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PROCEEDINGS

GEOTHERMAL PROGRAM REVIEW IV

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Sponsored by:

U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY
CONSERVATION & RENEWABLE ENERGY
GEOTHERMAL TECHNOLOGY DIVISION

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INTRODUCTION

The Department of Energy's Geothermal Technology Division (GTD) held its Program Review IV in Washington, D.C. in 1985. This year attention was directed toward a comprehensive overview of GTD's research and development program with presentations on each of the major program elements by representatives of the operations offices, the national laboratories, contractors and by Headquarters personnel.

Program Review IV marks the first opportunity to review DOE's geothermal R&D program as it now appears under the new GTD organizational structure. As you know, in August of 1985, the management organization at Headquarters was restructured to enhance the efficiency of management of the Geothermal R&D Program. Simply put, the major R&D thrusts now fall into two major subprograms: (1) Geothermal Geosciences Research which addresses all research and program activities related to the advancement of technology for locating and exploiting geothermal resources; and (2) Geothermal Conversion Research which encompasses research activities related to advanced technology for geothermal energy conversion.

The Geothermal R&D Program is implemented by four organizations: GTD Headquarters with overall management responsibility, and the three operations offices in San Francisco, Albuquerque and Idaho who carry out the various R&D tasks and projects through the national laboratories and contractors. Program Review IV was thus presented in four sessions, each chaired by one of the four lead organizations. Appropriately, the presentations within each session were keyed to the various program responsibilities and R&D elements and tasks which fall under the purview of each of the four organizations. In doing so, Program Review IV addressed each of the major initiatives within the Geothermal R&D Program.

The annual program review meetings are an important element of our efforts to develop, refine and expand the technology base through which the nation's vast geothermal resources can be technically and economically utilized. These meetings provide a forum through which conference participants can obtain an up-to-date report on DOE's geothermal research and development programs, and where significant R&D thrusts can be explored. The annual Program Review Meeting also provides an invaluable opportunity to compare and exchange information with co-workers and interested participants, thus facilitating the transfer of technology among DOE, state and local governments, and industry organizations.

Program Review IV accomplished these goals due in no small measure to the dedication and hard work of the speakers and the session chairpersons who shared their knowledge and enthusiasm, and to the general audience who contributed their interest and perspectives to the meeting. Special thanks must go to my fellow session chairpersons -- Tony Adduci of San Francisco Operations, George Tennyson of Albuquerque Operations and Susan Prestwich of Idaho Operations -- who put a great deal of effort into organizing and conducting their sessions. A sincere note of thanks must also go to Mrs. Linda Kurkowski of Meridian Corporation who helped organize Program Review IV, and to her most able staff including Claudia MacDonnell, Kelly Poe, Tee Ragland, Cheryl Ben-Ami and Kerry Schwartz.

The technical papers and the remarks of invited speakers contained in these Proceedings have been reproduced from the best available copy, and are arranged in the order in which they were presented at Program Review IV.

John E. Mock

Dr. John E. Mock
Director
Geothermal Technology Division
U.S. Department of Energy

KEYNOTE ADDRESS

Miss Donna Fitzpatrick
Assistant Secretary for Conservation
and Renewable Energy
U.S. Department of Energy

The keynote address delivered by Miss Fitzpatrick to the participants in Program Review IV is reproduced here in summary form. As one of the Administration's leading proponents of geothermal energy, Miss Fitzpatrick has actively supported and has made a number of public appearances on behalf of the geothermal research and development program. Program Review IV marks the second occasion that Miss Fitzpatrick has addressed the annual program review meeting. She delivered the keynote address at Program Review III last year in El Centro shortly after joining the Department of Energy. Throughout her address, Miss Fitzpatrick made a number of pertinent points and observations which are summarized below.

Importance of Geothermal Energy

- Geothermal energy is a "here and now" resource. The technology needed to exploit a large portion of the resource in an efficient, economic and environmentally safe manner is in place. The U.S. is generating over 1500 MWe of electricity from geothermal resources, with a total of over 3800 MWe of generating capacity worldwide.
- Significant advances have and are continuing to be made in the technologies needed to further exploit geothermal energy, with the United States leading in advancing the technology.
- The worldwide potential for electrical generation alone from geothermal resources in truly enormous. The United States Geological Survey estimates this country's potential on the order of 95,000-150,000 MWe. Worldwide, the electrical generating potential has been estimated at upwards of 4 million MWe.
- The importance of geothermal energy to the United States is reflected in the role of this resource in the energy mix that is closely tracked and projected for the U.S. under the National Energy Policy Plan.

DOE Initiatives on Behalf of U.S. Geothermal Industry

- DOE's Geothermal Technology Division has prepared a digest entitled "United States Geothermal Technology-Equipment and Services for Worldwide Applications," which was released at the GRC Conference in Hawaii.
- The digest highlights the technological advances made in the United States that have solved many of the critical engineering, materials and environmental issues that once surrounded this source of energy, and have made geothermal energy a practical, economic, and environmentally compatible element of the U.S. energy picture.
- The digest is directed at an overview level to energy decision-makers and, in more detail, to their technical experts who will be evaluating their options for supplying the energy demand of their respective nations and areas of the world.
- The digest further focuses the attention of the foreign marketplace upon the U.S. geothermal industry as the leading source of expertise, goods and services to assist them in development of their own resources.
- The digest is intended for use not just by DOE, but also by U.S. industry in their own efforts to enter the international marketplace and to expand upon existing opportunities.

Technology Transfer

- o DOE's Geothermal Technology Division is preparing a Technology Transfer Catalog which will become available in the very near future. The catalog is directed at geothermal energy developers, users and the service industry as a complete up-to-date source of federally sponsored research and advances in geothermal technology development that are in place and nearing readiness for field application.

Recent Accomplishments

The U.S. continues to maintain and expand upon its role as world leader in the development and use of geothermal technology and geothermal energy.

- o Just this year the 45-MWe proof-of-concept binary plant at Heber, California went into operation. It is the first binary plant over 10 MWe anywhere in the world and was sponsored as a joint U.S. government/industry project. This plant is expected to yield refinements in binary technology which will make use of the abundant moderate temperature geothermal resources around the world more efficient and economically attractive.

- o A major step forward was taken this year at DOE's Fenton Hill experimental site when the hydraulic connection between the two hot dry rock wells was successfully completed. The research and technology advances at this facility are helping to bring the hot dry rock resource to actualization as a viable economic component of our geothermal resource base. This work has been sponsored by DOE under a multilateral agreement with Japan and West Germany developed through the International Energy Agnecy.

- o The Salton Sea Scientific Drilling Project is at the leading edge of geothermal technology development. This project, which will commence drilling operations this month, is expected to yield valuable information which will enable us to tap the abundant energy contained in the hostile environment of deep, high-pressure, high-temperature geothermal resources and to convert those vast amounts of energy into useful applications. This project will also provide valuable information on mineral recovery from geothermal brines.

CORECT and Geothermal Energy

- o The Committee on Renewable Energy Commerce and Trade (CORECT) was established under the Renewable Energy Industry Development Act of 1983 (P.L. 98-370).

- o The goal of the CORECT is to increase the efficiency of the federal government in providing renewable energy export assistance to help to ensure the U.S. renewable energy industry maintains or stengthens its world leadership position.

- o Comprised of 14 agencies, the CORECT met for the first time on February 6, 1985. At this meeting, four major issues emerged which merit further examination. These areas -- education, market development assistance, trade policy and technical competitiveness -- were reviewed by subcommittees who reported their findings at the CORECT meeting in June at the RETSIE Conference.

- o DOE through its Geothermal Technology Division, has embarked on a number of initiatives such as the digest and Technology Transfer Catalog mentioned earlier, which complement and further the goals of CORECT.

OVERVIEW OF THE U.S. DEPARTMENT
OF ENERGY GEOTHERMAL PROGRAM

Dr. John E. Mock
Director, Geothermal Technology Division
U.S. Department of Energy

Good morning once again, ladies and gentlemen.

As we begin this 4th review of our own geothermal research and development program, we do so in the wake of the exciting reports on worldwide geothermal development presented to the International Symposium on Geothermal Energy just two weeks ago. While we are still the world leaders in developing this resource, we are confronted with some stiff competition from abroad. This competition is very welcome -- first, because we support and applaud increased use of geothermal energy by all countries endowed with the resource. Second, it serves to keep us on notice that, to remain in the forefront of technology economics and performance, we must proceed apace with the research and development program in which all of us are involved.

This program supports the goal of the Department of Energy to assure an adequate energy supply, at reasonable cost, composed of a balanced and mixed resource base of both conventional and renewable energy resources. Specifically, we in the Geothermal Technology Division aim to assist in building the technology base to enable the private sector to develop the various geothermal resource types. Our ultimate objective is to promote advancement of the state-of-the-art of geothermal technology thus increasing the availability of the United States' abundant geothermal resource as a viable alternative to fossil energy.

We at GTD see an appropriate Federal role in performing specific R&D tasks which have both near- and long-term implications. In formulating our R&D strategy, the key guideline is cooperation, not competition, with the private sector. We have several industry review panels to whom we present specific aspects of the program on a regular basis. These groups provide a forum to assure that our research is timely and allow us to work with industry to improve the technology base for use of geothermal energy in the near future. In the long term, we at GTD exercise prime responsibility for developing advanced technology for the use of nonhydrothermal resources such as geopressured brines, hot dry rock, and magma.

I now want to give you an overview of the Department of Energy's Geothermal Program, in the context of what is the appropriate Federal role in encouraging geothermal development. I will leave it to the individual project managers of the various activities to go into the technical details of their work in the sessions scheduled over the next two days. Besides the program overview, I will also discuss some changes which have been implemented in the management structure at DOE, and review the status of the Fiscal Year 1986 budget as it stands today.

In the past couple of months, the Conservation and Renewable Energy Programs of DOE have undergone a significant reorganization in order to streamline the management structure and better address the program priorities. This has affected the geothermal program in a number of ways. First, and most immediately obvious, is that the DOE Hydropower Program has been separated from the Geothermal Program and will be managed at the Office level in the Office of Renewable Technology. The former Geothermal and Hydropower Technologies Division, or GHTD, is now known simply as the Geothermal Technology Division.

Within GTD, the former management structure consisted of three Branches: Advanced Energy Systems; Technology Development; and Program Integration. This structure has been eliminated and all activities are handled directly at the Division level. For ease in program management, the programs have been split into two functional research areas. Referring to Figure 1, you can see the division of activities between Geothermal Geosciences Research and Geothermal Conversion Research. These do not replace the branches which were official management units with assigned chiefs. This is an informal program split designed to allow us at headquarters to manage the program along technical lines, grouping together research activities which employ similar technologies, regardless of resource.

The Geothermal Program embraces a two-pronged approach to technology development. One thrust is on hydrothermal resources where both near- and long-term research is being conducted to remove technical barriers to hydrothermal exploitation and to increase the economically recoverable resource base. The second thrust of the program is to increase the resource base with long-term R&D which will ultimately lead to the demonstration of the viability of other forms of the geothermal resource, specifically geopressured brines, hot dry rock, and magma.

One of the most important advances in the past year has been the successful connection of the two major boreholes at the hot dry rock test site at Fenton Hill, New Mexico. Drilling is continuing into the large fracture zone produced from the lower well to establish a significant flow circulation path. In collaboration with West Germany and Japan, we expect to complete the thermal loop next year and perform extensive testing to determine many of the operational parameters before installing a heat exchanger system for thermal drawdown testing. If this long-range research proves this technology to be economic and to have application in all hot dry

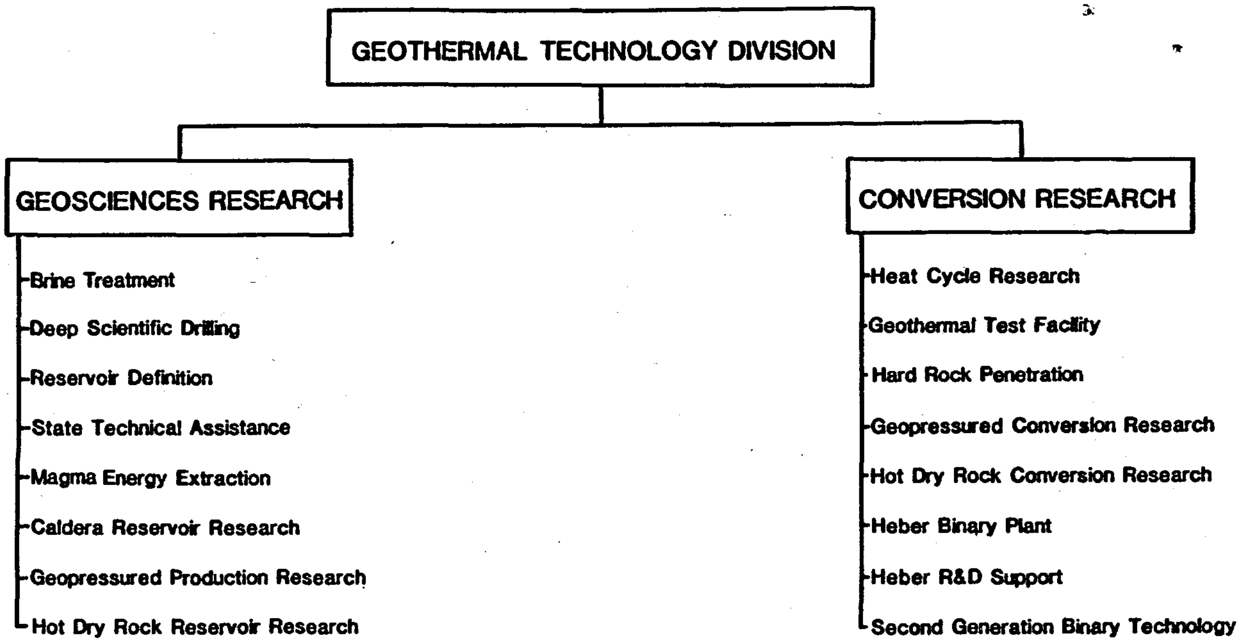

Figure 1: DIVISION ORGANIZATION

rock systems, the geothermal economic resource base will be increased substantially. The present magma program was started in FY 1984 to perform research and development on the technical feasibility of extracting usable energy from magma. We have narrowed our site selection for the eventual experiment in a major magma body to two primary candidates, both in California: the Long Valley Caldera, and Coso Hot Springs.

We are currently conducting extensive geophysical studies at those sites, in collaboration with the USGS and other interested groups. We are also investigating various materials for compatibility with magmas at temperatures about 1000°C. Research is being performed to study methods of energy extraction and to develop the necessary technology to drill into a magma body. This, like the hot dry rock program, is long-range research attempting to increase the usable geothermal resource base by showing the feasibility of extracting energy from geothermal resources other than from hydrothermal systems.

DOE's geopressured geothermal program has thus far provided us with the location and general characteristics of geopressured aquifers along the Texas and Louisiana Gulf Coast. Methane and thermal energy extraction experiments have been performed, and the technology is being improved. We are currently conducting long-term testing of the Gladys McCall and Pleasant Bayou wells. We are also beginning the installation of equipment to generate power in an experiment that is being cost-shared with the Electric Power Research Institute (EPRI) on the Pleasant Bayou well. Next year, we plan to: (1) run experiments at this site on total energy recovery with EPRI; (2) carry out experiments involving variable flow rates and pressure build-up to investigate the areal extent of various sandstone strata and locate the confining or leaking faults; and (3) model the hydrodynamic characteristics of the systems using the new data and the accumulated data of prior years testing.

There are a number of program areas which cross-cut the different types of geothermal resources. These are hard rock penetration, technology transfer, and the state assistance programs.

R&D tasks in hard rock penetration research are attempting to solve technical and economic problems related to geothermal well drilling and completion. In research which could have significant near-term impact, we are looking for ways to solve the critical problem of lost circulation in geothermal wells. New materials are being developed and tested in Sandia's Lost Circulation Test Facility. Many other efforts with potential near-term impact are underway to extend conventional oil and gas drilling technology to the higher temperatures experienced in the geothermal environment. These tasks include the development of high temperature electronics for logging tools, and the development of high temperature drilling fluids. Sandia has also recently begun to develop an "Advanced Geothermal Drilling System". This long-term project has the ultimate goal of reducing drilling costs for geothermal wells by a factor of two or more. The hard rock penetration research program is presented annually before an industry review panel which provides guidance in the direction of research and suggestions for areas of study which would be most effective in reducing the technical barriers related to geothermal drilling.

After almost a year of planning, discussion, and negotiation, the Geothermal Drilling Organization, or GDO, has come into being. This group has as its primary purpose the sponsorship of commercial adaptation and adoption of as-yet-under-utilized technology associated with geothermal drilling and completion. DOE has agreed to cost-share many of its projects where they require further development that will not be funded by industry alone. The first GDO project is the development of an acoustic borehole televiewer based on the prototype instrument successfully tested last year by Sandia.

Under the state technical assistance activity, we are providing assistance to several states where it is needed to assess as-yet-undeveloped, but promising, geothermal prospect areas. In addition, the technology transfer program of the Geo-Heat Center at the Oregon Institute of Technology is supported to provide assistance to those seeking to use lower temperature geothermal resources.

Technology transfer first became a line item in the budget last year and this approach was continued this year to emphasize dissemination of the results of DOE research and development programs through the Geothermal Resources Council seminars, workshops, and data management activities. As will be seen later, no funds are requested specifically for technology transfer in 1986, but technology transfer efforts will continue, as they have traditionally, as an integral part of each individual ongoing program.

Our hydrothermal research efforts are keyed for both long- and near-term goals in a number of areas. These are shown in Figure 2.

