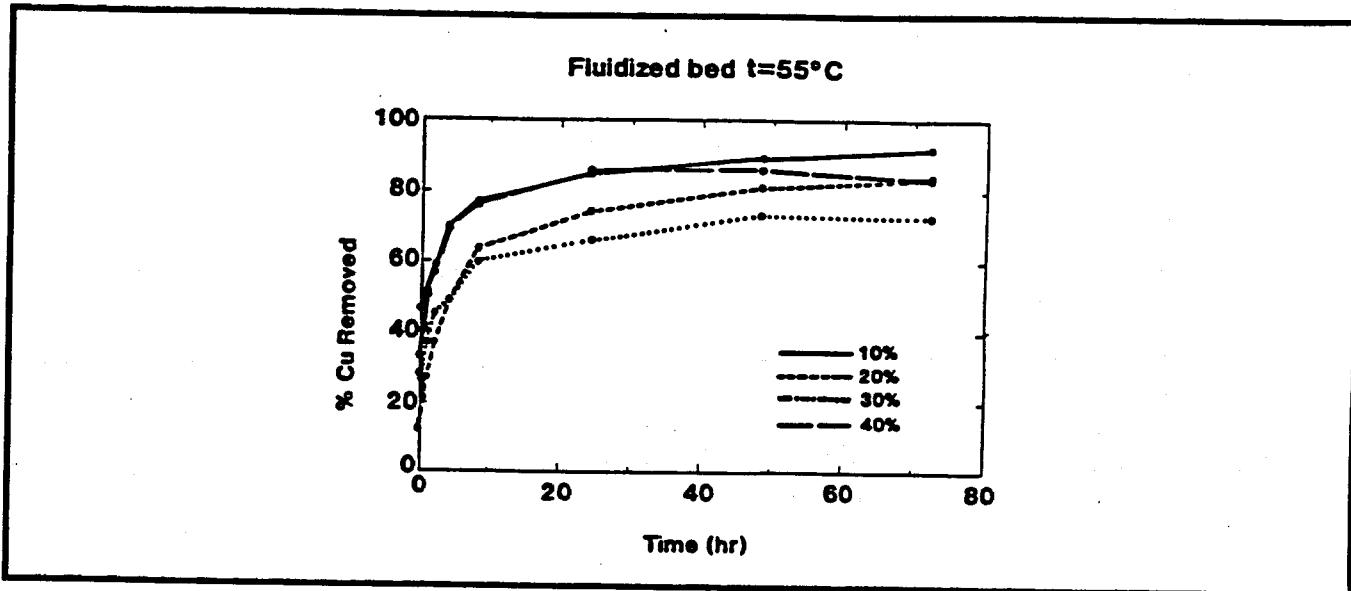


Figure 9.
Copper Removal from Geothermal Sludge Versus Time at Various Sludge Loadings

GEOPRESSURED-GEOTHERMAL RESEARCH

Geopressured-Geothermal energy comes from brines, which are saturated with methane and exist at moderate to high temperatures under high pressure, about 1½-5 miles beneath the surface of the Earth. The dissolved methane makes these brines a promising energy resource.

Researchers operate wells (such as Figure 10, below) to demonstrate the technology, to develop practical methods for use of the resource, and to resolve problems that could arise in commercial operations. Three wells were tested in Fiscal Year 1991, one of which was originally a gas well.

Research in the geoscience and related technology promotes an improved understanding of the behavior of the geopressured-geothermal

brine reservoirs—especially for long-term, high-production exploitation.

The objectives tree (on the next page) displays the objectives at three levels—Levels I, II, and III—and their interrelations. The overall program objective, the Level I objective located on the right side of the figure, concerns the scientific information/technology base for industry. The Level II objectives, shown in the middle of the figure, support the overall objective. These apply to the major subdivisions of the program: the tasks. However, some apply to more than one task.

The Level II objectives are, in turn, supported by the Level III objectives, shown on the left. These apply to the subdivisions of the tasks: the projects. Some projects in different tasks share the same Level III objectives.

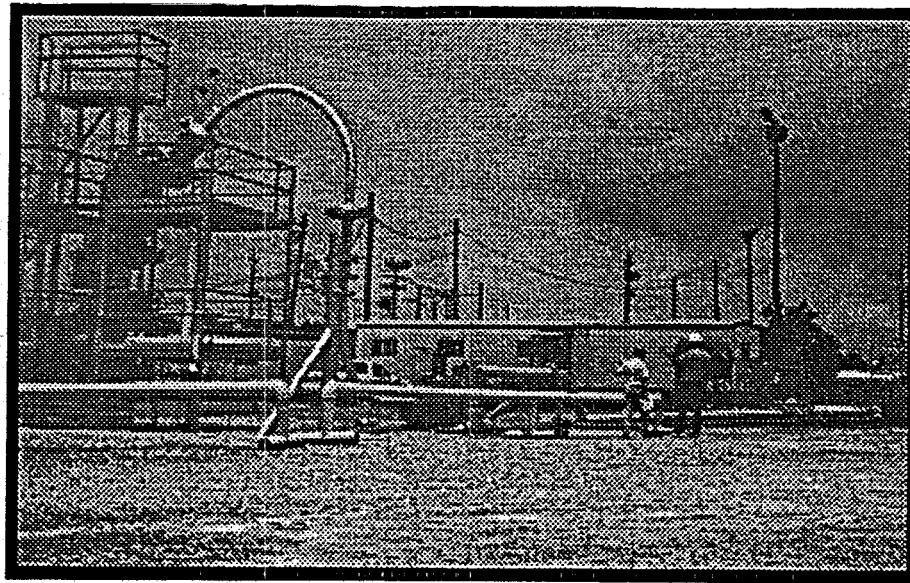


Figure 10
Geopressured-Geothermal Well

LEVEL III

RESERVOIR LOCATION EVALUATION

DEVELOP TECHNIQUES TO INCREASE RELIABILITY IN LOCATING AND EVALUATING GEOPRESSED RESERVOIRS BY 1993

WELL DESIGN

DETERMINE THE DRIVE MECHANISMS OF GEOPRESSED-GEOTHERMAL WELL DESIGN BY 1993

LIQUID HYDROCARBONS

DETERMINE NATURE AND SOURCE OF LIQUID HYDROCARBONS, SOURCE OF METHANE, AND RELATED FLOW MECHANISMS BY 1993

PERFORMANCE PREDICTION

DEVELOP, BY 1993, A TEST PROCEDURE THAT CAN PREDICT THE PERFORMANCE OF ANY GEOPRESSED-GEOTHERMAL RESERVOIR FOR AT LEAST FIVE TIMES AS LONG AS THE TEST PERIOD

LEVEL III

FLUID PRODUCTION

TO MINIMIZE FLUID PRODUCTION OPERATING EXPENSES BY 1993

DOWNTIME MINIMIZATION

TO DEVELOP, BY 1993, MATERIAL SPECIFICATIONS, EQUIPMENT SPECIFICATIONS, AND MAINTENANCE PROCEDURES TO GUARANTEE OVER 95% ANNUAL AVAILABILITY AND ONLY 2 WEEKS' ANNUAL SHUTDOWN FOR ROUTINE MAINTENANCE

SCALE INHIBITION

DEVELOP A MODIFIED SCALE INHIBITION PROCEDURE BY 1993

LEVEL III

FLUID DISPOSAL

**TO DETERMINE BY 1995 IF
FLUIDS CAN BE DISPOSED OF
IN A MANNER ACCEPTABLE TO
THE ENVIRONMENT**



LEVEL II**LEVEL I****LONG-TERM RESERVOIR PERFORMANCE**

IMPROVE UNDERSTANDING OF LONG-TERM RESERVOIR BEHAVIOR; IMPROVE PERFORMANCE PREDICTION CAPABILITY

LONG-TERM FLUID INJECTION/ MULTIPLE SITES

PROVE THE LONG-TERM INJECTABILITY OF LARGE VOLUMES OF SPENT FLUID AT MULTIPLE SITES BY 1993

FLUID PRODUCTION

MINIMIZE FLUID PRODUCTION OPERATING EXPENSES BY 1993

FLUID/ENVIRONMENT CONCERNs

DETERMINE ENVIRONMENTAL ACCEPTABILITY OF PRODUCTION AND DISPOSAL OF FLUIDS FROM GEOPRESSURED- GEOTHERMAL RESERVOIRS BY 1995

GEOPRESSURED- GEOTHERMAL RESEARCH

PROVIDE SCIENTIFIC INFORMATION/ TECHNOLOGY BASE SUFFICIENT FOR INDUSTRY TO MAKE RATIONAL COMPARISONS IN INVESTMENT DECISIONS CONCERNING ENERGY SOURCES

GEOPRESSED-GEOTHERMAL PROGRAM

In the Geopressed-Geothermal Research program, researchers seek to harness the energy potential in the fluid from Tertiary rocks, rocks about $1\frac{1}{2}$ to 5 miles beneath the surface of the Earth and 65 million to 2 million years old. (See Figure 11, below, for a typical location and section showing the Tertiary and other layers.) The geopressed-geothermal (GPGT) fluid consists of moderate- to high-temperature methane-saturated brines, typically around 300° F. Because the rocks above the GPGT layers isolate the brine thermally and mechanically, the pressure and temperature of the fluid are both significantly greater than would be expected.

Methane dissolved in the water offers an energy resource, in addition to the thermal energy. For example, the U.S. Geological Survey estimates that the geopressed-geothermal energy reservoirs in Gulf Coast sandstones contain 5,700 trillion cubic feet (ft³) of methane and 11,000 quadrillion BTU (quads) of thermal energy. Another form of energy possible from this resource is the mechanical energy from the pressure of the liquid, but this form of energy offers much less of a resource than the first two forms. Its main advantage is in minimizing the need for pumping.

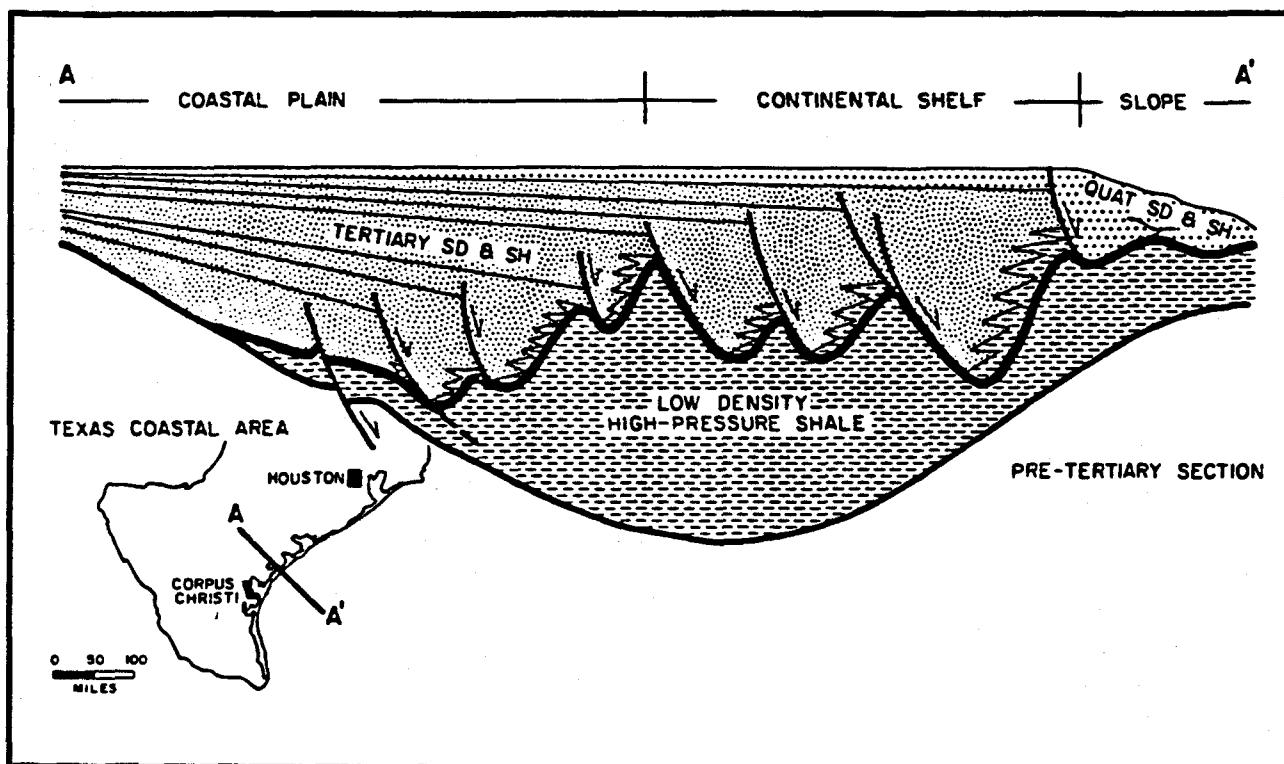


Figure 11
Typical Geopressed-Geothermal Reservoir Location and Section

GEOPRESSEDURED-GEOTHERMAL PROGRAM

The GPGT resource comprises extensive reservoirs scattered throughout various parts of the United States (Figure 12, below). Drillers for oil and gas first discovered GPGT reservoirs in the Gulf of Mexico region of Louisiana and Texas.