Brine Injection continues to be an area of risk and uncertainty, but work with tracers and the modeling of fluid migration is helping us to understand the behavior of injected fluid. We plan to complete the analysis of drift phenomena in the East Mesa injection backflow data, to perform injection tests in cooperation with one of the ongoing field development programs, and to develop and test additional tracers and geophysical monitoring instrumentation. We will continue the development of accurate particle monitoring devices, particle control techniques, and chemical conditioning methods to prevent adverse chemical reactions in the well and nearby injection zones. In addition, we plan to develop advanced well completion techniques to extend the useful life of injection wells, including methods of preventing casing-cement failures and preventing permeability degradation near the wellbore.

Reservoir definition also continues to be a critical area in our efforts to increase the geothermal resource base. In this program, we have field tested several fracture mapping and reservoir engineering techniques and completed initial modeling of the Los Azufres and Broadlands fields. We are renewing our cooperative agreement with Mexico which will now emphasize the reservoir at Los Azufres. We plan to do detailed modeling of these fields for correlation with well field data and to confirm the models and verify production potential. We plan also to perform research and evaluation of the capability of various surface and subsurface techniques to locate natural fracture systems so that they can be more effectively and efficiently targeted for drilling. Lawrence Berkeley Laboratory, the lead laboratory for this effort, has formed an industry review panel, like that of Sandia in hard rock penetration, to assist it in staying abreast of industry needs, priorities, and activities and to review the DOE program.

HYDROTHERMAL R&D AREAS

- Heat Cycle Research
- Materials Research
- Reservoir Definition
- Brine Injection
- Caldera Reservoir Investigation
- Salton Sea Scientific Drilling

Figure 2: HYDROTHERMAL RESEARCH

The heat cycle research program pursues both theoretical and empirical research, principally aimed at improving the efficiency of moderate temperature binary cycles. This reflects a primary goal of the program to develop a "second generation" binary system to make use of the widespread moderate temperature hydrothermal systems. Heat cycle research field experiments are carried out at the Heat Cycle Research facility, now located at the Geothermal Test Facility at East Mesa. We are currently conducting a methodical series of tests with various mixtures of hydrocarbons to determine the behavior of hear exchangers and turbines in supercritical and two-phase expansion cycles. In addition, we are continuing to evaluate submersible electric brine pumps for application to binary plant operations.

In our materials research program, we have been developing and testing non-metallic coatings for casings, liners, piping, and other components. In particular, we have field tested both polymer concretes and EPDM elastromers with great success. Next year we will investigate waste disposal techniques, high temperature cements, well casing liner materials, and innovative heat exchanger materials.

The Salton Sea Scientific Drilling Project (SSSDP) is a scientific research effort of DOE, the USGS, and the National Science Foundation to study the roots of the Salton Sea hydrothermal system in southern California's Imperial Valley. The program had its beginning within the Continental Scientific Drilling Program (CSDP) and is the first project of its type to specifically address issues related to thermal regimes beneath continental spreading zones and the genesis of ore forming minerals. Since its inception about a year ago and the subsequent contract between DOE and the prime contractor, Bechtel National, Inc., the SSSDP program has undergone downscaling due to funding limitations. Engineering aspects of the study have been given lower priority in favor of enhancing the scientific program to the degree possible. We still anticipate, however, that we will be able to complete a significant scientific study of the deep hydrothermal system beneath the Salton Sea. Drilling is slated to begin this month.

The purpose of the Cascades research program is to conduct research on the geothermal resources of the Cascades Volcanic Region in California, Oregon, and Washington. The objectives of the program are to stimulate development of the region's geothermal resources by making data publicly available, and to increase knowledge of both applicable exploration techniques and the depth required to penetrate the overlying cold groundwater system that masks and suppresses surface evidence of the underlying hydrothermal system. Work in the area includes geophysical exploration as well as the cost sharing of four deep thermal gradient wells. We are now in the process of negotiating cooperative agreements for the drilling of these wells. Two will be on the north and south flanks of the Newberry Caldera, a third in the Santiam Pass area, and the fourth in the Breitenbush-Clackamas area.

I hope that this overview of the geothermal program research areas has proven informative to those not familiar with it and has provided a sufficient background for the technical presentations to follow this afternoon and tomorrow.

Now I will give a brief overview of the Fiscal Year 1986 Budget as it stands today. Figure 3 lists the Department's Congressional Budget Request along with a summary of the marks of the House and Senate Appropriations Committees. As yet, we have not received notice of the results of the House and Senate conferees decision on the final budget to be submitted to the President.

The first two columns of Figure 3 list, by specific subactivity, the budget authorization for fiscal year 1985 and where we intend to spend the money requested for 1986. The House, in its deliberations, has added one million dollars to the total budget to be used for continuing the testing and monitoring of geopressured test wells. They have also directed that at least one million dollars of available funds be redirected to support the Salton Sea Scientific Drilling Program.

The Senate Appropriations Committee recommendation for fiscal year 1986 was $27.2 million, $2 million over the budget request and $1 million over the House allowance. The Senate recommen-

	FY 1985 APPROPRIATION	REQUEST	HOUSE MARK	SENATE MARK
HYDROTHERMAL INDUSTRIALIZATION	$990	$0	$0	$2,000
GEOPRESSURED RESOURCES	$5,400	$3,600	$4,600	$3,600
GEOTHERMAL TECHNOLOGY DEVELOPMENT	$24,429	$20,800	$20,800	$20,800
• HOT DRY ROCK RESEARCH	$7,500	$5,500	N/S	$7,500*
• MAGMA ENERGY EXTRACTION RESEARCH	$1,400	$4,500	N/S	N/S
• HARD ROCK PENETRATION RESEARCH	$4,400	$2,600	N/S	N/S
• HYDROTHERMAL RESEARCH	$9,729	$8,200	N/S	N/S
- Brine Injection Technology		(2,400)		
- Reservoir Definition Technology		(1,900)		
- Heat Cycle Research		(600)		
- Geothermal Test Facility		(200)		
- Materials Research		(400)		
- Caldera Reservoir Investigations		(2,000)		
- Salton Sea Scientific Drilling Project		(500)	(1,000)	(1,000)
PROGRAM DIRECTION	$1,025	$ 800	$ 800	$ 800
	$31,844	$25,200	$26,200	$27,200

* Plus $425 thousand for hot dry rock commercialization project.

N/S: Appropriation not specified in committee report.

Figure 3: FY 1986 BUDGET DATA ($000's)

SESSION I

Chairperson: John Mock, Director, Geothermal Technology Division
U.S. Department of Energy

dation includes $2 million for Hydrothermal Industrialization, of which $320,000 will be used to continue the state technical assistance programs, and $1.06 million for building retrofit work and pipeline construction for the Boise geothermal district heating system. The Senate agreed with the administration request for the Geopressured Program. They also concurred with the House recommendation that $1 million be redirected to the Salton Sea drilling project. The Senate has also recommended that $2 million be redirected, within available funds, to hot dry rock research to restore it to the fiscal year 1985 level. Finally, the Senate has also recommended that $425,000 be redirected for a hot dry rock project in the southern Rocky Mountains.

The House and Senate conferees are currently working on a compromise appropriations bill for submission to the President. Once the budget process is completed, we in the Division will have to determine, based on R&D priorities, how to redirect the available funds to abide by the dictates of Congress.

It has been a pleasure to present the DOE Geothermal Program to you today. I hope you enjoy the rest of our program.

STATUS OF U.S. GEOTHERMAL INDUSTRY

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ABSTRACT

Forces were at work in the early- to mid-1970's which pointed to a rosy future and the rapid development of the geothermal industry for the production of electric power. During the past ten years, the industry has seen a dramatic downturn. Utilities are not exercising options for new generation. As a result, the geothermal industry is going through a period of retrenchment and the names of the players are changing. The importance of current industry activities, a possible scenario for the near-term future of the industry during the rest of this century, and the need for additional work will be discussed.

INTRODUCTION

During the last week in August, I attended the second International Symposium on Geothermal Energy in Hawaii. The symposium was convened by the Geothermal Resources Council and was sponsored by several agencies, including the U. S. Department of Energy. Representatives from the geothermal industry made presentations on subjects ranging from drilling and geology through power production and direct use, to economics and project management. The speakers came from the United States and no less than 18 other countries. Attendance at the symposium was just under 700, not including spouses and other guests.

I came away from that symposium with the clear feeling that the geothermal industry was alive and well. It is in good shape technically and is growing at a rapid rate overseas. But it is a different and leaner industry from the one that existed just a few years ago. Here in the United States, however, it faces a new set of challenges and opportunities. How it will respond to those challenges and, perhaps more importantly, take advantage of the opportunities remains to be seen.

I would like to focus my remarks on that group within the geothermal industry whose goal is to use this resource for electric power production in the United States. The players might be utilities that own and operate power plants, or third parties that sell their product to utilities. This may be a parochial approach, but I believe that, if we can penetrate this market, the fallout from our success will benefit the entire geothermal industry.

EARLY DAYS

In the early- to mid-1970's, events occurred that had a profound impact on the geothermal industry. At that time, many utilities in the southwest United States were heavily dependent on oil for the production of electric energy. Their version of resource diversification, if they had such a goal at all, was to commit to large, central station nuclear, coal, and oil projects. Geothermal power production simply did not fit into their resource plans for at least three reasons:

1. Oil was cheap, about $2.50 a barrel.

2. New nuclear and coal plants were projected to produce power at lower costs than oil.

3. Most importantly, the technology for power production from geothermal resources had not been demonstrated. Except for The Geysers in northern California, the utility industry had no data to use for making informed commitments to geothermal power development and production.

By the mid-1970's, the utilities had changed dramatically. The oil crisis caused oil prices to soar to as high as $40.00 or more per barrel. Unfortunately, there were no more Btu's in that barrel than the one we paid $2.50 for. Occurring at the same time as the rising oil prices was a dramatic increase in inflation rates. This drove up the cost of all new utility industry generation, either planned or under construction. Within a matter of months what had been an orderly, if not imaginative, approach to new generation fell into complete disarray.

The utilities' response was to explore alternatives to nuclear, coal, and oil plants. Regulatory commissions helped this trend along by ordering the utilities to pursue alternative energy options more vigorously. For utilities in the Southwest, geothermal was an obvious choice. It was an optimistic period for the geothermal industry. Utilities were turning to geothermal power production in a big way and the nuclear, coal, and oil "competition" did not present much of a challenge.

The net result of these developments was stepped up activity in the geothermal industry. The pace of exploration and reservoir evaluation quickened. A number of power plant projects were studied and pursued. The future of the geothermal industry looked bright indeed. Unfortunately, the geothermal industry was not yet prepared to offer a truly viable generation option using hot water resources to the electric utilities.

CURRENT STATUS

More recently, during the past five years, the pendulum has swung in the opposite direction. Today, the geothermal industry is going through a period of depression and upheaval. Four factors have been largely responsible for the present situation:

1. Oil prices have leveled off and, in fact, have been significantly reduced. At the same time, the overall inflation rate is down dramatically. As a result, the competition (usually measured in terms of a utility's avoided cost) is much more difficult to meet.

2. Conservation, a reaction by customers to high electric energy costs, has slowed the rate of load growth. Utilities in the Southwest, therefore, do not need new generating capacity regardless of the source of the energy.

3. Coal generation has taken a large share of the market, particularly in the eastern United States.

4. Mergers, takeover attempts, and reorganizations of the resource developers have diverted their attention from pursuing geothermal development.

We are now experiencing a slowdown in the growth of the geothermal industry. Drilling and reservoir evaluation in the United States has slowed. Many utilities have dropped, scaled down, or deferred plans to use geothermal energy to meet future load demands. These trends are causing the demise of some smaller, perhaps marginal, members of the geothermal industry. Participants with adequate financial resources are still pursuing their geothermal goals, but it is questionable how long some of them will continue.

THE FUTURE

In the near-term, say the next five years, I expect a continued shakeout of participants in the geothermal industry. The result will be a stronger and leaner industry. Continued development at The Geysers is probable. On the plus side, we will also see a few small wellheads and large power plants come on line at hot water resources. These will include units employing both flash and binary technologies. Utilities will closely monitor the performance of these units, but will not be making commitments for new generation, whether constructed or purchased by them, much before 1990.

RECOMMENDATIONS

So far, this summary sounds like the voice of doom, but the thought I would like to leave you with is far more upbeat. I believe the geothermal industry has an unprecedented opportunity during the rest of this decade to position itself for a marketplace that will be wide open in the 1990's. Most utilities in the Southwest are predicting a need for new generating capacity in this time frame. By the end of this decade, I predict utilities will be scrambling to identify and commit to new generation. Some of the criteria they will be using to make their decisions will be:

1. There must be sufficient hard cost data available for evaluation by utilities, which includes reservoir and power plant capital, maintenance, and heat costs.

2. The reliability of the technology must be demonstrated here in the United States.

3. Permitting and environmental issues must be identified and, if possible, resolved.

4. Water for cooling must be available or easily obtained.

5. Transmission to the utility's load center must either be available or easy to obtain. Few geothermal projects can justify the cost of new major transmission lines.

During the next five years, we in the geothermal industry have an opportunity to go a long way toward satisfying each of these criteria.

Obviously, the geothermal industry must place in service the units now planned or completed. Cost and operating experience must be made available, in terms and details that are acceptable, to both utilities and third parties who would build power plants. No one, least of all the geothermal industry, will be well served if this information is incomplete or misleading. Even if the costs are higher than nuclear or coal options, geothermal generation has other advantages that may make it very attractive to the utilities in the 1990's. These advantages include a favorable regulatory climate, short lead time, and the ability to closely match new generating capacity to load growth.

Now is the time for the geothermal industry to look at the permitting issues that could be raised if our candidate geothermal reservoirs are to be developed. Baseline studies on such issues as environmental impacts and land use could be performed. This work is not too expensive and is useful in identifying institutional risks for a project. If these studies are already performed, the lead time for completing a project can be reduced. Such data could also serve as the basis for obtaining, in advance, permits and zoning changes to expedite a project.

Another aspect of the permitting process that could be addressed in advance is the entitlement of an adequate cooling water supply for a proposed project. Options for obtaining and delivering cooling water to candidate reservoirs could be identified and evaluated. Few geothermal sites in the Southwest have cooling water readily available, and obtaining assured supplies can be a long, arduous effort.

Utilities have generally done a masterful job in avoiding potential geothermal sites when deciding where bulk transmission systems would be located. In fact, lack of readily available transmission lines may be the largest single impediment to rapid geothermal development. Obtaining permits and constructing bulk transmission lines can be as difficult and costly as these activities are for major power plants. The geothermal industry can help utilities make the decisions we would like them to make by identifying transmission options and helping to obtain the best option.

Finally, I would like to mention some specific RD&D work the geothermal industry should concentrate on to help satisfy the criteria I mentioned earlier. All of this work affects the reliability and costs of geothermal power production.

1. The geothermal industry needs to continue to improve its ability to evaluate and predict reservoir performance. Perhaps more importantly, we need to provide utilities with evidence of the reliability of our evaluations and predictions based on actual in-the-field operating experience.

2. We need to continue to reduce the costs of developing and operating field facilities. This includes the reduction of drilling costs and the evolution of more efficient and reliable downwell pumps.

3. Ways should be found to reduce power plant capital and operating costs. Even at 50 megawatts, we are on a fairly steep point of the "economy-of-scale" curve. As far as operating costs are concerned, the infrastructure required for a 50-megawatt plant is almost as large and expensive as what is required for a 500-megawatt plant.

CONCLUSION

In conclusion, I believe the next five years can be among the most exciting and productive the geothermal industry has ever seen. We can take advantage of this period to obtain and provide the answers to questions we know will be asked. If we do the job well, utilities will be beating paths to our door. We might not be the only game in town, but we can certainly be the best.

GEOSCIENCES RESEARCH IN DOE - 1985

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Office of Basic Energy Sciences
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Washington, D.C. 20545

As we see from a 1980 joint study by NSF and the Department of Education (Fig. 1), the earth sciences are tagged for substantial growth during this decade. The Department's technology needs depend on the earth sciences. DOE's need for fundamental research in the geosciences is implicit in the fact that all energy resources are found in the earth and the sun; all energy wastes are returned to the earth and its atmosphere. The Geosciences Program of the Office of Basic Energy Sciences has as its objective to support and provide basic, long-range research in the earth and near-space sciences in areas relating to the energy and military missions of the DOE (Fig. 2). Emphasis is given to the quantitative, analytical approach which leads, we believe, to the development of predictive understanding in the geosciences.

To qualify for support in the Geosciences Program, proposals must satisfy at least two criteria: scientific excellence and relevance to the DOE mission. Some of the areas of relevance are shown in Fig. 3. and some specific examples of relevant scientific problem areas to the technology interests of DOE are given in Fig. 4.

The support of basic, energy-related geoscience research was started under AEC in the latter half of the 1960's with the recognition within the Division of Physical Research that much of AEC's activities were dependent upon geoscience information. AEC management was not strongly supportive of the Geosciences but did permit the inclusion of relevant long-range research projects in the geosciences to be included in the activities of the Physics and Mathematics research program.

With the imposition of the Middle East oil embargo, it was widely recognized that the energy responsibilities of AEC would have to be broadened beyond nuclear to include alternate energy resources such as geothermal and solar as well as oil, gas and coal. Along with this recognition came a greater emphasis on the Geosciences in the thinking relating to the evolving research structure - a recognition that has slowly been accepted by energy-research management that the Geosciences were comparable in importance to nuclear physics and chemistry in the research objectives of the AEC. Thus, as shown in Fig. 5, substantial increases were made in the Geoscience research budget of OBES in interval FY 1974-76. However, the momentum for growth in the Geosciences was not maintained beyond FY 1976. Although the percentage fiscal year) were somewhat above the average OBES percentage increase, the small size of the total Geoscience effort precluded any significant change in the balance of the energy-related research efforts among the disciplines supported by OBES.