Research has focused on evaluating the geopressedured reservoirs and developing the technology for extracting and using the thermal,

chemical, and hydraulic energy from the resource.

The program, active since 1975, has acquired a large amount of data about geopressedured resources by conducting extensive well tests and by operating an experimental power plant using the resource. Oil field technology has been successfully adapted to enable sustained, large-volume production of geopressedured brines.

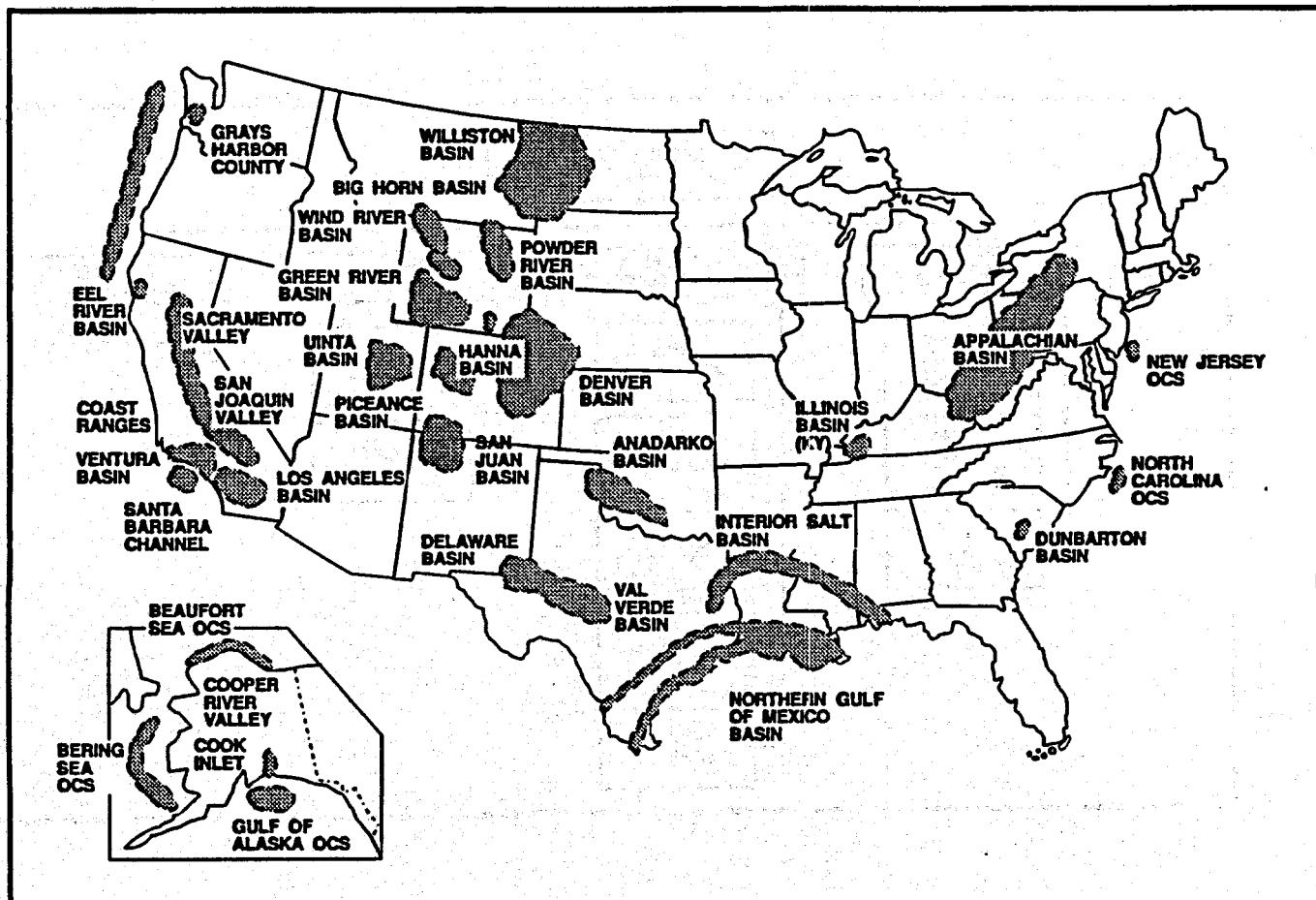


Figure 12
Map of United States Showing Distribution of Geopressedured-Geothermal Reservoirs

GEOPRESSURED-GEOTHERMAL PROGRAM

Figure 13 (below) shows the active tasks in the work breakdown structure. The Geopressured-Geothermal Program previously encompassed four tasks, but work had already been completed on one: Energy Conversion. Two projects came to a close in Fiscal Year 1991 (FY91), and two more ended soon after that.

As Figure 13 shows, three active tasks progressed through FY91:

- Well Operations—a dominant part of the Geopressured-Geothermal Program, concerned with testing and demonstrating

the operation of Department of Energy (DOE) GPGT wells;

- Geosciences and Engineering Support—research on GPGT science and technology and monitoring of environmental effects of the GPGT wells;
- Management Support—the management and technical support that INEL gives the Department of Energy, Idaho Field Office (DOE-ID).

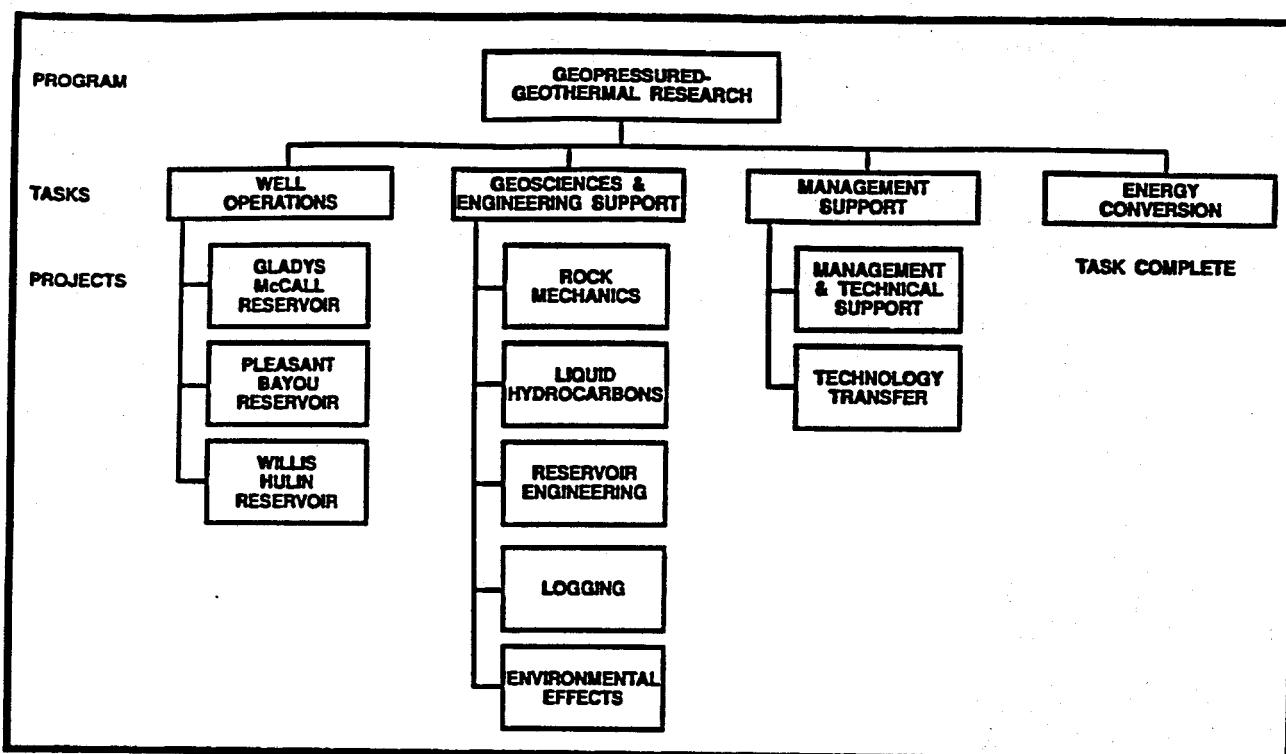


Figure 13
Geopressured-Geothermal Research Work Breakdown Structure, Active Projects

WELL OPERATIONS

Background

In the Well Operations task, the researchers operate wells to find the most economical and practical methods for reservoir use and to resolve problems that could arise in commercial operations. The task contains one project for each of three wells in the Gulf Coast area active in Fiscal Year 1991 (FY91):

- Gladys McCall Well near the Rockefeller Wildlife Refuge, in Cameron Parish, Louisiana
- Pleasant Bayou Well in Brazoria County, Texas
- Willis Hulin Well near Erath, Louisiana

The Willis Hulin Well is part of the Wells of Opportunity (WOO) test program, which has used wells in the Gulf Coast area of Louisiana and Texas. Companies in search of oil or gas originally drilled them but found them unproductive. Researchers on behalf of the Department of Energy (DOE) flow tested the wells for short periods of time to determine parameters such as gas/water ratios and brine salinity.

The wells other than the Hulin Well have since been plugged and abandoned or returned to their original owners.

GLADYS MCCALL WELL

The Gladys McCall Well site borders on the western edge of the Rockefeller Wildlife Reserve, in Cameron Parish, Louisiana. The well replaced the original Gladys McCall Well No. 1, which entered the Well of Opportunity (WOO) program in 1977 or 1978, when the

On the other hand, the Pleasant Bayou Well is a design well, a test well drilled specifically for geopressured-geothermal research. The Gladys McCall Well was also a design well, although it replaced a WOO.

Objectives

In the Well Operations task, researchers pursue four objectives:

- To improve understanding of long-term reservoir behavior and to improve performance prediction capability
- To determine if GPGT fluids can be produced and disposed of in a manner safe to the environment by 1995
- To prove the long-term injectability of large volumes of spent fluid by 1993
- To minimize fluid production operating expenses by 1993

Approach

Researchers operate and flow test the wells and seek economic methods to produce electricity from the wells. They monitor reservoir performance and resolve problems in reservoir use.

Buttes Oil and Gas Company reopened and flow tested it. The later version stood about 50 ft from its predecessor.

Recently, the Gladys McCall Well completed a long-term pressure build-up test to help refine

GEOPRESSURED-GEOTHERMAL PROGRAM

the reservoir model. Researchers monitored the well under shut-in conditions to obtain buildup data. It had been scheduled to be plugged and abandoned during FY91, after a Site Evaluation and Readiness Review, but plugging and abandonment were later postponed to Fiscal Year 1992.

Researchers monitored the well with periodic bottom hole pressure measurements to analyze the pressure recovery of the reservoir after producing a little over 27 million barrels (bbl) of brine and 677 million ft³ of gas. After noting that the pressure was still increasing and was within 700 pounds per square inch (psi) of the original shut-in pressure, the researchers conducted a Site Evaluation and Readiness Review, in preparation for testing. This testing, conducted in October 1991 (FY92), included short buildup, and bottom hole pressure and temperature measurements.

Major future work elements include pressure testing sand zones adjacent to the production zone, plugging and abandoning the well, continued environmental monitoring, and final sampling and analysis as required.

After 4 years under shut-in conditions, the pressure was still increasing and was within 700 psi of the original shut-in surface pressure of about 5,900 psi absolute (psia). The shut-in tubing pressure at the wellhead continued to build up the entire year. The pressure increased from 5,217 psia on September 30, 1990, to about 5,247 psia on October 28, 1991.

This work represents substantial progress toward the objective, furthering the understanding of the reservoir drive mechanism. Soon, the project will be complete and all the accomplishments expected will be achieved.

The activity is 95% complete.

PLEASANT BAYOU WELL

The Pleasant Bayou Well that was active in FY91 was the second design well drilled at the Pleasant Bayou site. The Hybrid Power System experiment, which played a central role in the Energy Conversion task, took place at this well in 1989 and 1990.

The Institute of Gas Technology, Eaton Operating Company's subcontractor, placed the Pleasant Bayou Well No. 2 on long-term flow-test production in May 1988, after installation of production facilities.

The activity for the Pleasant Bayou Well for FY91 was long-term flow testing, which had continued through Fiscal Year 1990. The well, surface equipment, and disposal well continued flow testing at varying rates up to about 24,800

Stock Tank Barrels per day (STB/d) to enhance the understanding of the reservoir.

Researchers dismantled and removed the hybrid power system from the site, with the exception of the Electric Power Research Institute heat exchangers. Also they completed workover of the injection well and initiated higher flow rates. They continued flow testing at the higher rates through FY91.

At the Pleasant Bayou Well, flow-testing will continue through 1992.

Potential future work elements are:

- Completion of higher rate flow testing
- Pressure buildup test
- Final well test

GEOPRESSURED-GEOTHERMAL PROGRAM

- Plugging and abandoning the well or turning it over to industry
- Completion of environmental and safety monitoring
- Final sampling and analysis

The flow rate increased in FY91.

Progress was made toward curbing the three greatest production obstacles at this well site: sanding, scaling, and corrosion. At Pleasant Bayou, sanding is controlled by changing the flow rate, and calcium carbonate scaling is controlled by a phosphonate inhibitor. Corrosion and erosion effects have been reduced by reducing turbulence in the surface piping.

This work represents substantial progress toward the objectives. Work at the Pleasant Bayou Well for the Hybrid Power System has contributed significantly to GPGT technology.

The activity is 85% complete.

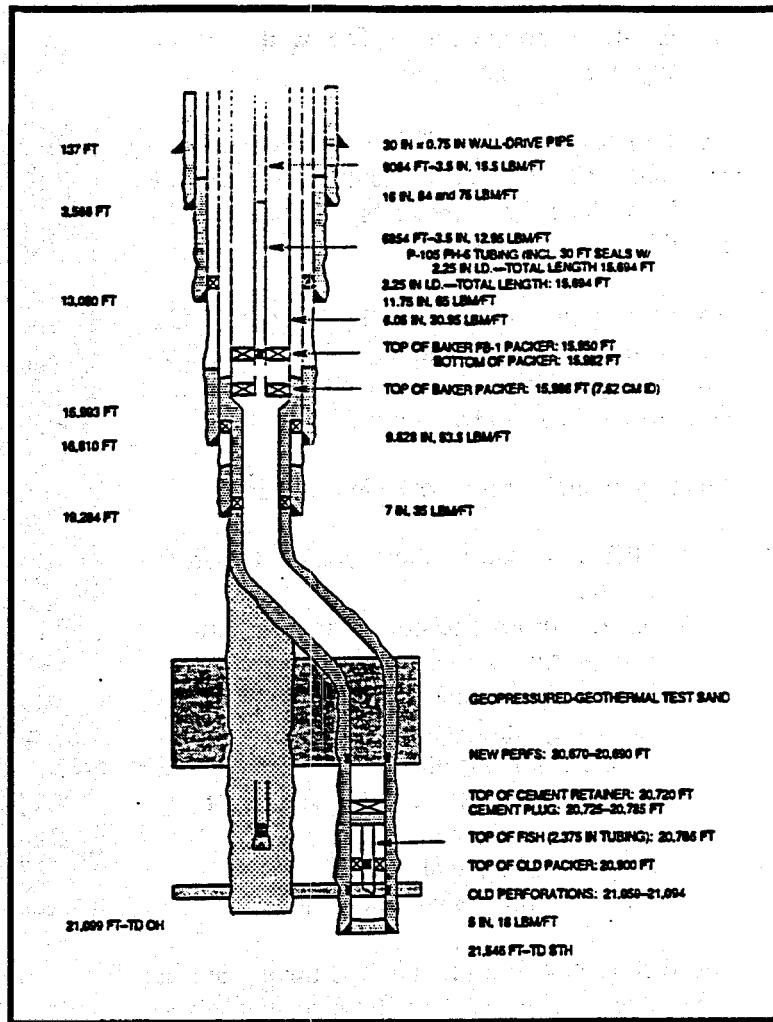


Figure 14
Willis Hulin Well Schematic

WILLIS HULIN WELL

The Willis Hulin No. 1 Well (Figure 14, above), in Erath, LA, began as a gas well, which the Superior Oil Company drilled in 1978. Because of a decline in wellhead pressure and subsequent difficulties, Superior Oil abandoned it and later transferred it to DOE. Preliminary test data indicated that the well had penetrated a thick GPGT sand. This well serves

as an example of a reworked gas well, used instead of a specially drilled GPGT well.

After the well had been shut in for 10 years, rework of the well began in 1988, and low-rate short-term flow testing followed in FY 1990. Results indicated that the well might be capable

of long-term production. The well was on standby in Fiscal Year 1991.

Total dissolved solids (TDS) for the well are 194,000 mg/l. Bottom hole temperature is about 340° F. The gas content is estimated at 34 scf/bbl.

The activity for the Hulin Well project for FY91 was maintaining the Hulin Well on standby. Monitoring of the shut-in facility continues. (Figure 15 shows the wellhead.)

Major potential future work elements are:

- NEPA documentation required before testing
- Review of long-term flow-testing plan
- Long-term flow testing
- Monitoring of subsidence, micro-seismicity, and water quality
- Monitoring/controlling the effect of high TDS on injection well and equipment
- Plugging and abandoning the well
- Final sampling analysis
- Final environmental monitoring

The Hulin Well was on standby, under shut-in conditions, during FY91. It is available for long-term flow testing if necessary.

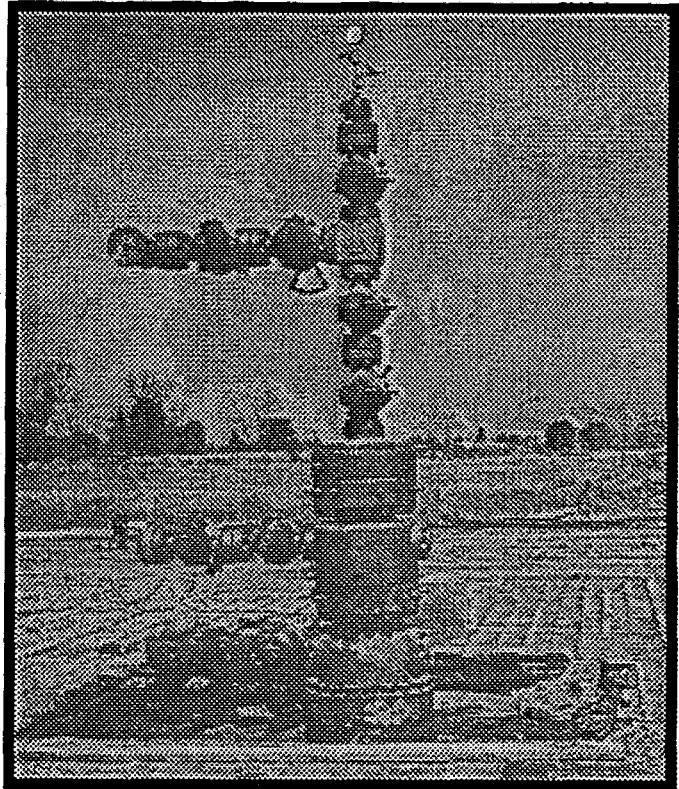


Figure 15
Willis Hulin Wellhead

The Hulin Well successfully demonstrates the use of a converted gas well. At the end of FY91, the activity was 50% complete.

Well Operations Discussion

The accomplishments of the Well Operations have promoted the objectives in obtaining data and analyses for better evaluation of GPGT reservoirs. The data gained has helped increase understanding in the development of a test procedure to predict long-term reservoir activity. Well Operations have proved that large volumes

of brine can be reinjected for long durations without environmental harm. They have led to safe operations and system optimization. Material specifications and maintenance procedures that guarantee maximum availability of the resource have been developed.

GEOSCIENCES AND ENGINEERING SUPPORT

Background

The Geoscience and Engineering Task focuses on analyzing geopressured-geothermal well data and understanding the responses of the reservoirs to long-term, high-volume production. Reservoir analysis and modeling will determine reservoir characteristics and drive mechanisms and will ultimately enable long-term prediction of reservoir behavior. Various research projects support the modeling and analysis. Also, researchers conduct environmental monitoring to ensure that the wells do no harm to the environment.

ROCK MECHANICS

Researchers at the University of Texas at Austin in the Rock Mechanics project work toward a better understanding of the effect of compaction and tension on geopressured-geothermal reservoir rocks and the well bore stability. They seek to determine stress-strain relations of the reservoir rocks. Studies include strength and mechanical module testing of Pleasant Bayou sandstone and coordination of geologic and microstructural rock properties.

During Fiscal Year 1991 (FY91), Rock Mechanics work focused on compiling data for an archival report and developing illustrative examples that show the magnitude of factors that would contribute to the pressure-fluid production volumes relationships for Gulf Coast GPGT reservoirs.

The task consists of the following projects:

- Rock Mechanics
- Liquid Hydrocarbons
- Reservoir Engineering
- Logging
- Environmental Effects

Objective

Work in the Geoscience and Engineering Support task promote the objective that all the tasks share: to improve understanding of long-term reservoir behavior.

The archival report will provide test data on rock mechanics testing for GPGT reservoir samples. The report will include:

- How the various experimental measurements are carried out;
- Rock mechanical properties that were measured, such as permeability, porosity, resistivity, P-wave and S-wave velocities, stress-strain curves, Young's modulus, and Poisson's ratio;
- Behavioral or loading paths used for the various tests, such as uniaxial compaction, triaxial compaction, and hydrostatic pressure;
- Failure strength tests in compressional, tensional, and combined loading paths;
- Time-dependent tests; and
- Hysteresis tests.

LIQUID HYDROCARBONS

The Liquid Hydrocarbons researchers seek to determine the extent to which hydrocarbons from geopressured-geothermal (GPGT) wells can be indicators of the geochemistry of the reservoir and the dynamics of reservoir production. Researchers sample brine and cryocondensates (light aliphatic hydrocarbons) from the well and compare analyses and measurements against known features of the reservoir.

For the Liquid Hydrocarbons project, the contractor, the University of Southwestern Louisiana (USL), measured the solubility of certain aromatic hydrocarbons and sampled for cryocondensates in the geopressured brine.

USL completed sampling and monitoring of Pleasant Bayou and Hulin Wells as scheduled and conducted analyses for changes in the concentration of the cryocondensates during flow tests.

The laboratory had developed and tested a harsh environment pH probe that enabled continuous monitoring of data previously collected individually. A field test of the probe in surface facilities had been planned for Fiscal Year 1991.

USL had to discontinue the pH probe work because of the lack of availability of a key element: the ion-sensitive field effect transistors.

A research team (Texas Bureau of Economic Geology and Louisiana Geological Survey) conducted collocation studies in Texas and Louisiana, in which they developed maps of:

- Collocated geopressured brine and heavy and medium oil in Texas and Louisiana; and

- Collocated geopressured brine and oil in the Deep Wilcox reservoirs, the Jackson Group, and Mirando sandstones in Texas;

Future elements include, for Pleasant Bayou:

- Cryocondensate sampling
- Analyses
- Dismantling and removing sampling facility

Findings

From the sampling and measurements for liquid hydrocarbons and cryocondensates, USL determined the time dependence and the brine production dependence of the cryocondensate concentration.

The collocation maps were completed on schedule.

Discussion

This work will assist in determining the range of hydrocarbon saturation to be expected in geopressured brines. The sampling and analysis of brine and cryocondensates will contribute to the understanding of hydrocarbons in the geopressured reservoirs. The correlation of cryocondensate yields with well operations will assist in understanding hydrocarbon movement in geopressured reservoirs during the production of brine. It is planned to continue this work at Pleasant Bayou.

The collocation studies help to advance commercialization, as well as contribute to the knowledge base of the location of the resource and the geological strata involved.

The activity is about 90% complete.

GEOPRESSED-GEOTHERMAL PROGRAM

RESERVOIR ENGINEERING

Reservoir Engineering researchers seek a better understanding of the nature of the geopressed-geothermal (GPGT) reservoirs and how it is revealed from well test data. Of particular interest is the understanding of the flow of liquids through fractures in rocks and through porous media. The project consists of:

- Analysis and synthesis of test data from design wells;
- Site-specific geological research; and
- Reservoir simulation.

For Fiscal Year 1991, the main activity was analysis and synthesis of test data and reservoir simulation. Reservoir simulation predicts the behavior of GPGT reservoirs through mathematical modeling. It is useful, in many cases, in inducing basic reservoir features from observed behavior.

Principal investigators in this project are:

- S-Cubed
- The University of Texas at Austin (UTA)

- Lawrence Berkeley Laboratory (LBL)
- EG&G
- The Louisiana Geological Survey (LGS)

S-Cubed analyzes data from the ongoing flow testing of the Pleasant Bayou well and synthesizes the data into the reservoir simulator. The model produces a good match to the observed pressure history. S-Cubed also analyzes the bottom hole pressure and temperature data from the Gladys McCall well.

EG&G uses TETRAD, a commercially available simulator, to model the behavior of the Pleasant Bayou reservoir. Table 10 lists the data used in the TETRAD simulator.

LBL researchers analyzed data from the GPGT L.R. Sweezy Well taken in the mid-1980's. Also, LEL researchers derived an integral equation for the transient flow rate of brines in GPGT reservoirs, through pressure-sensitive formations, as a function of pressure.