As shown in Fig. 6, the balance of effort among the four B&R categories given on the top half of the figure indicates roughly comparable support to the first three categories and substantially less to solar-terrestrial/atmospheric interactions. There are two reasons for this - the first being the relatively small Geoscience research component needed for solar energy as compared with other energy resources and the second being the establishment of a separate office within OBES to handle the CO_2 problem although the problem first identified under the OBES Geosciences Program, i.e., the NAS/NRC Geophysics Study Committee). Also, problems dealing with the troposphere and troposphere-biosphere interactions have traditionally been handled under OHER, Ecological Research Division.

Our areas of program emphasis are given in the bottom half of Fig. 6. Note that the top half and bottom half of the figure are not additive. They are merely two different ways of looking at the same funds. Note also that continental scientific drilling is the largest area of program emphasis. This is an area where the DOE's Geosciences research program has taken the lead in helping to establish a truly cooperative national continental scientific drilling program by working closely with the U.S. Geological Survey and the National Science Foundation. It is also an area calling for substantial increases in funding if it is to move forward at a reasonable pace toward achieving its scientific goals.

Looking for a moment at some achievements, or accomplishments, of the Geosciences research effort, the first two listed in Fig. 7 are by now well known to the geothermal community. Less well known, perhaps, are the last two. The first experiment is shown in Fig. 8 and was carried out by Professor Syun-Ichi Akasofu, of the Geophysical Institute of the University of alaska. Professor Akasofu's work deals with the aurora borealis and magnetic substorms. Professor Akasofu reasoned that the changing magnetic fields associated with magnetic substorms should induce electric currents at the surface of the earth. Since the oil pipeline which runs between Prudhoe Bay and Valdez,

FIELDS WITH OVER 40% GROWTH IN NEXT DECADE

PSYCHOLOGY	STATISTICS
EARTH SCIENCES	ECONOMICS

FIELDS WITH LESS THAN 10% GROWTH

ATMOSPHERIC SCIENCE	MATHEMATICS
PHYSICS	ASTRONOMY

(FROM "SCIENCE AND ENGINEERING EDUCATION FOR THE 1980'S AND BEYOND." NSF — DEPT. OF EDUCATION 10/80).

EAR 81-1038
3-24-81

(FIG. 1)

GEOSCIENCES RESEARCH OFFICE OF BASIC ENERGY SCIENCES

OBJECTIVE

TO SUPPORT AND PROVIDE BASIC, LONG-RANGE RESEARCH IN THE EARTH AND NEAR-SPACE SCIENCES IN AREAS RELATING TO THE ENERGY AND MILITARY MISSIONS OF THE DOE. EMPHASIS IS ON THE ANALYTICAL APPROACH AND THE DEVELOPMENT OF PREDICTIVE UNDERSTANDING

PEOPLE INVOLVED

136 SCIENTISTS PLUS A ROUGHLY EQUAL NUMBER OF STUDENTS

		SMY
— 01	GEOLOGY, GEOPHYSICS AND EARTH DYNAMICS	35
— 02	GEOCHEMISTRY	42
— 03	ENERGY RESOURCE RECOGNITION, EVALUATION AND UTILIZATION	49
— 04	ATMOSPHERIC — SOLAR/TERRESTRIAL	10

(FIG. 2)

GEOSCIENCES
DOE RELEVANCE

- RESOURCE IDENTIFICATION
- EVALUATION OF RESERVES
- EXTRACTION OF RAW MATERIALS (EX- AND IN-SITU)
- CONVERSION OF RAW MATERIALS
- TRANSMISSION AND CONSUMPTION OF ENERGY
- NEED FOR PREDICTIVE UNDERSTANDING
- ISOLATION OF RADWASTES

(FIG. 3)

TYPICAL BES GEOSCIENCE AREAS RELATED TO DOE TECHNOLOGIES

MULTI-TECHNOLOGY
- ROCK-FRACTURE PHYSICS
- PHYSICS & CHEMISTRY OF EARTH SUBSTANCES
- MODELING NATURAL PROCESSES AND SYSTEMS
- GEOPHYSICAL REMOTE SENSING
- CONTINENTAL DRILLING

FOSSIL
- ORIGIN & MIGRATION OF DEEP MARINE PETROLEUM
- COALIFICATION FATES OF MINOR ELEMENTS
- HIGH TEMPERATURE/PRESSURE PROPERTIES OF NATURAL GAS

SOLAR
- SOLAR INFLUX DISTRIBUTION: SPACE, TIME, SPECTRUM
- GEOMAGNETIC SUBSTORM
- SOLAR VARIATIONS VERSUS CLIMATE CHANGES
- ENERGY TRANSPORT IN SPACE PLASMAS

ENV. & SAFETY
- TOXIC RELEASES FROM ROCKS IN ENERGY-RELATED PROCESSES
- SEISMIC STUDIES

GEOTHERMAL
- THERMODYNAMIC PROPERTIES OF SOLUTIONS & MINERALS
- CHEMICAL EFFECTS ON RESERVOIR STABILITY
- NATURAL ROCK STRESS
- MAGMA BODY LOCATIONS & EVALUATION
- HYDRODYNAMICAL MODELING

CONSERVATION
- GEOLOGIC STABILITY OF NATURAL ENERGY STORAGE

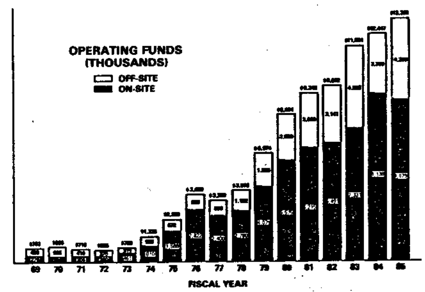
FACILITIES
- SITE USE-LIMITING EARTH MATERIALS & PROCESSES

NUCLEAR
- ORIGIN OF DEEP-SEATED U/TH DEPOSITS
- GEOLOGIC DISPOSAL OF RADIOACTIVE WASTES
  - CHEMICAL MIGRATION OF ELEMENTS
  - MECHANICAL PROPERTIES OF ROCKS
  - ROCK HOSTS
  - CONTINENTAL DRILLING

NATIONAL SECURITY
- ROCK EQUATION OF STATE UNDER TRANSIENT HIGH T & P
- ROCK PROPERTIES IN LONG-DISTANCE SEISMIC DETECTION
- SEISMOLOGICAL STUDIES

(FIG. 4)

GEOSCIENCES
HISTORICAL SUMMARY



(FIG. 5)

U.S. DEPARTMENT OF ENERGY
OFFICE OF BASIC ENERGY SCIENCES

GEOSCIENCES RESEARCH (OPERATIONS, $ THOUSANDS)

	FY 84 (ACTUAL)	FY 85 (ESTIMATE)
GEOLOGY, GEOPHYSICS & EARTH DYNAMICS	3,404	3,466
GEOCHEMISTRY	4,081	4,346
ENERGY RESOURCE RECOGNITION, EVALUATION AND UTILIZATION	4,201	4,785
SOLAR-TERRESTRIAL/ATMOSPHERIC INTERACTIONS	914	915
TOTAL	12,600	13,512
CONTINENTAL SCIENTIFIC DRILLING	3,219	3,459*
ROCK MECHANICS	975	772
ORGANIC GEOCHEMISTRY	838	718
BASIC STUDIES RELATING TO ENERGY WASTES ISOLATION	1,987	2,034

*NOT INCLUDING SSDP.

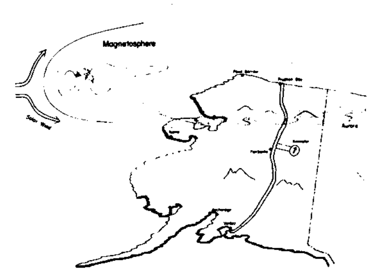
4/15/85

(FIG. 6)

SIGNIFICANT GEOSCIENCE ACCOMPLISHMENTS

- DEMONSTRATED SCIENTIFIC FEASIBILITY OF MAGMA AS AN ENERGY RESOURCE. NOW PURSUED UNDER GEOTHERMAL PROGRAM.
- FIRST LEGITIMATE FUNDING FOR HDR GEOTHERMAL
- DEMONSTRATED INDUCED CURRENTS IN ALASKAN PIPELINE FROM MAGNETIC SUBSTORMS
- SHOWED $\sigma_{T_{HIGH}} \gg \sigma_{T_{LOW}}$ FOR OILSHALE — PROVING FEASIBILITY OF REMOTE EM MONITORING OF BURN FRONT FOR IN-SITU RETORTING

(FIG. 7)



Electric Currents in the Trans-Alaska Pipeline Induced by Magnetic Storms
University of Alaska Project

(FIG. 8)

magnetic substorms might be expected to induce electric currents in it. Akasofu measured these currents and showed that such currents sometimes reach as much as 200 amperes and thus would represent a source of corrosion where the pipeline enters and leaves the earth. The information was made available to the Alyeska consortium who have put their engineers to work taking corrective action (e.g., grounding straps, etc.).

The second discovery, for which Dr. Al Duba of DOE's Lawrence Livermore National Laboratory is being awarded the Alexander von Humboldt award, is that the electrical conductivity of oil shale during retorting is a billion times greater than its value before or after retorting. Because highly conductive material inside insulators can readily be detected with radio waves, the retorting zone of an underground body of oil shale may be mapped remotely (Fig. 9).

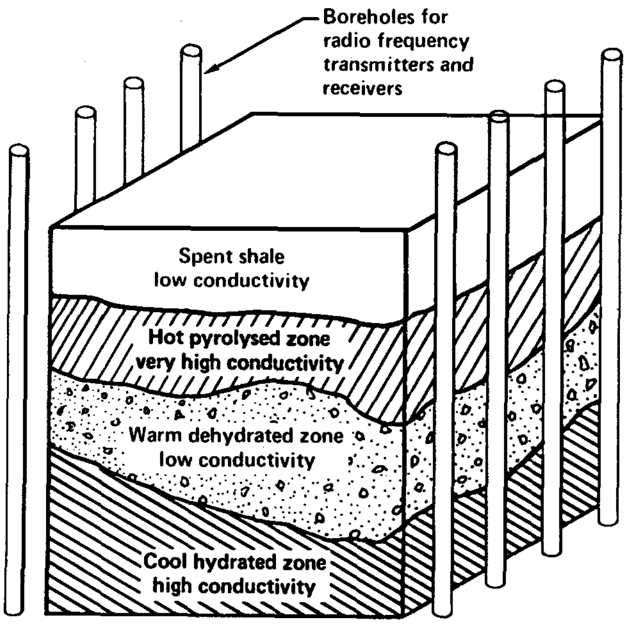
Let us turn now to continental scientific drilling, the largest area of program interest in the Geosciences Research Program. A brief chronology of events leading to the situation as it exists today is shown in Fig. 10. DOE involvement in continental drilling began in 1974 under ERDA. At this time, the Geosciences program was in its infancy and there were very few geoscientists in the Agency. Gene Shoemaker (USGS, Flagstaff, AZ) came to Washington to report to the various Federal agencies on the outcome of the Workshop on Continental Drilling held in Albuquerque, N.M., in June of that year. As a member of the FCCSET Committee on Solid Earth Sciences, I discussed the matter with the Committee and an ad hoc panel was established, chaired by Dallas Peck (the present Director of the USGS) to work out a suitable plan for a continental drilling effort for scientific purposes to be conducted with the support of the Federal government. The recommendations of that panel, issued in April, 1977, include the general plan for implementing a program of continental scientific drilling that is in place today, now backed up by a formal interagency accord.

In terms of funding priority, continental scientific drilling lost out to the Deep Sea Drilling Program in the Carter Administration but we in DOE succeeded in putting in place within the Geosciences research program of DOE a base program to provide a foundation for a National continental scientific drilling effort. Research starting with a workshop at the Los Alamos National Laboratory in 1978, sponsored by the National Academy of Sciences and with funds kindly provided to OBES by the Geothermal Energy Division of DOE. The report of this workshop has become the "bible" for the development of the U.S. program. The following year (1979) we took our first halting step into continental scientific drilling with OBES Geosciences funding of a computerized drill-hole information unit at the Lawrence Livermore National Laboratory. For two years running prior to FY 1979, continental drilling was included in our Geoscience budget requests, but each time we had to cancel out due to insufficient funding increments. I felt strongly that we should not attempt to develop a continental scientific drilling program in DOE at the expense of our other Geoscience research activities which broadly suport the DOE mission. Each year after FY 1979, further steps were taken to put in place the elements of a scientific drilling program based on the concept that "the science must lead the drill."

In 1980, a consortium of the three weapons laboratories and LBL undertook a comparative site assessment of the various thermal regimes site listed in the report of the 1978 workshop. The report of this consortium, "Comparative Site Assessment of Five Potential Sites for Hydrothermal-Magma Systems" (DOE/TIC-11303), Nov. 1980, was made available to the Department of Energy, the Continental Scientific Drilling Committee (NAS/NRC) and to the general public. From this document and from further studies conducted by the CSDC's Thermal Regimes Panel, we have now come to focus upon three study areas: the Salton Sea Geothermal Area, CA; the Valles Caldera in New Mexico; and the Long Valley/Inyo Domes-Mono volcanic complex in CA.

The Salton Sea Drilling Project, an effort spearheaded by Professor Wilfred Elders of the University of California, Riverside, CA, was first proposed to the CSDC and endorsed by them in 1982 and, again through the efforts of Professor Elders, funded by the Congress through the DOE Division of Geothermal and Hydropower Technology, in 1983. Unfortunately, no additional funding was provided for the science associated with the SSSDP. Nevertheless, DOE (Geosciences Program), NSF and USGS agreed to reserve about $500,000 each for the support of the science. With the 3 agencies working closely together, some 37 projects have been funded to carry out the science on the SSSDP and various support services for the science provided. The hole is scheduled for "spud-in" in October 1985.

A "3-DIMENSIONAL" VIEW OF AN IN-SITU OIL SHALE RETORT IS POSSIBLE USING ELECTRICAL CONDUCTIVITY STUDIES FUNDED BY OBES



(FIG. 9)

U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM
BRIEF CHRONOLOGY

1964 "DEEP DRILLING" IN NAS-NRC REPORT *SOLID EARTH GEOPHYSICS — SURVEY AND OUTLOOK*

1965 INTERNATIONAL UPPER MANTLE COMMITTEE SYMPOSIUM ON DRILLING FOR SCIENTIFIC PURPOSES, OTTAWA, CANADA

1973 "DRILLING FOR SCIENTIFIC PURPOSES" IN NAS-NRC REPORT U.S. PROGRAM FOR THE *GEODYNAMICS PROJECT — SCC^E AND OBJECTIVES*

1974 WORKSHOP ON CONTINENTAL DRILLING, GHOST RANCH, ABIQUIU, NEW MEXICO

1977 RECOMMENDATIONS OF THE PANEL ON CONTINENTAL DRILLING OF THE FCCSET COMMITTEE ON SOLID EARTH SCIENCE

1978 WORKSHOP ON MAGMA/HYDROTHERMAL DRILLING AND INSTRUMENTATION, ALBUQUERQUE, NEW MEXICO

1978 WORKSHOP ON CONTINENTAL DRILLING FOR SCIENTIFIC PURPOSES, LOS ALAMOS, NEW MEXICO

1979 DOE CONTINENTAL SCIENTIFIC DRILLING PROGRAM STARTED IN OFFICE OF BASIC ENERGY SCIENCES, DOE

1979 FIRST FEDERAL GOVERNMENT DRILL HOLE INVENTORIES PRFPARED BY LLNL

1979 TASK GROUP ON IMPLEMENTATION OF THE RECOMMENDATIONS OF THE NAS-NRC REPORT CONTINENTAL SCIENTIFIC DRILLING PROGRAM

1980 "DRILLING FOR SCIENTIFIC PURPOSES" IN NAS-NRC REPORT GEODYNAMICS *IN THE 1980's*

(FIG. 10a)

U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM
BRIEF CHRONOLOGY
(CONTINUED)

1980 CONTINENTAL SCIENTIFIC DRILLING COMMITTEE ESTABLISHED AT THE NAS-NRC

1980 *FIRST CSDP "HOLE OF OPPORTUNITY"*: NORTHERN ILLINOIS

1980 COMPARATIVE SITE ASSESSMENT MAGMA/HYDROTHERMAL SYSTEMS BY FOUR DOE LABORATORIES SNL, LANL, LLNL AND LBL

1981 SITE STUDIES BEGUN AT VALLES CALDERA

1982 SITE STUDIES BEGUN AT LONG VALLEY/MONO CRATERS

1982 SALTON SEA PROPOSED "HOLE OF OPPORTUNITY"

1983 START OF DOE SHALLOW DRILLING PROGRAM AT VALLES, LONG VALLEY AND SALTON SEA

1983 ESTABLISHMENT OF DOE GEOSCIENCES RESEARCH (GRDO) DRILLING OFFICE

1983 INITIATION OF INFORMATION BASES FOR VALLES, LONG VALLEY AND SALTON SEA

1983 BACA DATA BASE

1983 CONGRESS PROVIDES FUNDS TO DRILL SALTON SEA HOLE

1983 OBSIDIAN DOME, MONO CRATERS, CALIFORNIA — DRILLED AND CORED THROUGH FLOW

1984 DOE, USGS AND NSF SIGN INTERAGENCY ACCORD ON CONTINENTAL SCIENTIFIC DRILLING, FORMALLY ESTABLISHING A COOPERATIVE INTERAGENCY PROGRAM

1984 CONGRESS APPROVES RESOLUTION ENDORSING THE CONTINENTAL SCIENTIFIC DRILLING PROGRAM (S. RES. 439; SECT. 323 P.L. 98-473)

(FIG. 10b)

U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM
BRIEF CHRONOLOGY
(CONTINUED)

1984 INTERNATIONAL CONFERENCE ON CONTINENTAL SCIENTIFIC DRILLING, TARRYTOWN, N.Y.

1984 DRILLED AND CORED MAGMA CONDUIT OF OBSIDIAN DOME ERUPTION AT 55° TO HORIZONTAL (624m)

1984 DRILLED AND CORED INTRUSIVE DYKE BETWEEN OBSIDIAN DOME AND GLASS CREEK FLOWS. 60° SLANT HOLE, 829m DEPTH

1984 SHALLOW HOLE DRILLING STARTED AT SALTON SEA TO DEFINE BOUNDARIES OF GEOTHERMAL ANOMALY (20 HOLES)

1985 NSF SELECTS OPERATIONS/MANAGEMENT CONTRACTOR FOR ITS PART OF CSDP (DOSECC, INC.)

1985 FIRST WRITTEN SUPPLEMENT TO INTERAGENCY ACCORD SIGNED DEFINING THE ACTIVITIES WHICH CONSTITUTED THE U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM DURING FISCAL YEAR 1984

1985 HOUSTON WORKSHOP TO DEVELOP NSF PLAN FOR CSDP

1985 BECHTEL CORP. SELECTED AS CONTRACTOR FOR SSSDP HOLE. SCIENCE PLAN FUNDED BY DOE, NSF AND USGS

1985 DOE CORE REPOSITORY OPENED AT GRAND JUNCTION, COLORADO FOR CSDP CORES, SAMPLES AND LOGS. PROTOCOL ISSUED FOR CORE AND SAMPLE HANDLING

(FIG. 10c)

Two important events took place in 1984:

(1) At the initiative of the DOE Geosciences Program, an Interagency Accord on Continental Scientific Drilling was developed jointly by DOE, NSF and USGS and signed by the Director of Energy Research, DOE, the Director of the National Science Foundation and the Director of the U.S. Geological Survey in April 1984. This accord provides the formal framework for the operation of the U.S. Continental Scientific Drilling Program and defines in rather general terms the interests of the three agencies in this activity.