DATA FOR TETRAD PLEASANT BAYOU RESERVOIR MODEL	
SOURCE OF DATA	NATURE OF DATA
UTA and BEG	Geologic maps (including sand contour maps and fence diagrams showing sand continuity)
Published sources	Fluid properties from literature
S-Cubed analysis of transient testing	Permeability calculations
Eaton Operating Company	Production data and bottom hole pressure measurements

Table 10

GEOPRESSURED-GEOTHERMAL PROGRAM

UTA is determining how well the DOE BOAST simulator can be used to replicate previous simulation results from the Gladys McCall Well. UTA also formulates new analytical models that include possible pressure-support mechanisms.

In a special geological study for the calendar year, researchers reevaluated the Hulin reservoir. They interpreted data from 22 miles of seismic lines in the vicinity of the Hulin well and made a new estimate of the reservoir volume. From this interpretation, they developed a structure map and cross section for the Hulin reservoir from the new seismic data.

Major potential future work elements are to complete the modeling of the Hulin reservoir, to complete the analysis of different drive mechanisms, and to develop a Hulin model using production data.

The milestones for future work are the completion of the following:

- Modeling and analysis of different drive mechanisms
- Gladys McCall, Pleasant Bayou, and Hulin models

Findings

For an estimate of the Hulin reservoir volume, the researchers obtained less than 1 billion

barrels, much less than earlier estimates. They completed the Hulin reservoir structure map and cross section and the collocation maps.

The S-Cubed reservoir models for the McCall and Pleasant Bayou reservoirs were successful in modeling the total production histories. For the Hulin Well, S-Cubed researchers were successful in matching preliminary test data.

EG&G successfully modeled the Pleasant Bayou production data using TETRAD and post-1988 data.

LBL's results of the Sweezy Well test analyses show that the permeability calculated from the buildup tests is much higher than that of the drawdown tests, suggesting that pressure-sensitive permeability or stress-induced permeability hysteresis may be important factors. LBL solved the nonlinear problem of flow of a slightly compressible fluid through a pressure-sensitive porous medium with the relative flow rate function approach.

Discussion

A major accomplishment is the completion of the work on the Pleasant Bayou reservoir model in a commercially available program and LBL's exact semi-analytical solution for transient flow.

The project is 80% complete.

LOGGING

The Logging project concerns the use of well logs, pen charts of various measurements versus depth of the recording instrument in the well. In interpreting the charts, researchers seek to estimate rock type and permeability in the reservoirs, parameters useful for reservoir prediction. Also, researchers try to find the effect that boron makes on estimates of the presence of hydrocarbons from log data.

In this project, researchers follow test results at the wells and provide logging data as appropriate.

No future work is planned, because the project is complete.

GEOPRESSED-GEOTHERMAL PROGRAM

Findings

Data from GPGT and non-GPGT wells imply that the high temperatures and pressures encountered in GPGT formations have *not* had a major effect on boron diagenesis. A study of boron in various grades of casing steel from foreign and domestic sources indicates that boron content is quite low and should not be a problem in neutron log interpretation.

Discussion

Of particular value is the understanding gained on the effect of boron on log interpretation.

ENVIRONMENTAL EFFECTS

This project combines pretest baseline data, data taken during testing, and post-test monitoring data toward ensuring that no long-range adverse effects result from geopressed-geothermal (GPGT) brine production. Theoretical work strives to fit monitoring results to models of the GPGT reservoirs and the surrounding geological formations.

A specific project objective is to determine by 1995 if fluids can be disposed of in a manner acceptable to the environment.

The Louisiana Geological Survey (LGS) and Eaton Operating Company, Inc., maintained established systems for monitoring subsidence, seismicity, and water quality around test wells in Louisiana and Texas. In particular, they performed environmental monitoring of the Gladys McCall, Pleasant Bayou, and Hulin sites.

LGS monitored microseismic activity and subsidence and performed leveling surveys on well sites.

Eaton Operating Company, Inc., monitors the quality of the surface and ground water.

The research for the project is 100% complete and succeeded in furthering the project objective.

The Logging Consortium was a major accomplishment. The participation of 12 companies and a \$1 million contract between the University of Texas group and the Gas Research Institute augmented the proceedings.

Environmental Studies is an ongoing effort that will continue for 2 years after well operations cease at each well site. Future work elements include microseismic, subsidence, and water quality monitoring at all three well sites.

Findings

Researchers completed monitoring of the environmental effects as expected. No subsidence or microseismic activity resulting from program operations was detected. The environmental monitoring of the Gladys McCall, Pleasant Bayou, and Willis Hulin sites revealed no detrimental environmental effects resulting from the testing at these wells.

Discussion

Major accomplishments are continuation of monitoring of microseismic data, subsidence data, and surface and ground water quality. Concerns on baselining and quality control have led to the in-progress development of tighter monitoring guidelines and checklists. These will be implemented in Fiscal Year 1992. The activity is 80% complete.

GEOPRESSED-GEOTHERMAL PROGRAM

DISCUSSION

Fiscal year 1991 brought progress in reservoir simulation, in geoscience research and geological interpretation, in logging and liquid hydrocarbons studies, and in rock mechanics. Well operations contributed to the reservoir simulation of pressure draw down and pressure buildup, to the continued successful use of scale inhibitors, and to the increase in understanding of control of sand production by flow rate control.

The goal of the geopressed program is to provide a resource information and technology base that will enable industry to compare development options for geopressed-geothermal energy with those of other energy sources. This goal has largely been accomplished.

For a summary of the status of the work in the Geopressed-Geothermal program, see Table 11, below.

ACTIVITY STATUS SUMMARY		
TASK/PROJECT	ACTIVITY	AMOUNT COMPLETE (%)
WELL OPERATIONS		
McCall Well	Final test, plugging and abandonment	95
Pleasant Bayou Well	Long-term, high-rate flow testing	85
Hulin Well	Standby maintenance	50
GEOSCIENCE AND ENGINEERING		
Rock Mechanics	Final report	100
Liquid Hydrocarbons	Pleasant Bayou Well and Hulin Well cryocondensates	85
Reservoir Engineering	Reservoir Simulation	80
Logging	Final Report	100
Environmental Effects	Microseismic Monitoring	80
	Subsidence Monitoring	80
	Water Quality Monitoring	80

Table 11

HOT DRY ROCK RESEARCH

Hot dry rock (HDR) resources are defined as heat stored in rocks within about 10 kilometers (6 miles) of the Earth's surface. These hot rocks have few pore spaces or fractures and, therefore, contain little water and minimal interconnected permeability. Thus, the energy cannot be economically extracted by natural, indigenous hot water or steam as in hydro-thermal resources.

A "fracture system" must be created to extract heat from these rocks hydraulically by pumping high pressure water down an "injection well." The well's dimensions, location, and orientation are mapped using geophysical techniques. A second borehole is located and drilled to intersect the hydraulic fracture system. Water can then be circulated down one hole, through the fracture system where it removes heat from the hot dry rocks, and up the second hole. At the surface, the heat is recovered through heat exchangers and the cooled water is recirculated to recover more heat from the man-made reservoir. (See Figure 16, on the following page.)

Estimates as to the usefulness of this heat source vary with assumptions made concerning:

- The minimum temperatures required,
- The practical (technologically and economically) drilling depths,
- The characteristics of the geologic environment, and
- The effectiveness of the heat recovery method.

There is general agreement that the HDR resource is a very significant source of energy; e.g., the U.S. Geological Survey (USGS) estimates that there are at least 500,000 quads of useful heat in hot dry rock at currently accessible drilling depths beneath the U.S. This

is about 6000 times the total amount of energy currently used in the U.S. annually. In addition, the HDR resource is widespread, i.e., deposits lie beneath more than half of the nation's territory, with good potential deposits on the eastern seaboard. Economical recovery of even a very small fraction of this resource would contribute significantly to the nation's energy future.

Demonstrations are needed to validate the economics of long-term, large-scale operations of HDR systems. Independent cost analyses indicate that, with current technology, electric power could be generated at a bus-bar cost of electricity of 5-6 cents per kilowatt-hour to 16-18 cents per kilowatt-hour depending on the temperature of the resource. Further advances in such technologies as drilling could reduce this cost to as low as 3.5 cents per kilowatt-hour for the best resource.

Approximately 40 percent of the total HDR budget is used by drilling and service companies in a mutually beneficial arrangement in which industrial and program personnel have shared advancements in the technology of drilling, well completion, and hydraulic fracturing. Drilling and coring bits, downhole motors, open-hole packers, and other equipment developed for the HDR program.

The abundant HDR resource is, of course, a worldwide resource, and is attracting increasing international interest. Japan, the United Kingdom, France, Germany, and the former USSR, have significant research programs underway. The nation that leads in the development and commercializing HDR will take a large step toward energy independence, will solve many of its environmental problems related to energy production, and will create a

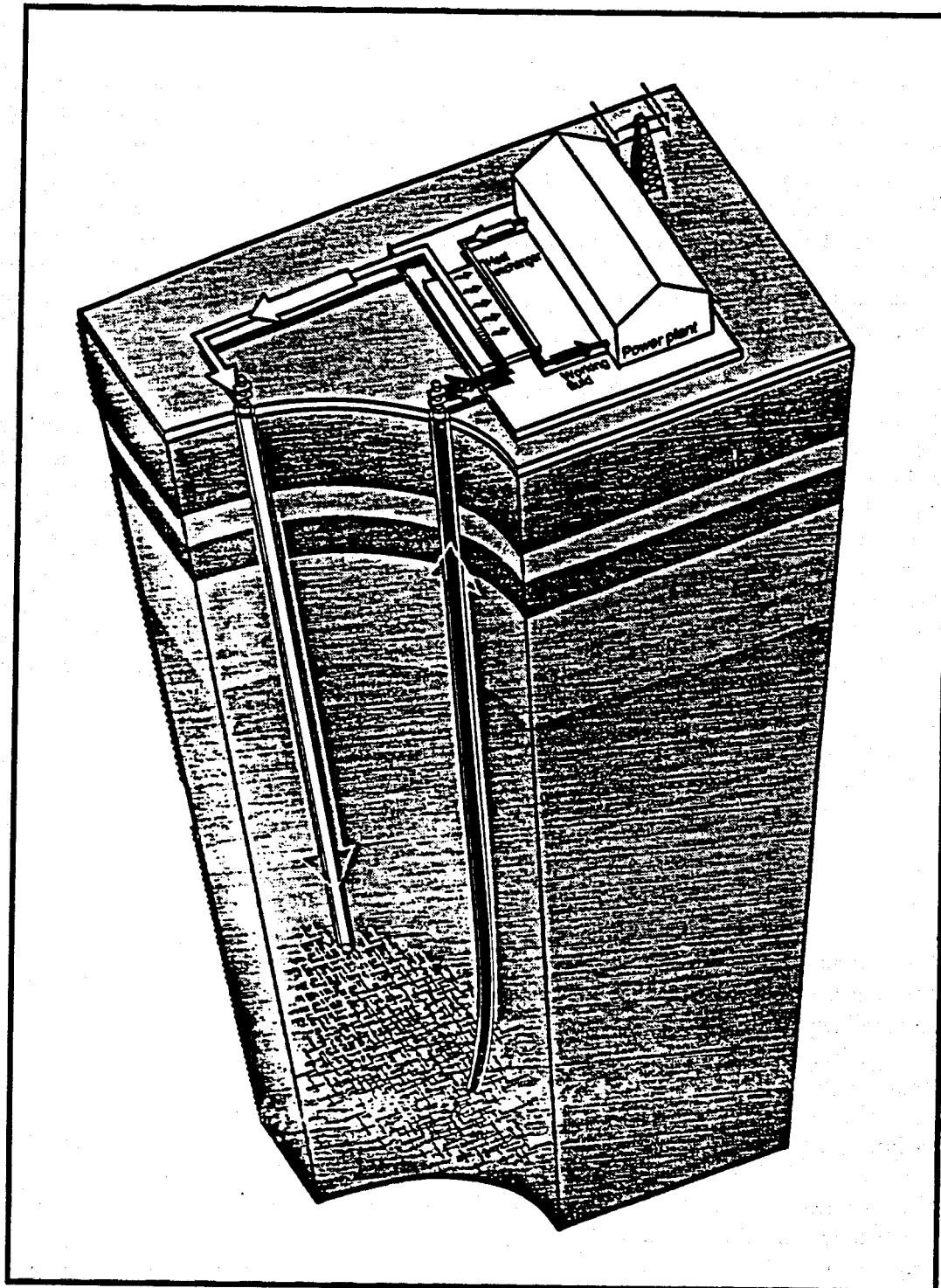


Figure 16
A Hot Dry Rock System

HOT DRY ROCK RESEARCH

large domestic and foreign market for geothermal drilling and service industries. The broad objective of the DOE-sponsored HDR Geothermal Energy Development Program is to solve the remaining technological problems limiting the cost-effective commercialization of HDR as a clean alternative energy supply and, thereby, to place the U.S. at the forefront of widespread implementation.