(2) At the initiative of Senator Larry Pressler, the Congress approved and passed into law a resolution endorsing the Continental Scientific Drilling Program (S. Res. 439, Sect. 323, P.L. 98-473). This resolution has been most helpful in giving helped give the modest but developing efforts of DOE, NSF and USGS credibility and a degree of acceptance they had not previously experienced.

DOE drilling efforts in the CSDP were begun in 1983 with the establishment of the DOE Geosciences Research Drilling Office (GRDO) at the Sandia Laboratories, N.M., and the start of DOE shallow drilling programs at the Valles Caldera, Long Valley and the Salton Sea. Four holes of less than 1 km each (i.e., shallow holes) have been drilled, 3 at Inyo Domes, CA and one at the Valles Caldera, NM. In addition, some 17 heat-flow holes are to be drilled near the boundaries of the Salton Sea KGRA and several more are being considered for FY 1986.

Fig. 11 outlines the objectives of the DOE part of the U.S. program in CSD. As in other areas where the Department supports basic research, suitability for DOE support is based on three major factors: scientific excellence, relevance to DOE mission and the availability of funds. The funds provided for CSD during the 7 years it has been supported by OBES Geosciences have grown as shown in Fig. 12, to nearly a third of the Geosciences Program. DOE management has not provided funding to the OBES Geosciences to permit drilling at greater depths (i.e., > 1 km). However, there is reason to hope that the national plan called for by the Congress will stimulate sufficient funding to permit deeper drilling.

The coordination of CSD efforts among the agencies (Fig. 13.) is carried out by the CSD Interagency Coordinating Group, established by the Interagency Accord on Continental Scientific Drilling. In view of the efforts by DOE and NSF to put in place suitable operational frameworks for their respective continental scientific drilling efforts (Fig. 14 for DOE and DOSECC for NSF), it was decided to terminate Federal support for the NAS/NRC Continental Scientific Drilling Committee (CSDC). The CSDC has done an excellent job of helping to stimulate a national continental scientific drilling program. Now that the appropriate apparatus is in place for the efforts of the various cooperating agencies, it is appropriate to replace the CSDC with the ICG and the various internal agency operational frameworks. As the agency systems get into operation, such coordination as was done by the CSDC may now be carried out within the cooperating agency programs.
Although the thermal regimes areas currently being studied under the DOE effort are those shown in Fig. 15, there are other potential thermal regimes sites for continental scientific drilling (Fig. 16) that may develop as the program matures. Continental scientific drilling is not a fixed or static effort and can be expected to change as the program evolves. The shallow drilling program at Long Valley may be drawing to a close this year or next, at least temporarily; thought is now being given to the development of a drilling plan to address the next phase beyond the shallow hole drilling. The current status of the scientific drilling activities at the SSSDP and the accomplishments at Long Valley are given in Fig. 17 and 18. We can look forward to a productive year at the Salton Sea and Long Valley in FY 1986 and hope that we will be able to solve the difficult technological problems we will be facing as we cross the 300 degree C isotherm at the Salton Sea.

In summary (Fig. 19), the Geosciences constitute a key area of science of broad importance throughout the DOE. The accomplishments of the Geosciences program have impacted a number of areas of energy technology and, indeed, have added a new energy resource (magma). Of the various geoscience initiatives, continental scientific drilling is the largest and most important. It is an area of research of high long-term relevance to DOE, especially in the area of thermal regimes. Other initiatives, such as chemical migration in the earth's crust, organic geochemistry and rock mechanics are also highly relevant to energy, and care must be taken to assure a strong, balanced effort throughout the Geosciences program of OBES so that the overall effort is not unduly distorted.

OBJECTIVE OF DOE/OBES CSDP

1) STUDY ROOTS OF HYDROTHERMAL SYSTEMS AND MINERAL DEPOSIT PROCESSES

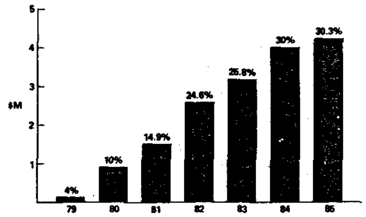
2) HOLES OF OPPORTUNITY — FE, NE, ONWI, GEOTHERMAL AND MILITARY

3) SUPPORT THE NATIONAL PROGRAM
- THERMAL REGIMES
  BASEMENT STRUCTURES
  MINERAL RESOURCES
  EARTHQUAKES
- DRILLING, LOGGING AND INSTRUMENTATION

- *AREAS OF DOE/OBES EMPHASIS*

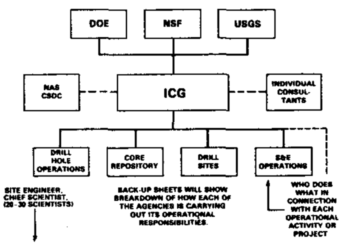
(FIG. 11)

CSDP FUNDING: 1979-85 DOE/OBES
(% of DOE GEOSCIENCES PROGRAM BUDGET)



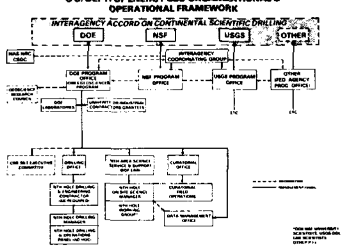
(FIG. 12)

CSDP ORGANIZATIONAL SCHEME



(FIG. 13)

U.S. DEPT. OF ENERGY CSD ORGANIZATIONAL & OPERATIONAL FRAMEWORK



(FIG. 14)

CSDP: THERMAL REGIMES STUDY AREAS

— LONG VALLEY/MONO

— SALTON TROUGH

— VALLES CALDERA

(FIG. 15)

DOE/CONTINENTAL SCIENTIFIC DRILLING PROGRAM
FY 1986 PLANS

- LONG VALLEY, CALIFORNIA
  — CRUSTAL OBSERVATORY (TARGET DEPTH 2500 FT.)
  — INYO DOMES DRILLING (T.D. 3300 FT., 67° FROM HORIZ.)
  — SHADY REST (T.D. 1500 FT.)
  — INTEGRATION AND SYNTHESIS OF MULTI-SOURCE SEISMIC *DATA SET INTO 3-D MODEL*
- SALTON SEA
  — SALTON SEA SCIENTIFIC DRILLING PROJECT (T.D. 300°C + 6000 FT.)
  — SHALLOW HEAT-FLOW HOLES (T.D. 250 FT. BELOW SEA FLOOR)
- VALLES CALDERA
  — SULPHUR SPRINGS DRILLING (T.D. 1650 FT.)
- OTHER POTENTIAL THERMAL REGIMES SITES
  — KATMAI, YELLOWSTONE, CASCADES, YOUNG CONTINENTAL BASINS (?)

(FIG. 16)

GEOSCIENCES RESEARCH
OFFICE OF BASIC ENERGY SCIENCES
SALTON SEA SCIENTIFIC DRILLING PROGRAM

OBJECTIVE. TO PROBE THE ROOTS OF A HYDROTHERMAL SYSTEM IN A TECTONICALLY RIFTING REGION

FTD ROLE. ENGINEERING AND LOGISTICS
— SCOPING, SITE PREPARATION, DRILLING, CORING, FLOW TESTS

BES/GEOSCIENCES. SCIENCE OPERATIONS (IN CONCERT WITH NSF AND USGS) — GEOCHEM, PETROLOGY, GEOPHYSICS, BIO-ORGANIC, *SCIENCE-RELATED TOOLS AND* EQUIPMENT — INTERFACE WITH OTHER PARTS OF CSDP

STATUS OF DRILLING
— CONTRACT MANAGEMENT: DOE/SAN
— DRILLING AND OPERATIONS: BECHTEL CORP.
— SCIENCE SUPPORT SERVICES: LLNL (DUBA)
— INTERAGENCY EXECUTIVE STEERING COMMITTEE
— "SPUD-IN" DATE: SEPTEMBER 23, 1985

STATUS OF SCIENCE
— ON-SITE SCIENCE MANAGER — USGS (SASS)
— *CONTRACTS/GRANTS/IN-HOUSE* FUNDING IN PLACE BY DOE, NSF AND USGS. 37 PROJECTS BEING SUPPORTED

PARTICIPATING INSTITUTIONS
(FY 86 I.F.P.)

DOE LABS	UNIVERSITIES
LBL (3)	U. CALIF./RIVERSIDE (McKIBBEN)
LLNL (3)	U. MARYLAND (VALETTE-SILVER)
LANL (1)	SO. DAK. SCH. OF MINES & TECH (PAPIKE)
	MICHIGAN TECH (McDOWELL)

(FIG. 17)

GEOSCIENCES RESEARCH
OFFICE OF BASIC ENERGY SCIENCES

ACCOMPLISHMENT

LONG VALLEY

- SEARCH FOR OPTIMAL DRILLING LOCATIONS. 3-D SEISMIC IMAGING
  — 4 FEDERAL AGENCIES — 1 INDUSTRY
  — 1 STATE AGENCY — TOTAL EFFORT ~$2.8M
  — 7 UNIVERSITIES — DOE ~20% OF THE EFFORT
- DRILLING
  — 1983, RDO-2a, OBSIDIAN DOME, INYO DOMES, CA, TO OBTAIN COMPETENT OBSIDIAN SAMPLES AND TO LOCATE THE UNDERLYING GRANITIC BASEMENT ROCK. 500 FEET
  — 1984, RDO-2b, OBSIDIAN DOME CONDUIT, *INYO DOMES, CA.* PENETRATED OBSIDIAN DOME CONDUIT. DRILLED TO A DEPTH OF 624m AT AN ANGLE OF 60°, CORED IN ENTIRETY. TOTALLY CASED. CORE RECOVERY 90%
  — 1984, RDO-3a, INYO DOMES DYKE. PART OF CONSORTIUM EFFORT INVOLVING 3 DOE NATIONAL LABORATORIES, 4 UNIVERSITIES AND THE CANADIAN AND U.S. GEOLOGICAL SURVEYS. GOAL: TO DELINEATE 8 km LONG SUBSURFACE DYKE SYSTEM WHICH FED THE INYO VOLCANIC EVENTS. DRILLED TO A DEPTH OF 829m AT AN ANGLE OF 60° TO THE HORIZONTAL

(FIG. 18)

IN SUMMARY

- GEOSCIENCES KEY IN DOE — IMPACT ALL TECHNOLOGIES;
- ACCOMPLISHMENTS HAVE HAD HIGH IMPACT ON ENERGY TECHNOLOGIES AND ADDED NEW ENERGY RESOURCE
- OF GEOSCIENCE INITIATIVES, CSDP IS LARGEST AND MOST IMPORTANT
- HIGH RELEVANCE OF CSDP TO DOE JUSTIFIES DEPARTMENT TO TAKE THE LEAD AMONG FEDERAL AGENCIES IN THERMAL REGIMES

(FIG. 19)

GEOTHERMAL ACTIVITIES IN CENTRAL AMERICA

Sponsored by U.S. Agency for International Development

by

John T. Whetten and Robert J. Hanold

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ABSTRACT

The Agency for International Development is funding a new program in energy and minerals for Central America. Geothermal energy is an important component. A country-wide geothermal assessment has started in Honduras, and other assessment activities are in progress or planned for Costa Rica, El Salvador, Guatemala, and Panama. Instrumentation for well logging has been provided to Costa Rica, and a self-contained logging truck will be made available for use throughout Central America. An important objective of this program is to involve the private sector in resource development.

INTRODUCTION

On February 8, 1985, M. Peter McPherson, Administrator of the Agency for International Development, and Senator Pete Domenici announced a new AID-funded program titled "Central American Energy and Mineral Development: A Path Toward Economic Security." The countries included are Costa Rica, El Salvador, Guatemala, Honduras, Panama, and, as appropriate, countries of the Caribbean. The program is coordinated and managed by Los Alamos National Laboratory. Initial funding is $10.2 million. It is expected to be a multi-year program. The objectives are to

- increase economic development and employment in Central America,
- provide a means for the private sector to develop energy and mineral resources, and
- provide training to counterpart scientists and engineers.

The resources targeted for assessment are geothermal, peat, and minerals. Some attention will also be given to coal and lignite; petroleum and natural gas; and wind, solar, and biomass. This program will not undertake resource development. That is a job for the private sector.

Much of the work on this project will be done by Los Alamos scientists, engineers, and economists. As appropriate, consultants will be utilized from the private sector, other laboratories, and universities. The U.S. Geological Survey is contributing to the overall program, particularly in the geothermal and minerals projects. The following discussion centers on geothermal activities that are part of this program.

PILOT PROJECT ON ST. LUCIA

This program was preceded by a geothermal project on St. Lucia, in the West Indies. Before 1983, attempts to assess and develop the geothermal resource had been made by British, Italian, and U.S. consulting firms. However, no production wells were drilled. In 1983, Los Alamos was funded by the Trade and Development Program of the U.S. Department of State to assess the resource and recommend drilling sites.

St. Lucia is a volcanic island. Steam fumaroles and boiling pools occur near the town of Soufriere within the Qualibou caldera, which formed 32,000 to 39,000 years ago. Regional linear faults and caldera faults appear to control the location of thermal springs within the caldera.

A 5.2-km-long dipole-dipole DC resistivity survey was conducted along a north-south trending line through the caldera (Fig. 1). An apparent resistivity high, greater than 1000 ohm-m, is located below the Belfond area. Beneath this high there is deeper low-resistivity material that is less than 10 ohm-m. A zone of very low apparent resistivity, less than 1 ohm-m, underlies the Etangs area. This zone is related to thermal upwelling along what is probably the caldera-bounding fault (Fig. 2).

Beneath Sulphur Springs at a depth of approximately 600 m is higher apparent resistivity material ranging from 40 ohm-m up to 150 ohm-m in the center of a 1-km-diameter high-resistivity closure. These data strongly suggest a very hot dry steam field.

Hydrogeochemical data from Qualibou caldera indicate a geothermal reservoir underlies the Sulphur Springs area that consists of (1) an upper steam condensate zone, (2) an intermediate vapor zone, and (3) a lower brine zone. Temperatures as high as 212°C were measured at a depth of 600 m during previous shallow drilling at Sulphur Springs. Geochemical evidence indicates the temperature of the brine may exceed 250°C.

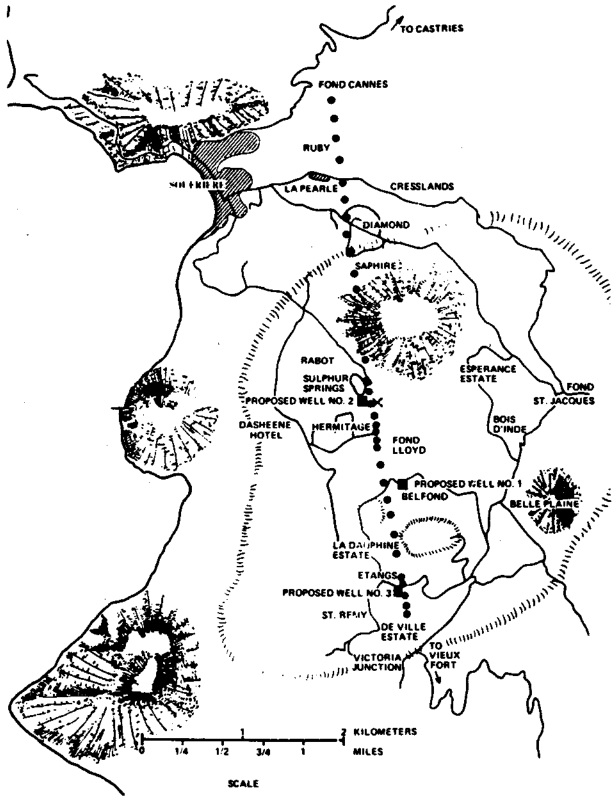

Fig. 1
Location of the 5.2-km-long resistivity profile line (containing 32 electrode stations) across the Qualibou caldera.