The objectives tree on the following pages displays the program objectives at three levels - Levels I, II, and III - and their interrelationship. The Level I objective provides a target for decreasing the total cost of electric power generated by industrial hot dry rock projects; Level II objectives address incremental improvements in performance and environmental and economic acceptability of major system components of hot dry rock technology; Level III objectives and associated research efforts provides a basis for evaluating progress toward the higher level (Levels I and II) objectives.

Background

The determination of the feasibility and economics of extraction of heat from the HDR resource has been a funded research program at the Department of Energy's Los Alamos National Laboratory (LANL) for more than two decades. The world's first experimental site was established at Fenton Hill, on the edge of the Valles Caldera in New Mexico, in 1976. Initial HDR programs at Fenton Hill concentrated on:

- Extraction of heat from hot crystalline rock of low permeability;
- The use of fluid pressure downhole (hydraulic fracturing) to create flow passages and heat transfer surface within the rock; and,

- The operation of a recirculating, pressurized-water loop to extract heat from the rock and transport it to the surface.

Between 1976 and 1980, the Phase I or "research phase" of the program successfully demonstrated the concept of an HDR energy system by proving that it was technically feasible to induce a permeable fracture system in hot impermeable rocks by hydraulic fracturing from a deep well. This Phase I system extracted heat from a depth of approximately 3000 meters (9850 feet) and brought it to the surface as pressurized hot water at rates up to 5 megawatts thermal. Some of the heat was used to generate 60 kilowatts of electricity. The operation was essentially trouble-free, and there was no detectable scaling, plugging, corrosion, or environmental effect. The Phase I research program did not produce an HDR system with sufficient heat to support economical operation of a power plant.

A Phase II ("engineering phase") research program was initiated in 1979 to investigate methods to develop a larger, hotter HDR system at Fenton Hill to provide necessary data to evaluate the full technical and economic potential of candidate HDR resources in the U.S. In Phase II, two additional wells were drilled and the reservoir was hydraulically fractured in 1983. Test operators performed short-term flow tests and extensively reworked both wells. In 1986, during a 30-day flow test (the Initial Closed Loop Field Test - ICFT), they pumped water through the reservoir at a rate of 220 gallons/minute to produce 10 megawatts of thermal power. The Phase II program in FY90-91 focused on preparing a Long-Term Flow Test (LTFT). Hopefully, the test will begin in FY92 and will demonstrate the thermal lifetime and reservoir productivity required to support a commercial-scale and economically competitive power plant.

LEVEL II

LEVEL I

FENTON HILL OPERATION

**EVALUATE PERFORMANCE
OF PHASE II RESERVOIR**

**DETERMINE ENVIRONMENTAL
ACCEPTANCE OF HDR
TECHNOLOGY**

**HOT DRY ROCK
RESEARCH**

**GENERATE
COMMERCIALLY
COMPETITIVE ELECTRIC
POWER**

**SCIENCE & ENGINEERING
SUPPORT**

**EVALUATE PERFORMANCE
OF PHASE II RESERVOIR**

**IMPROVE PERFORMANCE OF
DRILLING & COMPLETION
TECHNOLOGY UNDER HDR
ENVIRONMENTS**

**EVALUATE THE ECONOMICS
OF HDR TECHNOLOGY**

LEVEL III

LEVEL III

TOOLS & INSTRUMENTATION

IMPROVEMENT INSTRUMENTS AND HARDWARE TO CONTROL, LOCATE, AND MEASURE FRACTURE PROPAGATION

ESTABLISH MAPPING TECHNIQUES TO LOCATE DRILLING TARGETS FOR PRODUCTION WELLS

RESERVOIR ENGINEERING

DEVELOP TECHNOLOGY TO MONITOR RESERVOIR VOLUME & TEMPERATURE. CONFIRM DATA USING TRACERS

COMPLETE DETAILED RESERVOIR ANALYSIS AND CONFIRM MODELING OF HYDRAULIC/ THERMAL PERFORMANCE

DETERMINE MEANS TO ACCURATELY LOCATE FRACTURE INTERSECTIONS WITH WELLBORE

COMPLETE STUDIES ON WATER-ROCK INTERACTIONS AND THE EFFECT ON FLOW-THROUGH

TECHNOLOGY APPLICATIONS

DETERMINE IF PHASE II RESERVOIR COULD SUPPORT COMMERCIAL SCALE PRODUCTION OF ELECTRICITY AT A COMPETITIVE BUSBAR COST

PHASE II ENERGY EXTRACTION

EVALUATE DRAWDOWN CHARACTERISTICS OF PHASE II RESERVOIR

PHASE II ANCILIARY ACTIVITIES

VERIFY THAT ENVIRONMENTAL AND SOCIAL CONSEQUENCES OF HDR ARE ACCEPTABLE

SITE SUPPORT ACTIVITIES

MAINTAIN FENTON HILL SITE FOR PLANNED EXPERIMENTS AND TESTS

HOT DRY ROCK RESEARCH

Table 12 below shows the major tasks, specific activities, and objectives of the Hot Dry Rock Research Phase II Program:

HOT DRY ROCK RESEARCH PROGRAM		
TASK AREAS	ACTIVITIES	OBJECTIVES
Fenton Hill Operations	Phase II Extraction System Plant	Includes wellbore completion and surface facility design, system procurements, installation, and testing
	Phase II Ancillary Activities	Includes diagnostic logging and environmental monitoring
	Test Site Support Activities	Includes water supply and site maintenance
Scientific & Engineering Support	Engr. and Dev. Activities	Includes modeling; analyses of microseismic, tracer, and geochemical data; and the design of experimental programs
	Technology Applications	Includes technology transfer, report preparation, and a comprehensive Hot Dry Rock Systems Study

Table 12.

FENTON HILL SITE OPERATIONS

Evaluation of the system operating characteristics of the Phase II reservoir at Fenton Hill is the objective of the Phase II Long-Term Flow Test. This includes all aspects of plant construction and commissioning, reservoir management and testing, site environmental and safety measures, procurement of utilities, and

routine site maintenance. Specific activity consists of performance monitoring of thermal drawdown, energy output, reservoir impedance, and water consumption. Environmental assessment of the HDR system operation is also an integral part of the operational evaluation.

PHASE II ENERGY EXTRACTION SYSTEM

This project element includes all preparations for and conduct of the Long Term Flow Test (LTFT) of the Phase II reservoir (See Figure 17 at the top of the following page), as well as all preliminary work leading to the test. FY91 activity completed construction of the surface plant. Plant commissioning will be completed early in 1992. Initial flow testing will initiate a steady-state LTFT phase beginning in the second quarter of 1992.

Conduct of short-term and long-term flow tests at the Fenton Hill Phase II reservoir will support the Phase II energy extraction objective to evaluate drawdown characteristics of the reservoir. During thermal drawdown, measurements will be made of parameters such as reservoir behavior, geochemical interactions, and fluid loss. Researchers will develop testing and modeling techniques to determine the effective energy production and longevity of fractured HDR reservoirs.

Much of the Fenton Hill site activity in FY 91 focused on equipment purchase and installation for the surface plant, wellhead repair, site safety improvements, reservoir pressurization testing, and logging in the production wellbore. Figure 18, at the bottom of the following page, is a simplified schematic of the completed Fenton Hill surface plant system.

EQUIPMENT PURCHASE AND INSTALLATION

This research activity completed all aspects of procurement and installation of system components for the LTFT. Key activities included installation of pumps for injection, supply water, and make-up water; installation of a separator to remove particles and gases from the circulating fluid; improvements to the heat exchanger system; installation of a data acquisition and control system; completion of surface loop piping, rebuilding of the injection and production wellheads; a study of site safety; and a review of the design and construction of the surface plant.

The Injection Pumps: Two high pressure pumps designed to inject water into the reservoir were delivered to the Fenton Hill site in April 1991. The pumps are self-contained units in a heated enclosure that will deliver about 200 gallons/minute of water at a maximum pressure of 5,000 pounds per square inch (psi). Installation, hookup, and testing continued throughout most of FY91. Operators encountered no outstanding problems, although a number of adaptations and modifications were necessary to alleviate minor problems that occurred during testing. Operators used pumps to inject water into the reservoir in September 1991.

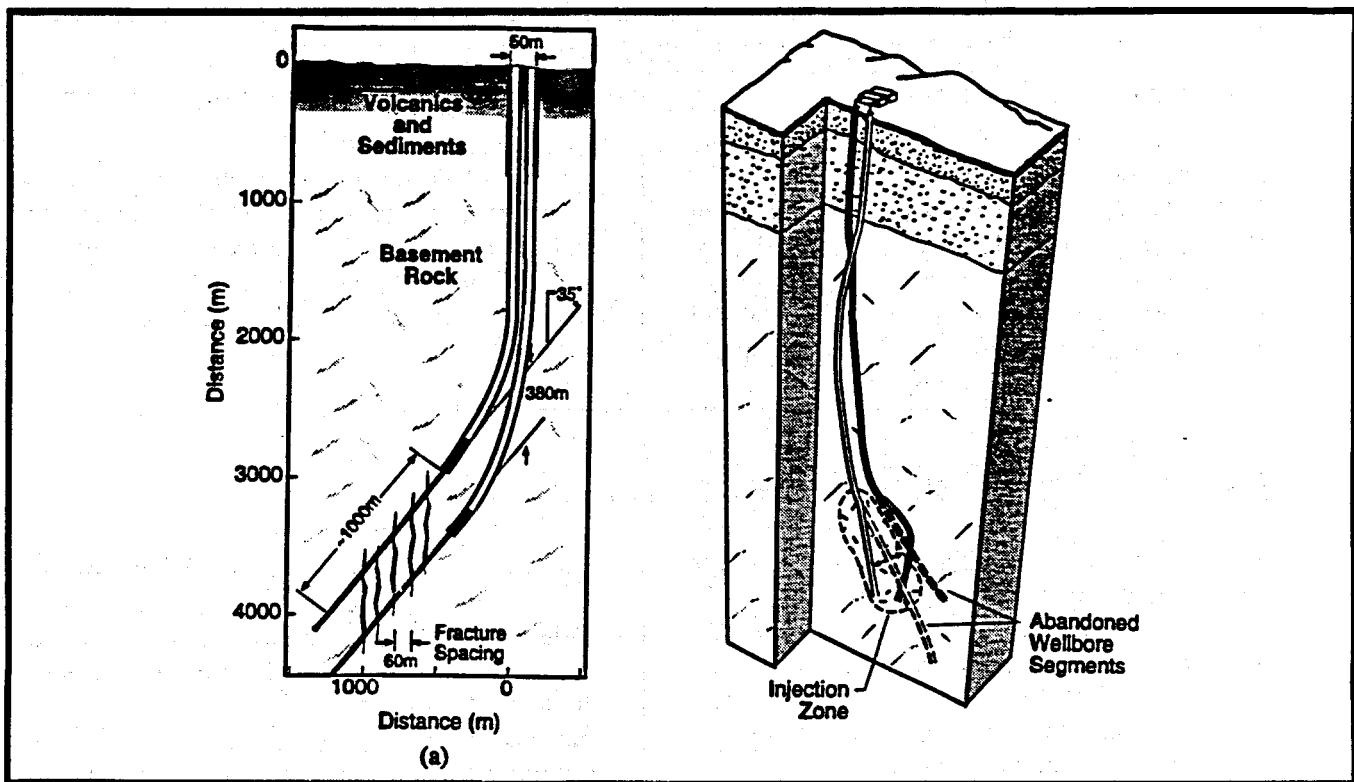


Figure 17
 (A) Original Conceptual Design of the Phase II Reservoirs (B) View of the Phase II Reservoir

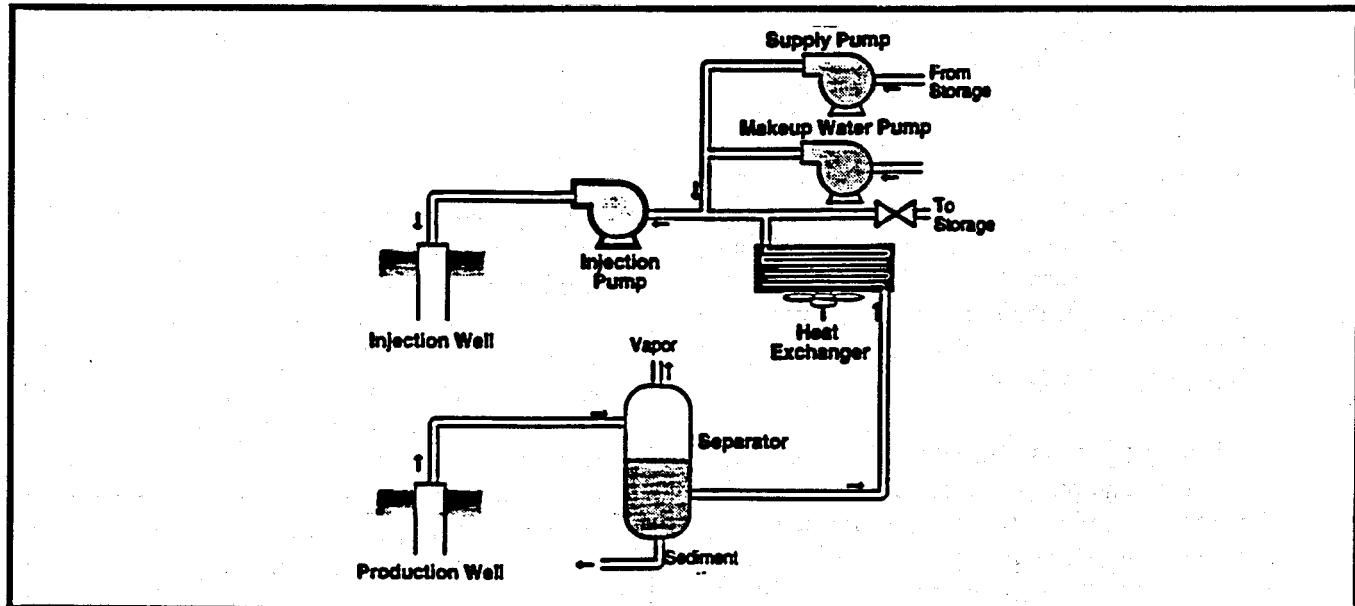


Figure 18
 Simplified Schematic of the Fenton Hill Surface Plant

HOT DRY ROCK RESEARCH

The Make-Up Water Pumps: Fenton Hill received two high pressure, low volume pumps, with a duplex starter controller, capable of delivering 25 gallons/minute against a pressure head of 1,000 psi early in FY91.