The recommended locations for exploratory drilling in Qualibou caldera are (Fig. 1):

(1) Craters of Belfond - Caldera-related faulting and recent phreatomagmatic volcanism indicate fracture permeability, and low resistivity suggests that geothermal brines occur at a depth of less than 1 km.

(2) Valley of Sulphur Springs - Hot springs and fumaroles, fluid chemical compositions, and low formation resistivity all indicate a geothermal brine reservoir about 2 km deep with the possibility of a hot dry steam field above the brine reservoir.

(3) Etangs - The southern caldera fault and a very low shallow resistivity suggest a reservoir of geothermal brine at a depth of about 1 km.

In summary, Qualibou caldera has excellent geothermal potential, and exploratory drilling should result in the discovery of a high-temperature brine reservoir. Geothermal brines (and perhaps dry steam) may be found at a depth of 1-2 km under the central and southern caldera area.

Field work on St. Lucia was completed within seven months of contract initiation, and in one year, detailed results were published in a series of Los Alamos Technical Reports (References 1-4). As a result of this assessment, U.S. AID and the U.N. Revolving Fund are providing over $5 million for drilling and testing to begin early in 1986. This money will go to the private sector, and at least $2.5 million must be contracted to U.S. firms.

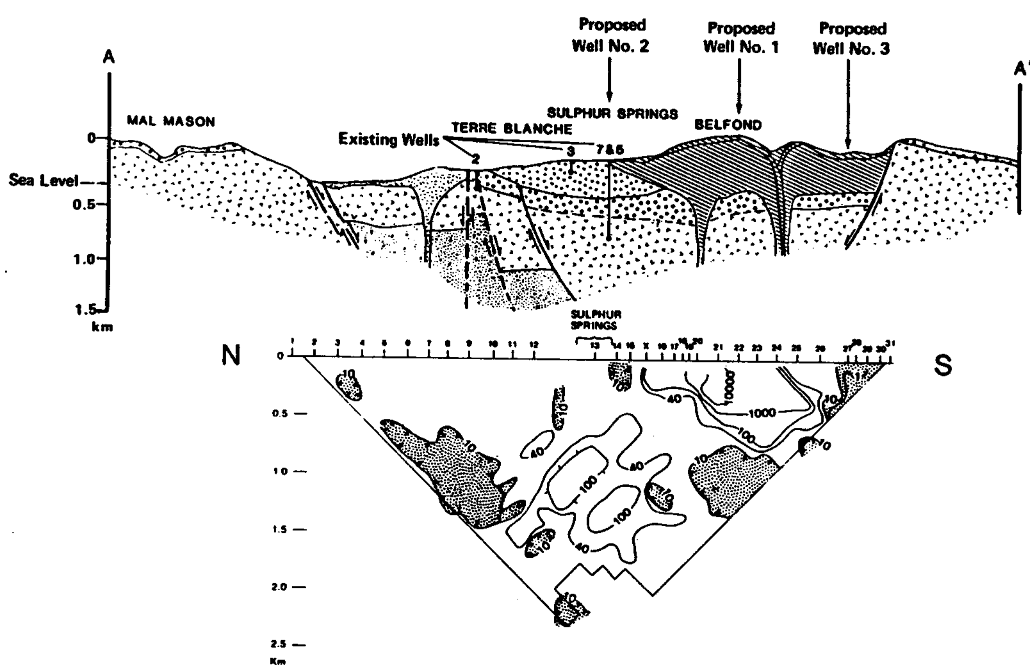

Fig. 2
Apparent resistivity data from the dipole-dipole survey plotted as a function of depth. Resistivity values are in ohm-m and are shown beneath the appropriate geologic cross section. Shaded areas depict resistivity contours of 10 ohm-m or less.

GEOTHERMAL ACTIVITIES IN CENTRAL AMERICA

Objectives - The long-term geothermal and assistance plan that is being formulated and implemented by Los Alamos and the U.S. Geological Survey is responsive to needs that were identified by scientists, engineers, and government officials from Central American countries. The plan is designed to

(1) Insure continued development of economical electricity derived from geothermal energy.

(2) Provide technical training to counterpart organizations for planning, operating, and maintaining geothermal plants.

Progress To Date - During the first six months of this project, reconnaissance geology and geochemistry studies were carried out at six geothermal sites in Honduras. Platanares, San Ignacio, and Azacualpa (Fig. 3) were selected for more detailed investigations, and these sites were examined by teams of Los Alamos/ENEE (Empresa Nacional de Energia Electrica) geologists, and emphasis was put on structural geology, stratigraphy, and detailed mapping of thermal springs.

Water samples were collected and analyzed from these sites by a joint Los Alamos/U.S. Geological Survey/ENEE team in order to estimate the subsurface temperatures of geothermal reservoirs. The samples are characterized by relatively high chloride waters having neutral to alkaline pH, characteristics that are typical of hot water-dominated geothermal systems. Estimates for subsurface geothermal reservoir temperatures are as follows: Platanares, 220°C; San Ignacio, 200°C; Azacualpa, 185°C; Pavana, 145°C; and El Olivar, 130°C.

Initial geothermal reconnaissance efforts in Costa Rica will center on the volcanic region surrounding the Miravalles geothermal development in Guanacaste Province.

Los Alamos personnel have overhauled a trailer-mounted well logging rig for interim use in the Miravalles geothermal wells, and logging is currently in progress. Temperatures up to 235°C have been measured. Measurements being made include pressure and temperature as a function of depth, wellbore diameter and contour, and fluid velocity in the wellbore. Samples of the geothermal reservoir fluid have been obtained. The presence of wellbore scaling in one production well, which was suspected by ICE (Instituto Costarricense De Electricidad) engineers, was verified.

The specifications for a self-contained well logging truck have been written, and the procurement process has begun. This truck will remain in Central America. It will have on board electric and hydraulic systems, a 3,000 m high-temperature logging cable, and all necessary equipment for logging geothermal wells in remote areas, including a selection of high-temperature downhole logging tools.

Fabrication of a high-output DC electrical resistivity system is nearing completion. This unit, similar to the system that was used on St. Lucia, will remain in Central America to support geophysical exploration activities. It will be used first in Honduras.

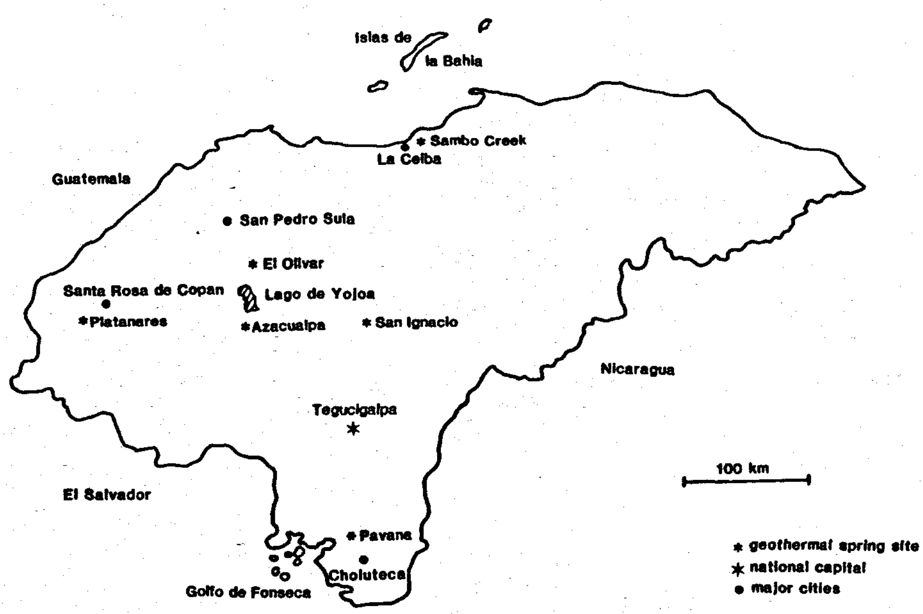

Fig. 3
Honduras Geothermal Prospects

GEOTHERMAL NEEDS OF CENTRAL AMERICA

Honduras - Before 1990, ENEE must make decisions on how to meet Honduras' growing electricity demands. ENEE has requested an assessment of the technical feasibility of geothermal power plants in Honduras and the most desirable locations for development. Thus, an extensive geothermal reconnaissance effort is now underway. After completing electrical geophysics measurements and drilling shallow temperature gradient wells, a site will be selected for drilling production wells. The production testing data from these wells will confirm (or deny) the reservoir potential of the site and provide ENEE with the information required to determine its future policy.

Costa Rica - With the Miravalles geothermal field undergoing active development, the most urgent need of ICE is for equipment and technical expertise to perform well logging measurements in the production wells. The measurements that have been given highest priority include well temperature surveys, pressure surveys, flow measurements to determine which horizons are producing the geothermal fluids, casing profile measurements to check for casing damage and wellbore scale accumulations, obtaining samples of the pressurized reservoir fluids for geochemical analysis, cement bond log surveys to assess the integrity of the bond between the casing and the formation, and reservoir interference tests for estimating the production capacity of the geothermal reservoir.

In addition to Miravalles, other regions within Costa Rica appear to have significant geothermal energy potential. The most promising of these regions will be identified as part of this program.

El Salvador - Electricity production from the Ahuachapan geothermal power plant has been declining steadily during recent years. The most urgent need of CEL (Comision Ejecutiva Hydroelectrica del Rio Lempa) is to reverse this trend and bring the plant back to its previous level of production. CEL has identified two probable causes: declining reservoir pressure because geothermal fluids are not reinjected into the reservoir, and mechanical damage in otherwise good production wells. CEL needs well logging measurements and reservoir engineering expertise to devise a plan for solving these problems and improving well production.

Adjacent to Ahuachapan is an undeveloped geothermal area at Chipilapa. CEL has requested equipment and personnel to conduct geophysical exploration activities to identify the geothermal reservoir and target the most promising production well locations.

Guatemala - The most urgent need of INDE (Instituto Nacional de Electrificacion) at the Zunil geothermal field is for equipment and technical expertise to log production wells. INDE has placed particular importance on cement bond logging because the wells are very hot, and production casings were cemented in place using conventional moderate-temperature cement. INDE would also like to have "tracer" tests performed to determine the communication between production wells through the geothermal reservoir.

INDE has also requested assistance in understanding the geology, hydrogeochemistry, and geophysics of the Amatitlan geothermal region.

Panama - The Valle de Anton region is currently being examined by IRHE (Instituto de Recursos Hidraulicos y Electrificacion) as a potential geothermal energy development site. IRHE has requested assistance in conducting a hydrogeochemical reconnaissance of the area. Emphasis will be placed on geochemical thermometry to determine if a sufficiently high-temperature reservoir exists in this region.

References

1) "Evaluation of the St. Lucia Geothermal Resource Summary Report," LALP-84-26, April 1984.

2) Ander, M., et al., "Evaluation of the St. Lucia Geothermal Resource, Geologic, Geophysical, and Hydrogeochemical Investigations," LA-10234-MS, August 1984.

3) Altseimer, J. H., et al., "Evaluation of the St. Lucia Geothermal Resource, Engineering Investigation and Cost Estimate," LA-10209-MS, August 1984.

4) Burris, A. E., et al., "Evaluation of the St. Lucia Geothermal Resource, Macroeconomic Models," LA-10212-MS, August 1984.

SESSION II

Chairperson: Anthony Adduci, San Francisco Operations Office
U.S. Department of Energy

SAN OVERVIEW/DISCUSSION OF HEAT CYCLE RESEARCH

ANTHONY J. ADDUCI
U.S. DOE SAN FRANCISCO OPERATIONS OFFICE

The San Franciso Operations Office's Fossil Geothermal and Solar Division has two branches: (1) Fossil and Geothermal; and (2) Solar. The Fossil and Geothermal (FG) Branch consists of seven scientists and engineers, (Table 1).

TABLE 1

PERSONNEL IN FOSSIL & GEOTHERMAL BRANCH

ANTHONY J. ADDUCI, BRANCH SUPERVISOR

JOHN CRAWFORD, GEOLOGY/ENGINEERING

LUCY GARCIA, TECHNOLOGY TRANSFER/ADMINISTRATION

HAROLD LECHTENBERG, PETROLEUM ENGINEER

GARY PETERSON, CHEMICAL ENGINEER

MARTY MOLLOY, GEOSCIENCES

PAUL THRASH, MECHANICAL ENGINEER

Under this branch our responsibilities range from basic science in chemistry and materials to major project management leading to commercial operations,

In addition, the FG Branch maintains state, and local government and DOD interagency coordination, has a very active technology transfer effort, and and is responsible for coordination of two international agreements under Headquarters direction.

The program and project listing presented in Table 2, provides an overview of the breadth of our efforts.

The SAN Office has been on the cutting edge of new and innovative methods of working with industry including the development of cooperative agreements for demonstration plants. At present, we are carrying out a complex management organization task for the Salton Sea Scientific Drilling Program. We have aggressively pursued in the past two years, new technology transfer methods with various industrial groups and organizations. These contracts will begin to take shape in FY 1986 and should be the pathfinder for other alternative energy technology transfer processes.

This array of programs is managed by the Office under Headquarters Direction. We at SAN have chosen to take this position for two reasons. First, we have the technical and scientific personnel with experience to undertake the necessary management activities, as well as make technical recommendations and evaluations. Secondly, but much more important is that federal funds are directed to be used for the development of technology or for a project and not to purchase contract management. This is the basic responsibility of the federal manager.

TABLE 2

ASSIGNED PROGRAMS/PROJECTS

GEOTHERMAL RESERVOIR TECHNOLOGY	NAVY/DOE GEOTHERMAL COOPERATIVE AGREEMENT*
GEOCHEMICAL ENGINEERING AND MATERIALS	GEOTHERMAL TEST FACILITY*
GEOTHERMAL STATE COOPERATIVE PROGRAMS FOR AZ, CA, HI, NV, AND THE PACIFIC TRUST TERRITORIES*	INTERNATIONAL AGREEMENTS: DOE/CFE (MEXICO) DOE/ENEL (ITALY)
GEOTHERMAL TECHNOLOGY TRANSFER	HAWAII GEOTHERMAL PLANT*
HEBER BINARY GEOTHERMAL POWER PLANT	GEOTHERMAL PUMP DEVELOPMENT PROGRAM*
SALTON SEA SCIENTIFIC DRILLING PROJECT	INTEROFFICE SUPPORT, ALO/IDO

* Not reviewed in-depth by other papers in the SAN chaired session

At this point I would like to stress the first part of our branch name "Fossil." With the reorganization of SAN in 1983, the Geothermal and Fossil Programs were combined and integrated. This brought to the Branch a skilled petroleum engineer and a chemical engineer (Table 1). Both have been integrated into the SAN Geothermal Program with the petroleum engineer and his drilling experience going to the SSSDP and the chemical engineer adding the chemical and materials program to his list of management items.

On the other side, the fossil groups gained assistance with the Elk Hills Petroleum reserve deep well. This is "a well of significant interest" to the Continental Scientific Drilling Program. SAN has made the initial contract and continues to coordinate with Elk Hills. This mutual enchancement of both programs at SAN is worthy of notice.

In the SAN-chaired session of the Annual Program Review there is not sufficient time to detail all the aforementioned programs and projects. In this session we are concentrating on the progams and projects which are of the greatest interest to this audience. My overview presented here will touch on those programs/projects which will not be reviewed in-depth by other papers in this session. These are so indicated in Table 2.

State Cooperative Programs of particular interest are presented in Table 3. First is the joining of California and Nevada in a mutual program to assess the Pickle Meadows/Newberry Crater area on the California/Nevada border. This effort is of extreme importance to both states. The California Energy Commission in fact has stepped in to fill the gap left when the California DMG respectfully declined DOE funding.

TABLE 3

STATE PROGRAMS

CA/NV COOPERATION ON

- NEWBERRY/BRIDGEPORT RESERVOIR ON THE STATE BORDER

HAWAII

- GEOTHERMAL SUBZONING
- HI TECH RESEARCH FACILITY

CALIFORNIA ENERGY COMMISSION LIAISON

- MAGMA PROGRAM
- HYDROTHERMAL DEVELOPMENTS
- NAVY PROGRAM

IMPERIAL COUNTY, SONOMA COUNTY LIAISON

The funding of Hawaii geothermal efforts in FY 85 and the application of Hawaii State funds has led to two significant events. First, Hawaii is the first state to designate geothermal development zones. Second, Hawaii dedicated its Geothermal High Technology Center on August 24 with speeches from DOE Assistant Secretary Donna Fitzpatrick and Governor Aryoshi. The central advantages of this center are many: it is located in the center of the Pacific Ring; it is on a public resevoir; the climate is very appealing; and the State, county and university all support it along with the Hawaii Natural Energy Institute. The Center was recently visited by delegations from Taiwan and Japan, who are both interested in conducting programs at the center.

SAN has also been working with the California Energy Commission to coordinate and assist with hydrothermal developments; help coordinate the Sandia Magma Program; and act as liaison with the Navy. We also work with Imperial and Sonoma counties to assist them with geothermal planning.