In February, the pumps were installed and start-up testing began. Hydraulic and mechanical operations went smoothly, but the control logic caused problems. These were corrected in early FY92.

The Separator: Researchers established mechanical design and fabrication requirements for this piece of equipment early in 1991. Fenton Hill received this unit in July 1991. Installation and hydro testing were completed in the late summer.

The Heat Exchanger: Evaluation in FY90 of the heat exchanger, which has been on site since 1974, found it to be in satisfactory condition. Improvements in FY91 included the installation of new motor controllers to provide more reliable operation of the cooling fans and

to bring the unit into compliance with the latest code provisions for the operation of large electrical equipment.

Data Acquisition and Control: Installation of the data acquisition and control system occurred throughout FY91. Figure 19 on the following page is a schematic showing access points or control operations.

The system was fully functional by the end of FY91. A complete back-up system was installed to provide a 100 percent redundancy in all functions.

Surface Loop Piping: Researchers designed and constructed all piping strings to meet American National Standards Institute (ANSI) requirements. Three functional sections comprise the piping system. (See Table 13.)

Fabricated, welded, inspected, and certified, the entire piping system was hydrostatically tested to be sound. At the end of FY91, the surface system piping was ready for LTFT experiments.

SURFACE LOOP PIPING SYSTEM		
SEGMENT	EQUIPMENT	OPERATING PRESSURE
LOW PRESSURE	Separator Heat Exchanger Make-Up Water Pumps	Up to 1,100 psi
PRODUCTION	Various Pressure Regulating Equipment	Up to 4,500 psi
HIGH PRESSURE	Pumps Injection Lines	Up to 5,000 psi

Table 13.

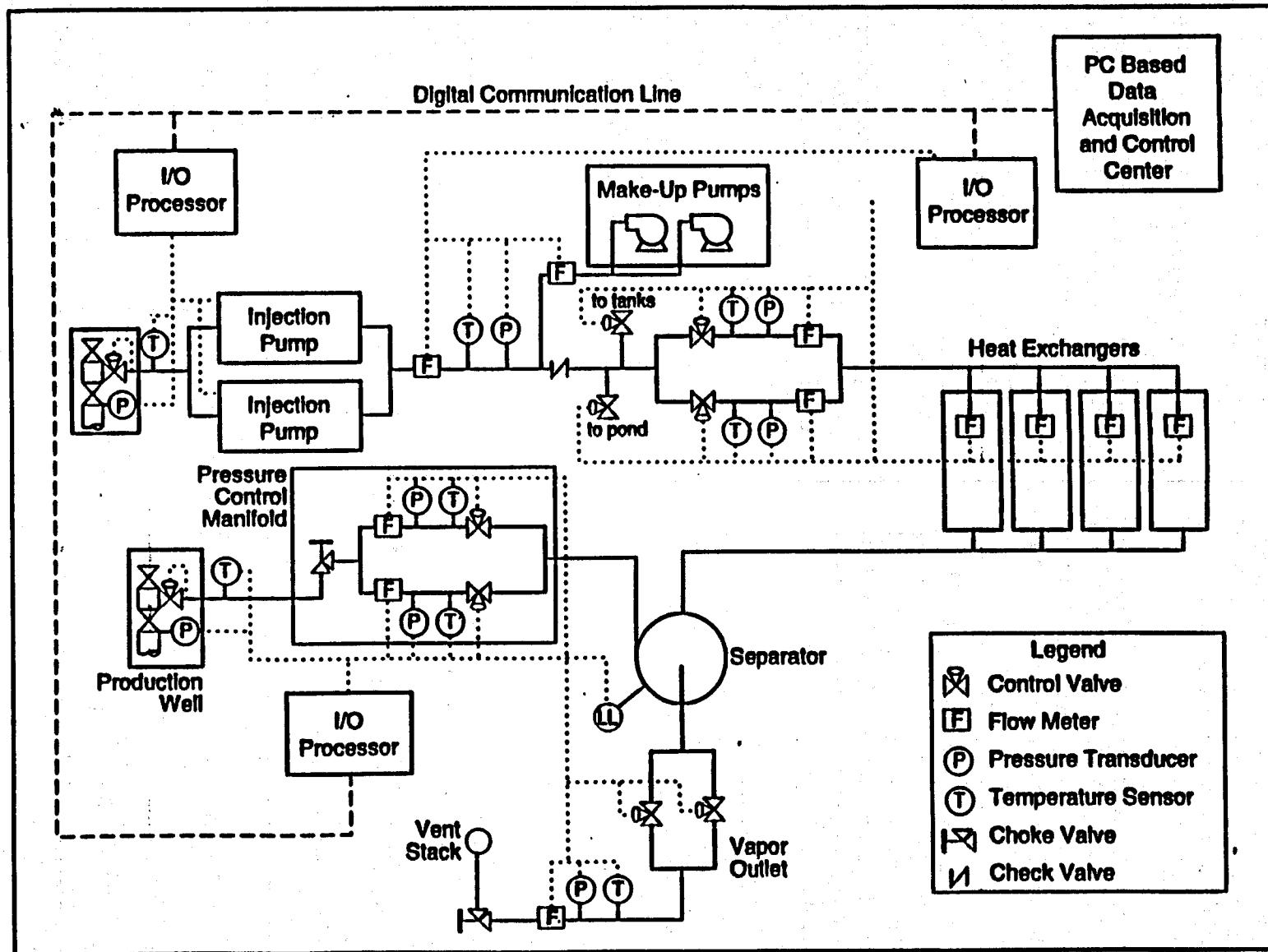


Figure 19
Loop Schematic Showing Data Acquisition and Control Points

The Wellheads: Both the injection and production wellheads were largely rebuilt in FY90. This work was completed early in FY91 with the final installation of valves on the production wellhead. Researchers decided to install structures around each wellhead. The structures consists of stairwells, ladders, platforms and multiple landings, to provide convenient access for operations and maintenance. Design and construction will comply with all applicable building codes and OSHA requirements.

Site Safety: In FY91, as part of the hazards review for the LTFT, researchers evaluated the potential for the production of hydrogen sulfide gas during the test, and evaluated procedures for dealing with its release. Seven new fixed hydrogen sulfide detectors and eight portable units were procured. Safety personnel at Fenton Hill placed warning signs on the perimeter of the site and at potential gas release points.

A USDOE "Tiger Team" conducted an intensive evaluation of all environmental, safety and health (ES&H) activities in FY91. The team identified five minor (OSHA, Category 3) violations and one compliance problem. All are being addressed.

Design and Construction Review: In the summer of 1991, a committee, comprised of LANL personnel not associated with the HDR program, reviewed the design and construction of the surface plant with respect to LANL policies and procedures in the areas of environment, safety, and health.

The review committee covered mechanical design, operating controls, quality assurance, and construction practices. The committee issued a preliminary report in the late summer 1991. HDR personnel were reviewing this report at the end of FY91.

Discussion

FY91 marked a significant milestone in HDR Program development with the completion of the construction of the LTFT surface plant at the Fenton Hill HDR site. Completion of this milestone prepared the site for a steady-state LTFT, which is planned for the second quarter of FY92. The length of the test will depend on the availability of FY92 funds.

RESERVOIR TESTING

The long-term pressurization study of the Fenton Hill reservoir that began in the spring of 1989 continued throughout FY91. Testing during the past year included extended intervals when reservoir pressure was maintained at 10, 15, 17, and 19 MPa (a range of 1450 to 2755 psi).

The pressurization work has continued to demonstrate that it is possible to maintain the reservoir at high pressure with very little water consumption, and that the reservoir does not grow even after prolonged periods of high pressurization. Data regarding reservoir characteristics (See Figure 20, on the following page) have been collected and analyzed throughout FY91, as discussed below.

Findings

10 MPa (1450 psi) Pressure Plateau Study - A nine week test at a constant pressure of 10 MPa (1450 psi) was conducted during March-April 1991 after the reservoir was allowed to slowly vent down from 15 MPa (2175 psi). Water loss was negligible during the test period. The reservoir pressure had been at least 15 MPa for several months prior to the establishment of a 10 MPa plateau for this test. It is likely that a broad isobaric region extending well beyond the limits of the fractured reservoir was established during the test stage.

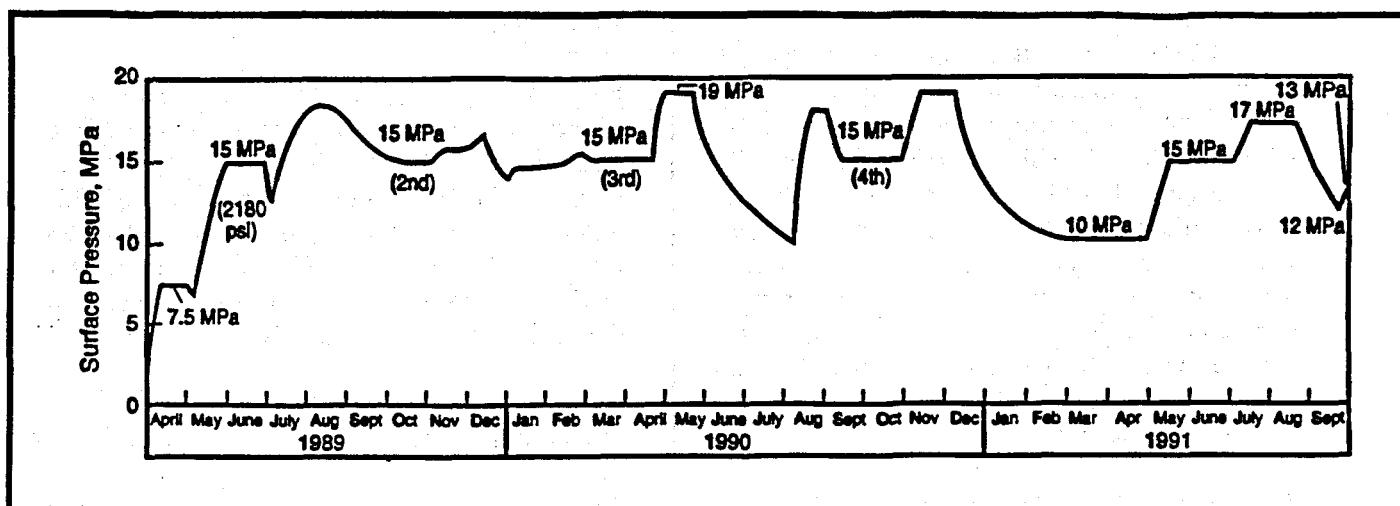


Figure 20
Reservoir Pressure Profile over the Term of the Pressurization Study

15 Mpa (2175 psi) Pressure Plateau Study - Researchers increased the pressure on the Phase II reservoir from 10 MPa to 15 MPa in early May 1991. Based on prior experience, this pressurization change was expected to take about three weeks to complete while consuming 424,000 gallons of water. The actual process took only 7 days and consumed 157,000 gallons.