Another area where SAN has been actively involved is in coordination with the Department of Defense through the Navy Cooperative Agreement (Table 4).

TABLE 4

NAVY COOPERATIVE AGREEMENT

EFFORTS INCLUDE:

- RESERVOIR ASSESSMENT
  - o FALLON
  - o LONG BEACH
  - o 29 PALMS
- LIAISON & COORDINATION WITH:
  - o CALIFORNIA ENERGY COMMISSION
  - o HAWAII DPED
  - o NEVADA
  - o ENEL/ITALY
- SUPPORT & INTERACTION OF NAVY ENERGY PLANNING

We have assisted the Navy in identifying the geothermal potential of and have provided advice on development of the 29 Palms, Fallon and Long Beach geothermal reservoirs. In addition, SAN has coordinated among the Navy and the States of California, Hawaii and Nevada. SAN was recently requested and funded by the Navy to aid in furthering development of geothermal resources on Navy property worldwide. This includes the re-evaluation of third-party power plants.

A program which still requires our attention is the Reno heating project. At present, the project is stalled within the legal system and until those intricacies are sorted out, the project will proceed slowly at best.

The last item I would like to address is the Geothermal Test Facility, (Table 5).

TABLE 5

GEOTHERMAL TEST FACILITY

OPEN TO EXPERIMENTS

- o SURFACE EQUIPMENT & MATERIALS
- o EXPERIMENTS
- o DOWN-HOLE INSTRUMENTS
- o RESERVOIR TESTING

INCREASE IN USE/CURRENTLY

- o SAN DIEGO STATE UNIVERSITY/WELL PROTECTION
- o USGS-FLAGSTAFF/DENVER
- o INEL/DIRECT CONTACT HEAT EXCHANGER
- o AMF SCIENTIFIC DRILLING/SPINNER
- o EIGHT OTHER INQUIRIES TO DATE

Most of you know of the existence of the Geothermal Test Facility (GTF) in the Imperial Valley near the Magma East Mesa Plant. The facility is alive and getting better. We have had 8 inquiries in the past three months and currently have two tests in progress: one by private industry (AMF) and one by DOE's Idaho National Engineering Laboratory. Last month we also had the U.S. Geological Survey (USGS) using our dedicated instrument well 31-1 to test their equipment in preparation for the Salton Sea Drilling Project. USGS will be back again in the next 9 months for more tests and calibration.

For those who are not familiar with the facility it is operated to support tests and experiments of equipment to be used in geothermal systems. This includes materials, valves, pipes, coatings, turbines, separators, heat exchangers, and surface instruments to mention a few. There is also a well available at any time for down hole instrument testing.

There is no charge for coming on the site, receiving brine, power, air, or office space.

The GTF will:

1. Receive your apparatus & help set it up
2. Provide fluid, utilities, office space and a corporate pad area
3. Help with tear-down and loading of experiments

The GTF will not:

1. Run your apparatus
2. Take data
3. Require patent rights
4. Verify your data
5. Approve anything for future use

In other words no DOE "seal of approval" is given.

This facility has been host to geothermal experiments which could not be tested anywhere else. Please take advantage of this facility.

The second portion of this presentation will concentrate on Heat Cycle Research, (Table 6).

TABLE 6

HEAT CYCLE RESEARCH

- o TWO-PHASE FLOW RESEARCH
- o HAWAII GEOTHERMAL PLANT
- o GEOTHERMAL PUMP DEVELOPMENT PROGRAM

This is a misnomer since the Heat Cycle Research Program has been assigned to Idaho Operations Office for several years. However, SAN does have certain efforts in heat extraction which I will mention along with our yet to be finalized plans for the newly assigned program of geothermal pump development.

First is the basic experimentation in two-phase flow research that is being conducted in association with Brown University. This program has been on-going for several years and is gradually defining two-phase flow regimes for well flows.

The principal heat cycle project which is still on-going is the Hawaii Geothermal Power Plant (Table 7).

TABLE 7

HAWAII POWER PLANT

(BASE LOAD OPERATION)

START OPERATION MARCH 1982

AVE. PRODUCTION: 2.4 MW

TOTALS (MARCH 1982 THRU JULY 85)	
OPERATING HRS	27,827
NON OPERATING HRS	2,220
MEGAWATT HOURS PRODUCED	67,102
AVE. AVAILABILITY FACTOR (CAPACITY FACTOR)	92.6%

This is the first operational well head power plant that has sustained long term operation for DOE. The well was drilled and the power plant designed, built and put into operation for $12 million. It is not economical in power output nor is it heat cycle efficient, discharging liquid at 375° F and at 250 psig. However the objective of tapping reliable geothermal energy from an active volcanic rift has been proven by this facility. The electric company has placed an RFP for a 24 MW plant and the basic need for the underwater cable project which DOE funds is due to the success of the HGP-A geothermal plant.

After a protracted start-up period the plant began sustained base load operation in March 1982 at approximately 2.5 MW output. (The plant never reached 3 MW due to the extensive use of steam for auxillary equipment). As you can see in Table 7 this plant has produced significant electricity and has achieved an availability factor in excess of 92% under base load conditions. What this table does not show is that the plant is so stable that scheduled maintenance cycles have been extended with no problems. The second scheduled maintenance will occur in September 1985. The plant requires only a day shift operator. The night and mid-night shifts are on an automatic start-down from the substation.

It is only fair to note that problems have been encountered at the facility. The brine percolation system does not work efficiently; the H_2S abatement system has high operating and maintenance costs and due to the inexpensive components used in the auxilliaries, overhaul or replacement is required. It should be stressed that the major question now is how long the plant will be kept in operation after the DOE contract terminates in 1988. Discussions have been going on for over a year with the State of Hawaii as to the future of the plant.

The principal new assignment to SAN in the area of Heat Cycle Research is the Geothermal Pump Development Program, (Table 6). This program was only recently transferred to SAN in August 1985. Thus, the level of detail presented here is very tentative. The assignment of this program to SAN includes some equipment and available test facilities to build upon. A FY 86 budget has not been allocated for the program at this time.

The significant items available to this program are noted in Table 8.

TABLE 8

GEOTHERMAL PUMP DEVELOPMENT PROGRAM

TANGIBLE ITEMS

1	PORTABLE PUMP TEST FACILITY
1	STATIONARY PUMP TEST FACILITY
1	80 HP REDA PUMP
1	300 HP REDA PUMP

OTHER ITEMS OF IMPORTANCE

ERPI SUPPORT ON TEST FACILITY ELECTRICITY COSTS (OFFER LAPSES 12/85)

CHEVRON OFFER TO TEST AN ACCEPTABLE PUMP AT HEBER

The portable pump test facility is operational; and the stationary pump test facility is at the GTF in East Mesa. It has not yet been tested and is not in operation. The rebuilt 80 HP pump was operated for a few weeks by REDA, and the 300HP pump was built by REDA. The program also has a proposal from EPRI to pay for electricity to operate the stationary pump test facility for some months. This offer lapses at the end of December 1985. Also in 1983 Chevron offered to operationally test a field ready and acceptable pump at the Heber Binary project. This offer needs to be rechecked.

The program in the past concentrated on down-hole submersible electric powered pumps. The future thrust of the program may be broader although a submersible pump will be the only type of pump considered. Other types will not be investigated since in discussions with developers over the past years it has always been the consensus that the submersible pump concept is the best. The source of power to drive the pump however, is the prime item of discussion and investigation. The basic need for a geothermal pump is for binary power systems. Binary systems require a liquid phase fluid to prevent heat exchanger thermal efficiency degradation through deposition. Other geothermal systems which need to supplement artesian well flow would also use the pump. The overall objective of the program are noted in Table 9.

TABLE 9

GEOTHERMAL PUMP DEVELOPMENT

OBJECTIVE:

TO DEVELOP A SUBMERSIBLE PUMP FOR GEOTHERMAL FLUID PRODUCTION.

NEED:

A CRITICAL COMPONENT FOR BINARY POWER PLANTS, NON-ELECTRIC APPLICATIONS MAY ALSO FIND PUMPS ADVANTAGEOUS.

Our first rough ideas at SAN are to formulate a plan to cooperate with the pump industry to develop a pump designed for geothermal operation and not just a modified water or oil field pump. This cooperation could take many forms including cost sharing of designs, fabrication of small prototypes, and offering to successful prototypes the use of both the portable pump test facility and the operational stationary pump test facility. Our initial plans for pump development are summarized in Table 10.

TABLE 10

GEOTHERMAL PUMP DEVELOPMENT

TENTATIVE PLANS

1. COOPERATE WITH INDUSTRY TO DESIGN A SUBMERSIBLE PUMP FOR GEOTHERMAL FLUID PUMPING.
2. COORDINATE WITH DEVELOPERS TO RECEIVE INPUT ON PUMP PERFORMANCE SPECS. AND FIELD TEST OPPORTUNITIES.
3. COOPERATE IN THE FABRICATION OF PROTOTYPES.
4. PLACE INTO AN OPERABLE CONDITION AND MAKE AVAILABLE BOTH PUMP TEST FACILITIES FOR INDUSTRY USE.
5. SCHEDULE TBD
6. FUNDS TBD
7. OTHER TBD

In the short month we have had the program we have made progress. Much depends upon FY 86 funding levels and programmatic discussions with Headquarters. At this time, neither a funding level nor a schedule for this activity budget can be accurately predicted. It does not look like an efficient reliable geothermal submersible pump will be ready for a field test for at least 3 years, however. It could be significantly longer depending upon the availability of funds. Based upon the success of the Heber Binary Plant these pumps will definitely be needed in the future especially if the present shaft pumps become the primary factor affecting plant efficiency and economics.

HEBER BINARY PROJECT

Tiffany T. Nelson
Robert G. Lacy

San Diego Gas & Electric
Post Office Box 1831
San Diego, California 92112
(619) 235-7754

ABSTRACT

The need to demonstrate commercial scale, binary cycle, geothermal technology was first expressed in the mid-1970's in EPRI Report ER-1099. From those initial conceptual plans, the Heber Binary Project has finally evolved into an operating plant. Engineering was kicked off in early 1981, and construction at the site began in June 1983. Construction was completed in June 1985, and following the start-up phase, the generator was synchronized in June 1985. Initial component data is starting to be gathered, and, as the second phase of brine field development comes on stream, more plant data will become available. A two-year, full-load demonstration period ending in 1988 is planned for the plant before it goes into commercial operation.

INTRODUCTION

Formally begun in September 1980 with the signing of a Cooperative Agreement between San Diego Gas and Electric (SDG&E) and the U. S. Department of Energy (DOE), the goal of the Heber Binary Project is to prove the economic and operational viability of binary cycle geothermal technology in a commercial scale geothermal power production. Also counted among the Project's sponsors are the Electric Power Research Institute, the State of California, Imperial Irrigation District, the Department of Water Resources, Southern California Edison, Pacific Gas and Electric, and Fluor Engineers, Inc. By providing a proven alternative to the flash process on low- to moderate-temperature (below 400°F) geothermal resources, the Project hopes to expand the worldwide development of geothermal energy into these lower- temperature resources.

LOCATION

The plant is located on a 17-acre site in the southern portion of California's Imperial Valley and will utilize geothermal brine from the Heber KGRA.

PROCESS DESCRIPTION

The process used by the plant is a supercritical Rankine cycle with a 90/10 mixture of isobutane and isopentane as the binary working fluid. Geothermal brine provides the heat source to vaporize the working fluid, and a wet cooling tower provides the heat sink to condense the exhaust from the turbine.

The geothermal brine is produced from pumped wells at an adjacent facility owned by the Project's heat supplier. Once the heat is removed, the brine is returned to the heat supplier for reinjection at his facility located about one and a half miles from the plant. Both the production and injection facilities utilize the island drilling concept with directionally drilled wells to minimize land use. Shaft-driven downhole pumps, set at about 720 feet in the supply wells, produce the brine at sufficient pressure to maintain it in the liquid phase throughout the process to minimize scaling and corrosion problems and to eliminate the need to remove non-condensible gases. With brine as the tube side fluid, a bank of eight shell and tube heat exchangers are arranged in two parallel trains and are used to transfer the geothermal energy from the brine. Variable speed brine return pumps are then used to elevate the cooled brine to reinjection pressure prior to its return to the heat supplier.

The hydrocarbon working fluid is contained within a closed loop. After being condensed, the liquid hydrocarbon is elevated to supercritical pressure by two sets of pumps operating in series. The liquid hydrocarbon is vaporized in the heat exchangers and flows through a knockout drum to remove any entrained liquids prior to the turbine. The hydrocarbon vapor expands through the turbine to drive the generator and exhausts to the condensers to complete the cycle.

The plant operates with a floating cooling cycle. Cooling water temperature, which determines condenser pressure, is allowed to fluctuate with ambient wet bulb temperature. As a result, generator output varies with ambient conditions for a given set of turbine throttle conditions. Floating cooling improves plant efficiency and reduces brine requirements for the designed 45 MW average annual output plant. Figure 1 shows the schematic of the plant with the major process stream conditions for rated plant output at 55°F wet bulb temperature.

PLANT DESIGN

During the course of engineering, the plant design evolved extensively from the early conceptual drawings. In addition to the requirements for normal steady state plant operations, features to facilitate plant warm-up, shutdown, system evacuation, and maintenance had to be added before arriving at the final design. The fire protection system and other ancillary systems were also added to support the plant. As system

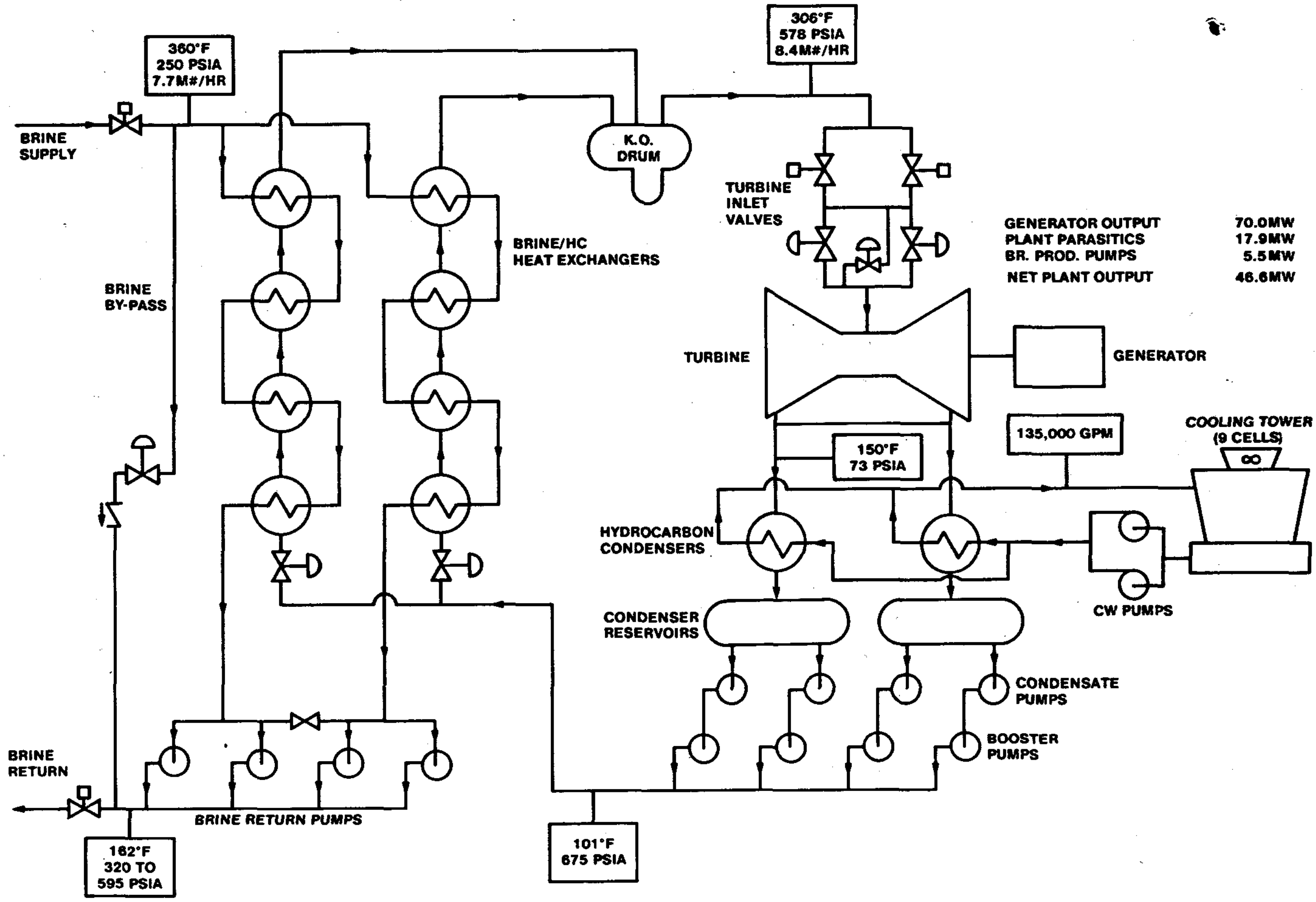

Figure 1 Plant Diagram with Full Load Stream Conditions at 55°F WBT

requirements were set, Fluor Engineers, Inc., the Project architect/engineer, also conducted numerous studies to optimize component size and configuration.

Within the brine system, the major components are the brine/hydrocarbon heat exchangers and the brine return pumps. The heat exchangers are plumbed in two four-shell trains with no provisions to valve out individual shells. The brine return pumps control brine flow through the plant and, in that way, are an integral part of the control scheme of the plant, since brine flow is directly related to the amount of heat added to the process. Hydraulic couplings were selected to give these pumps variable speed capability to meet both the varied flow and injection pressure requirements.