The lower water consumption may result from over two years of pressure maintenance. The rock mass surrounding the fractured reservoir may have become much stiffer. As a result, small changes in joint dimensions would occur during a pressure increase, thus consuming less water. The water consumption declined during the test, from a high of 5 gallons/minute in early May to less than 4 gallons/minute by the end of the month when the experiment was terminated. These results are consistent with previous tests at 15 MPa.

17 MPa (2465 psi) Pressure Plateau Study - On July 8, 1991, researchers raised and maintained the reservoir pressure to 17 MPa until August 22, 1991 when equipment problems forced an end to the test. During this long steady-state pressurization, water consumption declined linearly with the logarithm of time (as expected) from an initial value of 8.6 gallons/minute to 4.5 gallons/minute by early August, when it unexpectedly increased over a four day period to a level of 5.5 gallons/minute. After this as yet unexplained aberration, water consumption continued to decline as expected over the remaining few days of the test period.

19 MPa (2755 psi) Pressure Plateau Study - During the latter part of November and early December 1990, the reservoir pressure was maintained at 19 MPa. The same pressure had been maintained during May 1990. Between those times, the reservoir had been maintained at an average value of about 15 MPa (low of 10 MPa and a high of 17 MPa). The data show

HOT DRY ROCK RESEARCH

a significantly lower rate of water loss during the second 19 MPa pressure plateau than that observed in May 1990. The difference (about 1 gallon/minute) indicates a pressure gradient still developing at the reservoir periphery, and a somewhat higher far-field pressure during the second plateau period resulting in slower reservoir diffusion in November 1990.

The water loss data at 19 MPa are analogous to those observed at 15 MPa, and provide further evidence that water losses decline significantly during extended operation of the reservoir. These results predict low water consumption during the LTFT when the mean pressure at the reservoir periphery is expected to be at or below 19 MPa during reservoir operation at injection pressures of about 25.5 MPa (3700 psi).

Fluid Leak Through the Injection Wellbore Annulus - A continuous water leak of a few gallons per minute from the injection well at the Fenton Hill site has occurred over several years.

Analyses of samples of returned water indicate that it is probably reservoir fluid, i.e., a connection must exist at some point above the cemented-in section of the wellbore which is

supposed to seal off the reservoir from this exit pathway.

The flow rate has been found to change in response to changes in pumping schedules and reservoir pressure in a predictable manner. It has averaged 2-3 gallons/minute over the entire 2 1/2 years of the current pressurization experiment. This leak will continue to be closely monitored.

Long-Term Water Consumption - The total water usage for reservoir pressurization at Fenton Hill during 1990 was about 6 acre feet. Specific water usage throughout the operation of the HDR facility is shown in the Table 14, below.

LOGGING

On August 5, 1991, researchers conducted a temperature/ gamma/collar log wellbore with the well pressure at about 17 MPa (>2400 psi). This was the first logging activity at Fenton Hill in over 2 years, as well as the first time that the Los Alamos equipment had been used under high pressure conditions.

WATER USAGE DURING EXTENDED PRESSURIZATION TESTS IN 1990		
WATER USE	AMOUNT OR RATE	METRIC MEASUREMENT
Water Injected	3,174,000 Gallons	12,000 Cubic Meters
Water Vented	1,298,000 Gallons	4,912 Cubic Meters
Net Water Consumed	1,876,000 Gallons	7,108 Cubic Meters
Average Water Use	3.57 Gallons/Minute	0.225 Kilograms/Second
Average Reservoir Pressure	2223 psi	15.32 MPa

Table 14.

Findings

The temperature gradient between 10,860 and 11,560 feet is flat — the shallow depths within the interval exceeding virgin rock temperatures. From 11,560 to 12,186 feet, the gradient resumes the step-like temperature profile expected for a reservoir shut in for 30 months. The fractures contributing to fluid production are clearly evident over the latter interval.

Discussion

No clear conclusions emerge to explain the gradient between 10,860 feet and 11,560 feet.

Two hypotheses have been made:

- (1) Flow has taken place from a fracture located at 11,560 feet into the production wellbore, up the well to 10,860 feet, and then out into a fracture at that depth
- (2) The temperatures measured in the production well are representative of the reservoir as a whole at those depths. This results in little impedance to flow in the reservoir fractures and buoyant forces are slowly driving a large-scale convective system within the reservoir.

PHASE II ANCILLARY ACTIVITIES

The major objective of the Phase II Ancillary Activities is to verify that environmental consequences of HDR system operation are acceptable.

Seismicity at Fenton Hill and in the neighboring vicinity has been monitored continuously for over 10 years to establish a baseline against which LTFT operations can be compared. Samples from the area's springs, streams, lakes, and water wells have been analyzed periodically since 1975. Water from the on-site well is analyzed for organics monthly and a full chemical analysis is completed annually. Seismic monitoring is routinely conducted during injection and production experiments to detect any abnormal seismicity throughout the region. Microseismic event monitoring is used to determine the presence of thermal stress and the extent of the active reservoir. In addition, occasional noise level and illumination measurements are made during various types of

site operations. Surface and downhole seismic monitoring during and immediately following LTFT downhole pressure/flow operations, and sampling and chemical/biotic analysis of site water supplies will be completed.

SITE ENVIRONMENTAL SAFETY REVIEW

A comprehensive review of the design and construction of pressurized system components of the Fenton Hill system was initiated by an independent team of a safety engineer and two mechanical engineers. A technical safety appraisal was completed as required by DOE Order 5480.19. A review of Federal and State regulations that affect the operation of the Fenton Hill facilities was completed. A permit application was prepared for injection activities at Fenton Hill and submitted to the State of New Mexico through the State Oil Conservation

HOT DRY ROCK RESEARCH

Division, the group that permits and regulates all injection activities in New Mexico.

Findings

Technical Safety Appraisal - This appraisal included review of the following:

- Organization and administration,
- Quality verification,
- Operations and Maintenance,
- Training and Certification,
- Emergency preparedness,
- Personnel protection, and
- Worker safety and health compliance.

An assessment of risks to personnel and efforts to reduce them was also completed during a documented management review of Fenton Hill activities. Both the safety appraisal and risk assessment increased personnel and management awareness and response to the continuing environment, health, and safety requirements at the Fenton Hill facilities.

Review of Federal and State Regulations - A determination of environmental consequences of the release of hydrogen sulfide is required by Federal and State of New Mexico Clean Acts. Based on the documented amount of gas released during past flow tests at Fenton Hill, LANL's Environmental Management Division determined that the facility would not qualify for Air regulation under the Clean Air Act. Similarly, because of the low volume of hydrogen sulfide released and its low concentration in the stream of gases released, Fenton Hill would not have to be regulated as a public safety hazard.

Nonetheless, since hydrogen sulfide is present on site, it represents a potential health hazard to operations personnel and visitors. In this regard, Occupational Safety and Health Administration (OSHA) regulations apply. The following actions were taken:

- (1) Two additional self-contained breathing units and eight hand-held digital hydrogen sulfide monitors were located at two emergency locations,
- (2) OSHA signs warning of the possible presence of hydrogen sulfide gas were posted at each potential emission location along the site perimeter,
- (3) A windsock was installed at a second location for a clear indication of low level air movement close to the Phase II wellheads, and
- (4) All LANL and contract site personnel assigned to Fenton Hill were given training with respect to the hydrogen sulfide risk, its detection, and consequent actions to be taken.

Permit for Injection Activities - Injection activity in the State of New Mexico is regulated through the State Oil Conservation Division to insure that aquifer waters are not contaminated. Before starting injection operations, the hydraulic integrity of a well must be assured and insure verified every 5 years thereafter.

Once injection begins, monthly reports of the amount of fluid injected must be filed. As of the close of FY91, the State of New Mexico had not acted on the Fenton Hill permit application.

TEST SITE SUPPORT

The major objective of site support activities is to ensure that the Fenton Hill site is in a condition conducive to the conduct of the planned experimental program.

General responsibilities under this task include:

- access and on-site road grading
- graveling and snow removal
- building and utility maintenance
- housekeeping
- maintenance of the flow loop
- uninterrupted power supply system
- freeze protection system
- maintenance of emergency vehicles/facilities

- site security and safety
- maintenance of water storage/transfer
- handling of work towers
- handling of visitors

Improvement to Visitor Facilities - A conference room was built into the operations building to be used as an information center. Here, staff can review the status of operating parameters and recent component performance history. A viewing stand was installed next to the 1 million gallon pond for visitors to see the site without having to enter hazardous areas. Finally, a small visitor parking area was paved in front of the Operations Building.

SCIENTIFIC AND ENGINEERING SUPPORT

The research team will evaluate the performance of the Fenton Hill Phase II reservoir by measuring the thermal drawdown, energy output, reservoir impedance and water

consumption. The performance of drilling and completion technology will be improved and the economics of the HDR system operation will be evaluated.

ENGINEERING AND DEVELOPMENT

Engineering and Development Activities support research in:

- Reservoir engineering and modeling;
- Microseismic, tracer, and geochemical analyses; and
- Design and planning of the experiments at Fenton Hill.

Specific reservoir engineering activities are designed:

- To improve monitoring of reservoir characteristics,
- To complete detailed analyses of reservoirs and confirm hydraulic and thermal performance models, and
- To determine means to accurately locate the intersection of fractures with the wellbore.

During the Phase I energy extraction experiment, several techniques were used to estimate the size and lifetime of the reservoir. Chemically reacting tracers were used during the Phase II 30-day, open-loop circulation test at Fenton Hill. The test helped the development of implementation techniques and to verify tracer models to estimate thermal lifetime of the reservoir. Laboratory measurement techniques were identified for measuring very low concentrations (parts per billion) of tracer

species. Spectral analyses and fault plane solutions for seismic events, completed during past experiments, will be improved using data collected during the LTFT. Ongoing studies of the geochemistry at Fenton Hill provide:

- support for detailed reservoir analyses and modeling of hydraulic and thermal performance,
- aid in determining fracture locations, and
- information on water-rock interactions and their effects on flow through the reservoir.

As more knowledge is gained of the HDR process, models have been improved to better represent reservoir characteristics. Analyses to date have been sufficient to verify the HDR concept, but have not adequately reduced the technical and economic risk associated with commercialization. Analysis of the LTFT data will verify the hydraulic and thermal models and enhance their use as a basis for the design of commercial-scale power systems.

RESERVOIR ENGINEERING

Reservoir engineering is concerned with understanding and manipulating HDR reservoirs. Activities draw heavily on technology already developed in the oil and hydrothermal industries,

but must adapt the established principles to the peculiarities of HDR reservoirs. Activities are designed to develop an improved understanding of the fracturing geometry and thermal flow characteristics of the Fenton Hill reservoir, as well as to control all aspects of reservoir operation and performance. During FY91, efforts focused on the pressurization experiments at Fenton Hill. Much of this work has been discussed previously in this report. In addition, data were generated to determine other important reservoir characteristics, as described in the finding below.

Findings

Fluid Storage Partitioning in Joints and Microcracks - The Fenton Hill reservoir was shut-in from late May to early August 1990. The reservoir pressure declined from 19 MPa to 9.8 MPa, primarily due to the venting of fluid through the annulus leak in the injection wellbore.

Pressurization, fluid injection, and water outflow data were used to separately determine the volume fractions of fluid storage within the dilated joints of the reservoir and in the microcracks of the reservoir at a mean reservoir pressure of 10.5 MPa. On the basis of these data and certain assertions, the fraction of the reservoir fluid stored in the microcracks under steady state conditions at 10.5 MPa was calculated to be almost three-fourths of the reservoir storage, a counter intuitive result for a fractured HDR reservoir.

While storage partitioning at pressures in the range of 10 MPa appears to be largely in the microcracks of the reservoir rock, different factors appear to control storage at higher pressures. The reservoir pressurization profile in November 1990 consisted of a period of gradual increase in pressure, a rapid pressurization stage, a long period of gradual depressurization, and, finally, a period of rapid

pressurization. This profile has provided information for an understanding of the nature of reservoir storage at pressures somewhat above 15 MPa.

The flow and fluid storage data imply that there is no appreciable difference in slow and rapid reservoir pressurization at pressures in the range of 15-17 MPa (2380 psi average). This suggests that matrix microcracks are not contributing to storage at reservoir pressures above about 15 MPa. When reservoir pressure is increased above 15 MPa, however, this trend does not continue, i.e., a dramatic decrease in the rate of additional fluid storage occurs. This change by more than a factor of 2 supports the assertion that, at pressures greater than about 15 MPa, additional fluid storage is almost entirely in the joints.

These findings have important implications for the operation of HDR reservoirs since the process of storing fluid in the microcracks (lower pressures) is relatively slow while storage in joints (higher pressures) can be effected rapidly. Thus in any type of cyclic operation of an HDR system, it would be desirable to keep pressure on the low side of the cycle at a high enough level so that joint storage still predominates in order to maintain a tighter control over reservoir performance parameters.

Joint Spacing in the Fenton Hill Phase II Reservoir - Measurement of the spacing between the open joints of an HDR reservoir is extremely important to an adequate understanding of the thermal and flow performance of the HDR system. Measurements of storage volume in microcracks and joints obtained from the extended pressurization experiment during FY91 may provide a basis for quantification of joint spacing in the Phase II HDR reservoir.

Using these data and previous seismic analyses of the Phase II reservoir's shape, one can

calculate the total reservoir volume and an incremental joint opening.

Unfortunately, there is no unambiguous way to assign this total joint opening to one or more joints. Mathematical manipulations and certain assumptions on joint openings from previous experiments at Fenton Hill can be used to calculate that the most probable range of joint spacing in the Phase II HDR reservoir is 4-8 meters. Work now underway using the FRACNET model should provide a better quantification of the joint spacing based on flow impedance and tracer data.

MODELING

Modeling enables prediction of HDR system performance and aids in the selection of operating parameters for the conduct of various test programs. The development and use of realistic models is critical to the sound evaluation of HDR resources, the design of HDR plants, and the operational plans for HDR facilities. Efforts in FY91 continued to emphasize the development of models to explain reservoir behavior and the testing of these models by application to the Fenton Hill Phase II reservoir and operating experience.

Findings

The FRACNET Model - The FRACNET computer code simulates fluid flow and solute transport in fractured media. While this model was initially developed for steady-state conditions, recent work has been directed toward simulation of transient fluid flow and transport. The goals of these simulations are to predict reservoir permeability parameters and evaluate their reasonableness, as well as to provide a more detailed and quantitative explanation of the flow characteristics observed during the extended pressurization experiment at the Phase

II Fenton Hill reservoir. After simulation of other phases of this experiment and of other tests at high flow rates, the model, by then well-calibrated, will be used to make performance predictions of operations of the reservoir under varying conditions.

Fracture and matrix properties were adjusted simultaneously to match modeling results with experimental data over the first 100 days of the extended pressurization test. The fracture volumes at typical circulation pressures were fixed in the range which had been previously calculated on the basis of tracer measurements made during actual circulation tests.

A comparison of modeling results with experimental data indicates that all characteristics of interest, i.e., production well response to pumping at the injection well, the rate of pressure rise during constant injection, simulation of constant pressure plateaus, and the pressure decline during short shut-in periods, are well simulated by the model. Data from the next 200 days of the extended pressurization test was used to further evaluate the model. The model did not accurately represent reservoir performance. The model is now being revised to incorporate parameters that will maintain the excellent fit to the early experimental data throughout the remaining days of the pressurization test.

An enhancement to the model to incorporate solute transport was developed in FY91. This will allow validation of the model's current simulation of fluid flow (based on chemical engineering considerations) using the results of tracer and inert chemical species data collected in a variety of tests at Fenton Hill. The model can then be used to predict future concentrations of certain dissolved species of operational interest (such as dissolved gases), and provide insight into the fluid flow and transport processes occurring in the reservoir.

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Modeling of the remainder of the extended pressurization experiment is continuing to:

- determine fracture and matrix parameters appropriate for pressure increases above 15 MPa, and
- use data from the Initial Closed Loop Flow Test (ICLT) to fine-tune the parameters used to describe fracture clusters directly connected to the wellbores.

The GEOCRACK Model - Kansas State University (KSU) is developing a finite element, fully coupled rock/fluid/thermal model of geothermal reservoirs (the GEOCRACK model) that can be used in design and feasibility work on HDR systems. This effort complements LANL modeling work in multiphase flow and fluid flow in fractures. During the summer of 1990, KSU graduate students worked at LANL to adapt the GEOCRACK model to the SUN computer work-station.

The model uses a discrete approach wherein each joint and rock block, including the deformation of the rock and connecting joints, is separately considered.

Two analyses, structural and fluid, are separately calculated. Information is sequentially transferred in an iterative process between the two calculations until the results converge.

Model verification analyses are underway. Initial results show good agreement with earlier analytical solutions for one-dimensional fluid flow in a single loaded joint. Application of the technique to the more complicated situation of a realistic HDR reservoir is proceeding.

SEISMOLOGY

Seismic surveillance is one technique for continually monitoring the reservoir and assuring

that no detrimental environmental effects result from the work at Fenton Hill. Seismology will be critical to the development of future HDR systems by accurately mapping reservoir formation and locating drilling targets.

Seismic monitoring continued at Fenton Hill, some experimental upgrades were implemented, and significant work was carried out to improve the accessibility, quality, and usefulness of the vast amount of data collected in early experiments. The monitoring effort confirmed that the reservoir continues to be aseismic at pressures as high as 19 MPa or more.

Findings

Seismic Data Collection and Use - No new seismic data were collected during FY91. Transfer of data collected during the massive hydraulic fracturing (MHF) operation from the original magnetic tape medium to optical disk continued. These data are still used extensively for waveform analyses and reservoir definition work by increasingly sophisticated analytical techniques.

High quality seismic locations were selected for incorporation into a new video which will show the temporal and spatial evolution of the seismic zone during the MHF. Continued work on faster computers is producing an ever-clearer seismic picture of the Phase II HDR reservoir.

Reservoir Imaging - Imaging the reservoir using tomographic techniques continued in FY91. One area of interest is the degree to which the smoothing imposed on the final velocity model during the tomographic inversion affects the final results of the inversion process. Smoothing is imposed to provide a more realistic reservoir model and to help reduce the degree of non-uniqueness in the inversion. Plots of tomograms were made using inversion results incorporating smoothed model constraints as well as constraints that use relatively little

smoothing. The similarity of the two sets was high, leading to the conclusion that smoothing does not significantly affect the results.

Additional work focused on developing methods to constrain velocities determined by tomographic techniques from micro-earthquake signals. The use of a penalty function to constrain the ratio was found to work well.

Finally, to improve data quality, a method to evaluate the quality of micro-earthquake location was investigated in FY91. Approximately 4,000 events have been selected as having the best defined locations from a database of over 11,000 initial event locations. The spatial distribution of these selected locations is now being evaluated.

Tomographic work in the area of seismology was supported at LANL by funding from the DOE Office of Basic Energy Science. It is reported in this annual report because it uses data generated in the HDR Program and is of interest to increase the capability to quantify HDR reservoir characteristics.

Waveform Stacking - Early in 1991, results were obtained from a novel form of waveform stacking that can be used to determine detailed velocities of seismic signals from micro-earthquakes in small volumes of an HDR reservoir. A set of 50 micro-earthquakes was used from a set that occurred during the MHF experiment in December 1983. Also in FY91, efforts were directed toward stacking of

seismograms to identify signal scattering features in the HDR reservoir at Fenton Hill. The goal of this effort is to identify scatterers that may be fractures. Results show more tubular features than anticipated, suggesting that joint intersections may play a prominent role in conduction of fluids in the reservoir.

GEOCHEMISTRY AND TRACERS

Geochemical analysis is used to monitor the quality of the circulating geofluid and to assess the interactions of the circulating water with the reservoir rock. Tracers are used to estimate the size of the reservoir, to obtain information about fluid flow paths, and to provide experimental data for predictions of the thermal lifetime of the reservoir. Geochemical and tracer work at LANL in FY91 concentrated on preparations for the LTFT. In addition, a program to study rock-water interactions in simulated HDR systems was initiated at the Massachusetts Institute of Technology (MIT).

Findings

Geochemical Data Acquisition During the LTFT - Preparations are complete to collect geochemical samples and on-line geochemistry data during the LTFT of the Phase II reservoir. These include:

- Installation of software and hardware and interfaces for the collection of radioactive tracer data,
- Acquisition and calibration of on-line measurement probes for pH, electrical conductivity, etc.,
- Construction and testing of a system for measuring gas and liquid flow rates in a small side-stream of the surface loop.
- Installation of software for general chemical data acquisition and provision for transmission to the central data acquisition facility,
- Acquisition of specialized software for converting the raw data from gas chromatographic analyses to a more useful form,

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- Production of drawings of the geochemical sampling equipment, and
- Revamping of the equipment for injecting radioactive tracers to allow its operation under conditions of high pressure injection, and revision of the standard operating procedures for this work.

MIT Work on Rock-Water Interactions - MIT has initiated a study to determine the reactions of typical HDR reservoir rock with water at a variety of temperatures, pressures, and pH values. The objective is to better understand the effects of circulating water on the HDR matrix rock by simulating realistic reservoir conditions in the laboratory.

Eventually, this effort will evaluate specialized water sources, such as treated sewage and ocean waters, to determine their suitability for use in HDR systems.

Much of FY91 was spent procuring equipment necessary to perform dynamic dissolution experiments under high pressures and temperatures, and in obtaining baseline data. The first experiments used de-ionized water at relatively low temperatures. Recently, experiments have explored the effect of pH on quartz dissolution to obtain data on the suitability of using water from a variety of different sources in HDR systems.

TECHNOLOGY APPLICATIONS

Technology transfer activities are directed toward publicizing HDR technology to foster growth in the private sector. These activities include visits to LANL and the Fenton Hill site by industrial representatives, visits by HDR staff to industrial organizations, interactions at all levels of the media, attendance at professional and technical meetings, and the presentation and publication of HDR technology in a broad variety of forums. In the coming year, every effort will be made to encourage private sector participation in the LTFT at Fenton Hill.

TECHNOLOGY TRANSFER APPROACH

Efforts included working closely with industry, the media, the public sector, and several other interested parties to disseminate information about HDR and to promote the transfer of technology to private industry. In FY91, a total of about 200 official visitors from outside LANL were briefed on the HDR program and 43 separate visits were made to the Fenton Hill site. There were 22 foreign visitors from 7 countries;

Japan, England, Germany, France, The Netherlands, Italy, and Switzerland.

Findings

Industrial Interactions - Two industrial reviews of the LTFT program were completed to insure that the maximum amount of useful information for industry would be obtained. One review was conducted by the National Geothermal Association and included representation from a number of geothermal companies, utilities, the Electric Power Research Institute (EPRI) and the California Energy Commission. The second review was conducted by the Hot Dry Rock Program Development Committee, which consists of representatives from industry, regulatory boards and academia. These reviews have significantly modified the LTFT plan to emphasize continuous production of energy under commercially realistic conditions.

A number of industrial representatives visited LANL in FY91. Among these were five

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members of the International Association of Drilling Contractors and 55 visitors hosted by the Energy and Minerals Field Institute of the Colorado School of Mines.

Media Interactions - In FY91, five print and five broadcast people visited LANL and Fenton Hill, and telephone interviews were conducted with a dozen other reporters. Stories on HDR were carried in at least a dozen widely distributed popular and trade publications, including Discover magazine, the Denver Post, the EPRI Journal, Business Week, Science, Mechanical Engineering, Oil Daily, Electric Power and Light Bulletin, Geothermal Resource Council Bulletin, California Division of Oil and Gas Hot Line, and an Ingersoll-Rand Company publication.

Two Albuquerque television stations aired programs on HDR.

A new video discussing HDR was produced toward the end of FY91. The video has been distributed to several organizations for use in developing programs about HDR systems.

Education and Academia - A group of 11 Kellogg Fellows were briefed on HDR and visited the Fenton Hill site. College students working at LANL as part of a DOE-sponsored Science and Engineering Research Semester and high school students participating in an educational effort sponsored by the American Chemical Society were also briefed on HDR technology. Faculty members from a number of universities were briefed on the HDR program during visits to LANL.

Governmental Interactions - HDR was a topic of discussion in the Congressional hearing and town meeting sponsored by the office of Senator Jeff Bingaman of New Mexico.

Early in 1991, HDR was featured in a New Energy Technology reception hosted by the California Division of Oil and Gas in Sacramento, CA.

CLEARLAKE, CA HDR INITIATIVE

There has been a longstanding interest in the potential for HDR in the vicinity of the city of Clearlake, CA, which is located northeast of The Geysers hydrothermal field in northern California. A preliminary study in 1987-1988 indicated that an in-depth resource assessment was warranted. In January 1991, funding authorized by the California State Legislature was used by the California Energy Commission through the city of Clearlake to initiate the HDR resource assessment.

Findings

The assessment includes an evaluation of thermal gradients, geologic structures, geohydrology, seismology, surface hydrology, and comparative geothermal regimes. The work will continue into FY92 and result in a detailed report to the city.

This resource assessment may be followed by subsequent phases involving drilling, reservoir development, and construction of a practical HDR facility. A decision on whether to provide additional California Energy Commission funds for supplementary well log analyses is pending.

APPENDIX A

GEOTHERMAL R&D PROGRAM

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Geopressured
Resources,
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Energy Conversion

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Universities

- Stanford University
- Massachusetts Institute of Technology (MIT)
- Louisiana State University (LSU)
- University of Southwestern Louisiana (USL)
- 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

- BNF Technologies, Incorporated
- Meridian Corporation
- Oregon Institute of Technology (OIT)

APPENDIX B

GEOTHERMAL PUBLICATIONS

BY CATEGORY

HYDROTHERMAL

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