In addition to its major components, the brine system includes facilities to cool and store hot brine for system filling and to recirculate brine within the plant during warm-up. A 100% capacity brine bypass line allows the heat exchangers and return pumps to be bypassed on a plant trip while still maintaining flow in the supply and injection wells.

On the hydrocarbon side, the early manifolded arrangement of the hydrocarbon pumps was changed to a series arrangement of pump pair sets to simplify piping and pump minimum flow protection. Liquid inventory in the hydrocarbon loop is controlled in the reservoirs located directly below the condensers by transferring liquid to and from the storage tank. To accommodate warm-up, a liquid bypass between the heat exchanger discharge and the condensers is provided. A turbine bypass, sized for 20% flow, is also included for the later stages of warm-up just prior to rolling the turbine. The hydrocarbon system design pressure of 850 psi is sufficient to contain the pressure transient on a turbine trip, thus allowing the turbine bypass to only be sized for warm-up purposes. A coalescing filter has been added to remove water, rust scale, and other foreign matter. Its capacity is 2% of the total hydrocarbon flow.

The cooling water loop is a standard wet cooling tower system. Two settling ponds, gravity fed from the nearby irrigation canal, allow silt and other solids to settle out before entering the system. The canal water is first treated with a coagulant at the pond to promote the settling of suspended solids, and at the tower, it is treated with chemicals to reduce biological growth and stem corrosion rates. Cooling water is circulated through the system by two vertical cooling water pumps.

A digital, microprocessor-based control system has been used rather than a conventional analog system. The digital system offers greater flexibility, reduced control room size, and increased data acquisition capability. The main components of the central control system are the distributed control system, which controls the plant, the programmable controller system, which performs start/stop motor logic for all major pumps, and the data acquisition system, which provides all plant reporting and data acquisition. The plant is designed for base load operation with operator-commanded load change capability. The control scheme initiates the appropriate change in brine and hydrocarbon flow on any commanded load change with the rate of the process determining the rate of load addition. To prevent operation of the turbine in the two-phase region, turbine control valve actuation can be inhibited, based on inlet pressure and temperature, until sufficient inlet condition margin is achieved to support a higher load.

After the major process systems, the plant fire protection system is the most extensive. The plant's system is similar to those found in refineries, relying on water spray systems to keep equipment cool until the hydrocarbon source feeding a fire can be shut off and the fire allowed to burn itself out. An underground network of fire mains feeds the spray systems with the water provided by fire pumps, which take suction from the settling ponds. Cross-zoned ultraviolet (UV) detectors and combustible gas detectors comprise the hazard detection system, which actuates the water spray systems. Other major auxiliary systems include the hydrocarbon unloading and recovery system, flare system, inert gas system, and service water system.

MAJOR EQUIPMENT

The total equipment cost for the Project was $47.6 million. All equipment was competitively bid and purchased under the requirements of federal procurement regulations, which was a condition for DOE funding. Table 1 lists the costs and design specifications for the major plant components.

TABLE 1

Turbine-Generator	$5.7M
Four stage, double axial flow, 3,600 RPM turbine; 86% efficiency at guarantee point; 3 phase, 60 Hz, 13.8 KV, 77.8 MVA, hydrogen cooled generator	
Heat Exchangers	$7.2M
Two pass, counterflow, 1,584 MBTU/hr, 38,200 ft^2/shell, 850 psi, shell/tube side design pressure .75 in. OD, 20 BWG Al 29-4c tubes	
Condensers	$4.9M
Two pass, cross flow, 1,342 MBTU/hr, 203,260 ft^2/shell, .75 In. OD, 20 BWG Sea Cure tubes	
Brine Return Pumps	$1.5M
Single stage, horizontal split, 6,000 gpm, 1,250 ft. head, variable-speed hydraulic coupling, 2,500-hp motor	
Hydrocarbon Condensate Pumps	$.5M
Three stage, vertical can, 8,670 gpm, 570 ft. head, 900-hp motor	
Hydrocarbon Booster Pumps	$1.3M
Two stage, horizontal split, 8,670 gpm, 2,110 ft. head, 3,500-hp motor	
Cooling Water Pumps	$.8M
Single stage, vertical, 70,000 gpm, 100 ft. head, 2,250-hp synchronous motor	
Cooling Tower	$2.7M
Nine cell, induced draft, counterflow	

The turbine generator was the most unique piece of equipment procured by the Project, since no other similar machine of its size existed. The specification called for a complete turbine generator package with a guarantee of throttle flow at rated output of 70 MW and specific inlet and exhaust conditions. Included in the package are dual stop and throttle valves, a separate synchronization valve, separate lubrication and seal oil systems, and a flexible generator coupling. The barrel case construction of the turbine allowed side entry for the inlet and exhaust piping, eliminating an elevated turbine pedestal for a downward exhaust.

The largest single capital cost components are the heat exchangers and condensers, which represent about 25% of the total cost for equipment. To keep costs to a minimum, an extensive cost reduction study was undertaken concentrating primarily on the heat exchangers. Surface area and configuration were optimized, and excessive conservatism was removed from the design fouling factor. The surface area optimization revealed that capital costs increased about twice as fast as operating costs declined for narrowing pinch points. This pushed the optimized surface area towards a larger design pinch point and resulted in the selection of 12°F pinch point for the heat exchangers. The configuration optimization revealed that total cost of the heat exchangers dropped as the same surface area was packaged in fewer and larger shells until the size of the shells became too large. Other heat exchanger features are identical tube and shell design pressures, and a "no-tubes-in-the-window" baffle design. The condensers feature a cross-flow design with a two-pass shell.

Material selection for the heat exchanger and condenser tubes was the subject of another study. Considering corrosion resistance, cost, and a 30-year plant life, Alleghany Ludlum's AL 29-4c was selected for the heat exchangers, and Trent Tube's "SeaCure" was the selected material for the condensers. Both are ferritic stainless steel with chromium contents in excess of 26%. The remainder of the plant, for the most part, is carbon steel with fiberglass-reinforced plastic cooling water piping as the major exception.

HEAT SALES CONTRACT

Supplying the heat for the Project are Chevron Geothermal Company (Chevron) and Union Oil Company (Union), who are the two major leaseholders in the Heber KGRA. SDG&E initially negotiated the Project heat sales contract with Union. Chevron, as majority leaseholder in the Heber unit and unit operator, exercised its right to participate in the sale of heat to the Project. The development of the reservoir for the Project takes a phased approach, with 50% brine flow due in May 1985 and full brine flow due a year later.

The cost of heat will be made up of a commodity charge and a demand charge. Included in the pricing formula for both charges is a factor which removes from the payment the cost of heat used to generate the electric power for the brine production and return pumps, since the plant is supplying the power for those pumps. During the demonstration phase, the Project will pay the heat supplier's actual operations and maintenance (O&M) expenses in addition to the cost of heat. The base price for heat, which is $1.15 per million BTU's during most of the demonstration phase, excludes the heat supplier's O&M costs. Before the plant goes into commercial operation, an increment to account for field O&M will be negotiated and added to the $1.15 price. The base price is also adjusted by an escalation factor, which is a composite of several indices that relate to the heat supplier's cost of doing business.

CONSTRUCTION

The construction of the plant was organized into four major construction packages and three smaller ones. All packages were competitively-bid, fixed-price contracts overseen by a construction manager, Dravo Constructors, Inc. Construction began in June 1983 with the Site Development package, which entailed rough grading, installation of the settling ponds, and construction of the shop and main buildings. Shortly thereafter, in August, the Civil/ Structural contract, which contained all foundations, pipe supports, and underground piping and electrical conduit, was awarded.

The Mechanical and the Electrical contracts were awarded in April and June 1984, respectively, which encompassed the bulk of plant construction. The three remaining packages for painting, paving, and landscaping were separated out to allow small contractor participation in the Project. The first two were awarded in the first quarter of 1985. An additional contract was awarded to a specialty heavy lift contractor in the first quarter of 1984 to move the large vessels and heat exchangers from the local railhead to the site and rough set them on their foundations. This interim contract was required, since equipment delivery was coming at a time too early to award the Mechanical contract. Construction was completed and the Project turned over to Plant Operations in June 1985.

START-UP

Plant start-up officially began in October 1984 with the energization of the plant switchyard. Start-up is the responsibility of SDG&E and consists of process transmitter and control loop checkout, as well as actual equipment start-up. Start-up and turnover to Plant Operations of the auxiliary systems and cooling water system was completed in March 1985. Plant warm-up and initial turbine roll occurred in May. The generator was synchronized for the first time in June 1985.

OPERATIONS AND DEMONSTRATION

The operation and maintenance function at the plant has been contracted to WESTEC Services, Inc., who will be overseen by an on-site SDG&E plant staff, including a site supervisor, plant engineer, engineering assistants, and a plant chemist. Formal classroom operator training began in July 1984 and was later supplemented with on-the-job training as construction and start-up progressed. The plant is manned twenty-four hours a day by a four-man rotating shift consisting of a shift supervisor, control operator, assistant control operator, and maintenance helper. The maintenance staff is on-site during the normal work day and includes four instrument technicians in anticipation of the instrument calibration requirements of the Test Program.

The plant Test Program began after initial synchronization when the Start-Up Group turned the plant over to Plant Operations. The initial phase of testing will concentrate on individual plant components to verify contractually guaranteed performance and establish baselines for future performance measurement. Once full brine flow is achieved, the DOE Facility Acceptance Test will be performed signifying the start of the two-year Demonstration Period. During the Demonstration Period, the majority of the plant level steady state and transient tests will be conducted. These tests will determine plant performance under a variety of conditions, as well as indicate the speed of the process in reacting to upset conditions. In addition to these tests, component and plant performance will be measured on a regular basis to determine fouling and equipment degradation rates. In parallel with the Test Program data, plant and component reliability data will be maintained through Demonstration. A good plant availability record is a key for future plant development, and the Test Program is structured to minimize tests in the last six months of Demonstration to simulate the operating schedule of a commercial plant.

* One of the chief goals of Demonstration, in addition to the plant test data, is to determine the expected costs for future binary plants. A study is already underway to determine what the engineering costs for a second plant would be without the cost associated with designing a first-of-a-kind R&D plant. Other studies will look at construction and project management costs as these phases wind down. As operating data becomes available, potential plant design and component improvements will be investigated, all with goal of reducing equipment costs.

RESEARCH ON GEOTHERMAL CHEMISTRY AND ADVANCED INSTRUMENTATION

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ABSTRACT

Research at the Pacific Northwest Laboratory (PNL) focuses on long-term geothermal power plant reliability. Past work concentrated on development of continuous high-temperature probes for monitoring process variables. PNL also completed a comprehensive handbook of brine treatment processes as they relate to injection well longevity.

A recently completed study analyzed corrosion in the hydrocarbon system of a binary cycle plant. Over the two-year monitoring period, corrosion rates were less than 1 MPY in any part of the hydrocarbon system. The system was kept completely dry so the rates seem reasonable.

Present projects include:

- Determination of Gas Breakout Conditions at the Heber Binary Demonstration Plant Operated by San Diego Gas and Electric Company (later referred to as the Heber Plant).

  Brine chemistry data plus results of these tests indicate fairly low potential for calcite scaling at the Heber Plant.

- Generation of Water Mixing Solubility Data

  Experimental data from this project will be used in the data base of a computer program being developed at the University of California, San Diego. That program will predict scaling species for geothermal brines at various temperatures and pressures.

- Installation of Prototype Leak Detectors at the Heber Plant

  Four units have been installed to detect leaks of brine into hydrocarbon, cooling water into hydrocarbon, hydrocarbon into brine, and hydrocarbon into cooling water. All units still need field calibration.

- Evaluation of State-of-the-Art Particle Counters

  Laboratory testing is underway on a new model ultrasonic particle measurement instrument. A new laser unit is expected soon and will also be tested in the laboratory before field testing of both units.

INTRODUCTION

The history of geothermal power development shows that corrosion, scaling, and reinjection of waste waters have caused unexpected plant failures. Often these failures result in shutdowns of many months for repairs. The failures have occurred in valves, turbines, pumps, pipe materials, heat exchangers and injection wells. Since the geothermal market is small, there is little incentive for vendors to find the cause of failures and upgrade their materials and designs for service in hot brines.

The objectives of the PNL program have been to research the causes of corrosion and scaling failures in existing plants and to develop the science of the chemical processes involved so future plants can be economically viable. Advanced instrumentation is being developed and tested to collect data on scaling and corrosion. The instruments and data together should eventually provide early detection for plant operators so they can avoid possible problems.

PROJECT SUMMARIES

CORROSION IN HYDROCARBON SYSTEMS

Early in the operation of a binary cycle power plant, corrosion was noticed on the hydrocarbon side of heat exchanger tubes. Since water and brine had occasionally contacted the hydrocarbon side surfaces, it was unknown whether the corrosion was due just to the aqueous exposure or if the isobutane itself was somehow corroding the metal. A test program was designed to monitor the corrosion for a two-year period in order to answer that question and to test the monitoring equipment as well.

Four commercial resistance-type continuous corrosion probes were installed in the hydrocarbon loop of the binary cycle geothermal power plant. At each probe location, ten corrosion coupons were also installed. The locations were picked to monitor cool liquid, warm liquid, hot vapor, and cool vapor. Figure 1 shows a typical trace for a probe in the warm liquid. Probes in the other three locations showed similar low corrosion rates (i.e., less than 1 MPY). All coupon data also supported the continuous probe information. For the entire monitoring period, special care was taken to keep the hydrocarbon dry. Thus, the low corrosion rates would indicate that isobutane by itself is not corrosive to carbon steels.

GAS BREAKOUT EQUIPMENT

One prevalent scaling species in geothermal systems is calcium carbonate. It forms when carbon dioxide is released from the brine and the brine becomes supersaturated in calcium carbonate (calcite). Although the thermodynamics of calcite formation is fairly well understood, no reliable methods exist for predicting when flashing and resulting precipitation will occur in geothermal brines. (Dr. Weare at the University of California, San Diego is working on a computer model to make the predictions, but lacks some key experimental high-temperature solubility data.)

The consequences of calcite scaling can be a choking of production wells or process piping or plugging of the distribution plate in heat exchangers. Normally the effect is localized because calcite formation kinetics are so rapid. The calcite formation zone is always near the point of incipient flashing. The key to keeping the calcite in solution is simply overpressuring the brine to be sure carbon dioxide does not come out of solution. Too much overpressure adds to pumping costs. Thus, accurate knowledge of breakout pressures at any given temperature would allow optimum pump operation.

A field-style instrument has been developed which will experimentally determine breakout conditions for a pumped brine stream over a range of temperatures. The equipment is shown schematically in Figure 2. Its detailed operation is described in another document (Ref. 1). The instrument is mounted on three skids to enhance its portability. One contains the actual breakout equipment, a second contains recording instruments only, and the third is a radiator plus fan for cooling a recirculating water stream. All that is needed at a test site is electrical power for the radiator fan and the instrumentation. A portable generator can be used to supply the necessary power.

During operation the brine temperature can be varied and then controlled at any desired temperature by changing the flow through and the bypass around two heat exchangers. Pressure at a sight glass is controlled using an adjustable orifice. As pressure is reduced in the sight glass (at a fixed temperature), gas bubbles are eventually released. The pressure at which bubbles begin to form is termed the breakout pressure for that temperature. A gas breakout curve is generated by changing the temperature at the sight glass and recording the new breakout pressure. Figure 3 shows breakout curves for the East Mesa and Heber Known-Geothermal-Resource-Areas. The interesting difference in the two curves is the much higher pressure required to keep gas in solution in the East Mesa brines. The explanation lies in the significantly different brine chemistries of the two reservoirs. Table 1 shows a partial analysis of both brines with emphasis on components that affect CO_2 solubility. Heber brine has a much lower total gas content than the East Mesa brine. Also, the fraction of CO_2 in the gas is much lower for the Heber brine. Consistent with the gas measurements is a reduced total CO_2 content in the Heber brine.

TABLE 1. Partial Chemical Analyses of Heber and East Mesa Brines

Constituent	East Mesa mg/ℓ	Heber mg/ℓ
Na	2085	4070
Cl	3449	7730
Ca	51.5	806
HCO_3	492	40.5
Total CO_2	1519	164
Gas Analyses		
Total Gas ($g/10^6$ g brine)	460	42
CO_2 (mole %)	77.2	9.7
CH_4 (mole %)	17.4	13.2
N_2 (mole %)	5.2	70.3

WATER MIXING SOLUBILITY DATA

In any commercial geothermal power plant, the feed water is a mixture of fluids from many wells. Chemistry differences between the wells are to be expected. Only slight changes in chemistry are needed to cause undesirable precipitation reactions. Work at the University of California, San Diego is developing a computer code to predict scaling tendencies of brines upon mixing. Unfortunately, good experimental solubility data at high temperatures (300°C) is not available for many mineral species. The purpose of PNL's work is to generate some of the missing solubility data using laboratory scale equipment. Work to date has concentrated on calcite solubility.

Figure 4 shows a schematic of the equipment used. Simulated brines are prepared with known CO_2 contents. This brine is pumped slowly (1-2 ml/min) through a packed bed of calcite. The calcite bed is maintained at a constant temperature using a modified gas chromatograph oven. The effluent stream from the calcite bed is analyzed for calcium at periodic intervals. When the calcium content no longer changes, the brine is assumed to be at equilibrium with the calcite.

Figures 5 and 6 show some of the test data being generated. Test 1 shown in Figure 5 was the procedural verification run. PNL's data were compared with literature values generated earlier by Ellis and coworkers (Ref. 2). Although our data were slightly higher than those of Ellis, we were confident the system could generate useful numbers. Figure 6 shows new data not previously attempted by others. A matrix of conditions is being used with different salinity, CO_2 partial pressure, and bicarbonate content. The studies on calcite are nearly complete, but future plans are to study calcium sulfate solubility using the same techniques.

HYDROCARBON INTO BRINE (OR WATER) LEAK DETECTORS

The need for design and development of leak detectors became clear when heat exchangers at a binary cycle plant failed by pitting corrosion after less than five years operation. Massive hydrocarbon leaks developed and brine contaminated the turbine. Ordinary corrosion measuring instruments detect only uniform corrosion rates. Pits in heat exchanger tubes can penetrate the wall long before the bulk of the tube is seriously corroded. When pits do develop, hydrocarbon will be lost either to the brine or the cooling water depending on which heat exchangers are leaking. Early detection of any hydrocarbon losses can save operating dollars if the leaking tubes are found and their ends are plugged.

Two hydrocarbon leak detectors have been installed at the Heber Binary Demonstration Plant operated by San Diego Gas and Electric Company (later called the Heber Plant). One instrument detects isobutane leaks into brine and one detects isobutane in cooling water. Both units operate on the same principles. Details of their operation are documented in other publications (Refs. 3,4).

Figure 7 shows a schematic of a hydrocarbon leak detector unit. The leak detector samples a liquid stream continuously at a rate of about 0.2 gpm. Liquid pressure is reduced to near atmospheric. Conditions are such that any isobutane present will vaporize and pass out the top of the separation vessel while cool liquid brine (or water) passes out the bottom of the vessel. The isobutane is filtered and dried, then swept to an infrared detector which quantifies the isobutane present. In both units a nitrogen purge is used to maintain detector pressure and sweep any isobutane to the infrared detector.

The design guideline for the detectors was build them to be able to detect a leak rate of 1 gpm or less of isobutane into either the brine or cooling water stream. (This translates to less than 10 ppm hydrocarbon in the brine at the Heber Plant). One unit was tested at another plant site and detected the equivalent of about 0.2 gpm hydrocarbon loss in cooling water when data were adjusted to Heber Plant design conditions. Detection of less than 0.1 gpm hydrocarbon loss in the brine was predicted for the Heber Plant. These limits still need field verification at the Heber Plant.

WATER INTO HYDROCARBON LEAK DETECTOR

Under ordinary operating conditions, hydrocarbon pressure in the Heber Plant will exceed both the brine and cooling water pressures. Consequently, leaking heat exchanger tubes should result in hydrocarbon contamination of either the brine or cooling water. Past experience, however, has shown that the hydrocarbon fluid can get contaminated with brine or cooling water, especially during startup and shutdown of the plant.

If brine is present even in very small amounts in the hydrocarbon stream, the fluid combination is corrosive and can result in pitting on the hydrocarbon side of the tubes. Also, either water or brine in the hydrocarbon can cause turbine damage by condensing inside the turbine. Consequently, the detection of brine (or water) in the hydrocarbon is essential to maintain reliable long-term operation.

Figure 8 shows the conceptual diagram for either the brine or water leak detector. Their principles of operation are identical. Operational details are given in other documents (Refs. 3,5). Basically, the units continuously sample a hydrocarbon stream. The hydrocarbon is cooled if necessary to close to ambient temperatures. It flows to a settling chamber which greatly reduces its velocity. If any water or brine is present, the aqueous phase will drop to the bottom of the settling chamber because it has a higher density than the hydrocarbon. Presence of the aqueous phase is detected by a capacitance probe. As the settling chamber fills with water, the probe produces a higher and higher output voltage. The unit is designed to be self-emptying, so the size of a leak can be related to the number of fill/empty cycles the unit sees in a given time period. The unit was field tested at another site. Detection limits for it are governed by solubility of water in the isobutane. If the water concentration is above saturation, the leak detector will respond to it. Saturation is close to 100 ppm H_2O in the hydrocarbon for normal leak detector operating conditions.

PARTICLE COUNTERS

PNL has just completed a comprehensive study on current brine treatment processes primarily as they relate to operation of injection wells. The document (Ref. 6) covers process chemistry, injection formation compatibility, current instrumental/operational aspects as well as future technical possibilities for brine treatment. A summary report of the document is also available (Ref. 7).

The report documented injection problems encountered in several countries throughout the world. Very few of the plugging problems were accompanied by particle size information. It is recognized the particle sizing information will be a key to extending the lifetime of injection wells. To date, no existing particle sizing instruments have been successful for continuous operation on geothermal brines. PNL is developing improved commercial versions of prototype instruments that show promise of working in the geothermal field. Two different principles are under development: a laser optical unit and an ultrasonic unit.

Laser Unit

A unit is being constructed to withstand geothermal brine at temperatures to 400°F with pressures to 700 psia. These conditions make the instrument compatible with both flash and binary plants. It should also operate either upstream or downstream of the injection pump.

The unit will be tested in the laboratory on particles in the 1-30 micron range at concentrations varying between 1 and 100 ppm. These sizes and concentrations cover the documented ranges of interest to geothermal injection operations.

Ultrasonic Unit

This unit records ultrasonic echoes from a transducer which can be placed on either the main piping flow or a smaller side-stream. The unit currently being tested has a low-temperature (190°F-rated), off-the-shelf transducer with an advanced control package. The advanced control package is being tested to determine how effectively it can size particles. Normal units indicate total concentration only. The manufacturer is currently making some experimental high-temperature transducers (goals are 275°F and 100-200 psia). PNL plans to test these, also. A successful combination of some sizing capability with high-temperature transducers will give the instrument a good usable lifetime in geothermal service. Figure 9 shows some sizing responses which were obtained in the laboratory tests at ambient temperature.

Status

The following tests will be the initial runs on the two particle counters.

	Laser	Ultrasonic
Sizing Ability	Prototype Tested	In Progress
Detects Hard Crystalline Particles (i.e., Binary Plant)	Prototype Tested	Yes
Detects Soft Silica Gel (i.e., Flash Plant)	?	Yes
Concentration Response	Prototype Tested	In Progress

ACKNOWLEDGMENTS

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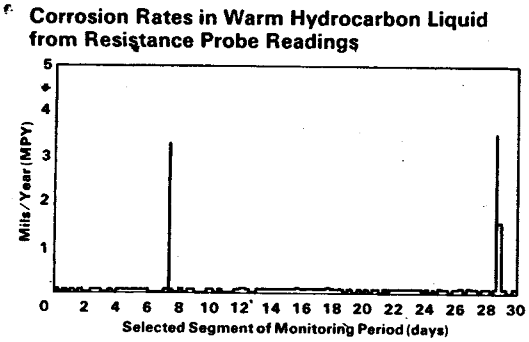

FIGURE 1. Measured Corrosion Rates in Isobutane Stream.

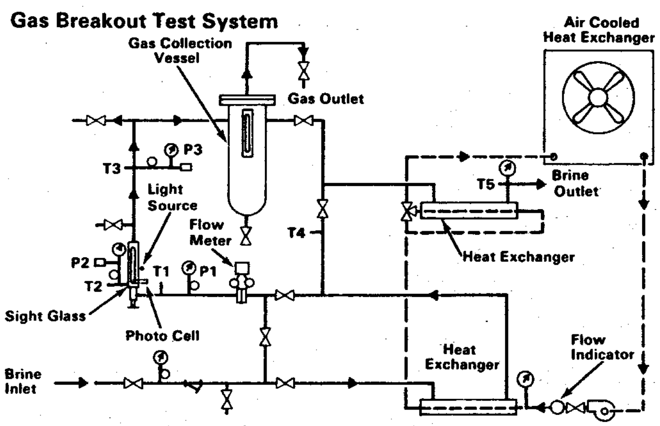

FIGURE 2. Equipment for Measuring Gas Breakout Conditions.

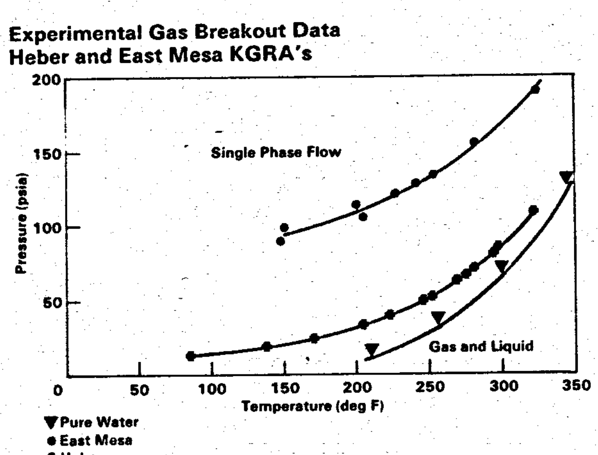

FIGURE 3. Examples of Gas Breakout Curves

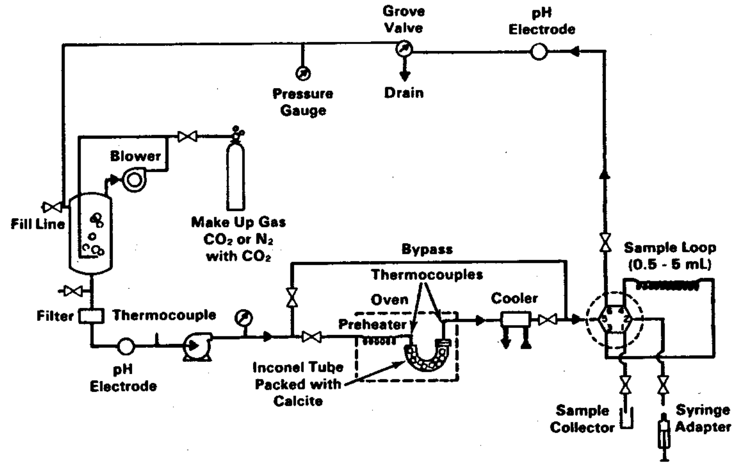

FIGURE 4. Equipment for Determination of Mineral Solubilities.

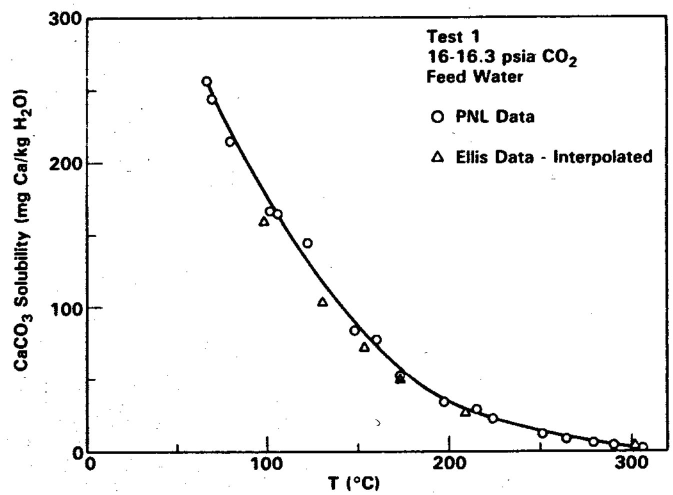

FIGURE 5. Comparison of PNL and Ellis Calcite Solubility Data.

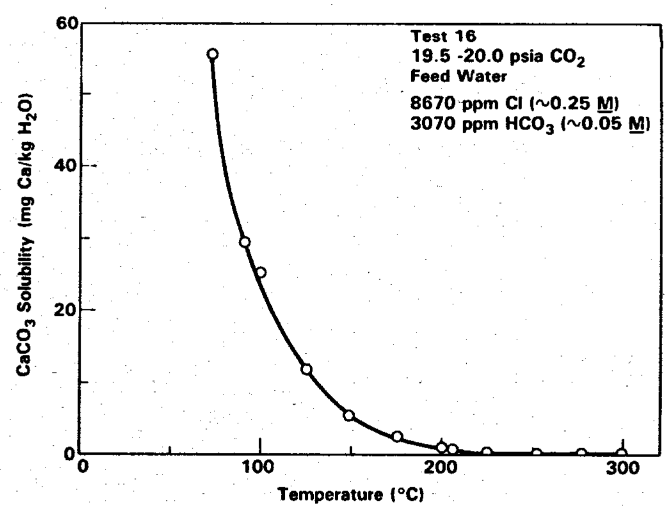

FIGURE 6. Sample Calcite Solubility Data in Mixed Brine.

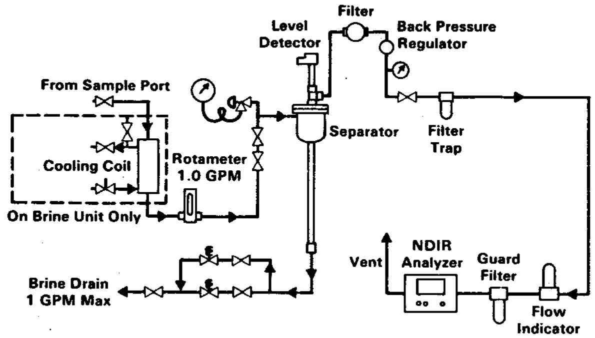

FIGURE 7. Schematic for Hydrocarbon Into Water Leak Detector.

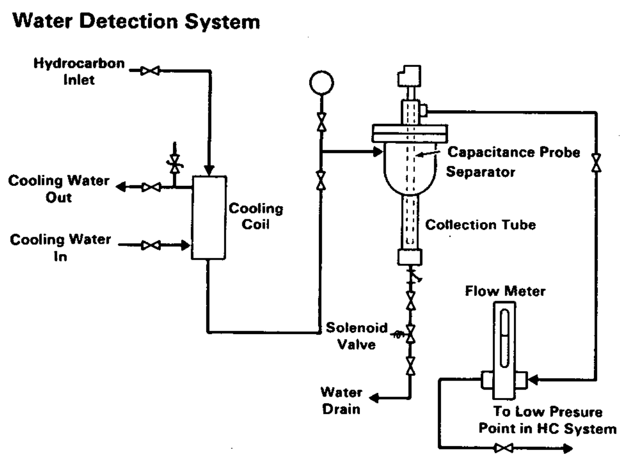

FIGURE 8. Schematic for Brine Into Hydrocarbon Leak Detector.

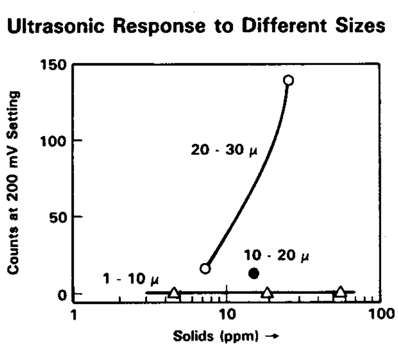

FIGURE 9. Response of Ultrasonic Unit to Particles During Laboratory Testing.

SALTON SEA SCIENTIFIC DRILLING PROGRAM:
DRILLING PROGRAM STATUS

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SUMMARY

The project is within a few weeks of the start of drilling. At this time, major components of the program scope are as follows:

- Total depth is targeted for 10,000 ft
- $1 million is budgeted for coring, which could yield over 1,000 ft of core
- Three limited flow tests are planned
- Over 250 hours are allocated for logging and downhole sampling during drilling
- An additional 6 month standby period will be available for monitoring and sampling after drilling is completed

Site earthwork was finished in August. The installation of utilities, trailers, and other support facilities will be performed during the remainder of September. Drilling equipment rig-up will begin the first week in October, with spud-in expected on about October 7 (Figure 1).

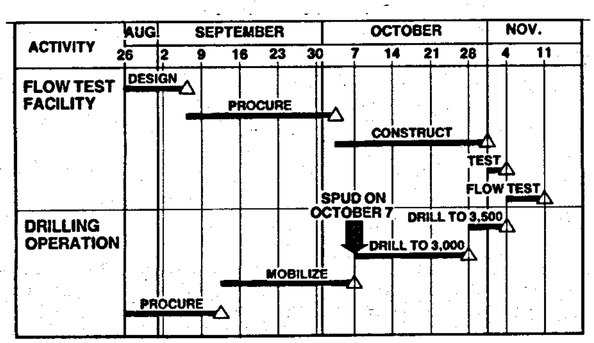

Figure 1
Three-Month Schedule

The timing of the first flow test depends on the procurement/construction schedule for the flow test facility. The best estimate is for the first flow test to occur the week of November 4. This test should provide near pristine fluid samples from the first lost circulation zone below the 3,000 ft casing point. The flow test facility has been designed in accord with the science program requirements for sampling and flow measurement. Spent brine will be reinjected into the well after a brief settling period. A similar flow test will be conducted at the first lost circulation zone below the 6,000 ft casing point.

At the completion of drilling, a final flow test will be made of the entire open hole interval from 6,000 ft to total depth. It is planned to dispose of the spent brine from the test off-site in an approved dump.

The overall schedule (Figure 2) now shows program completion in November, 1986. A decision will be made by Kennecott, the lease holder, whether to take over the well for additional commercial testing at least two months prior to this time. Should Kennecott chose not to take it over, the plan calls for the well be plugged and the site abandoned as the last task in the program.

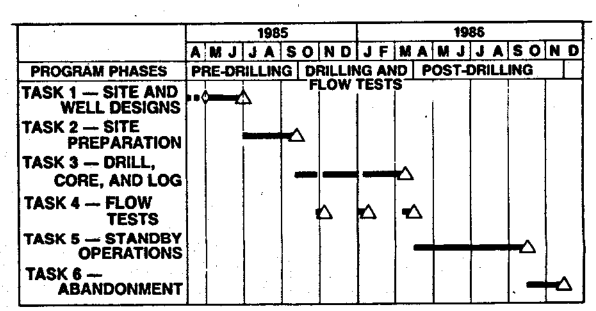

Figure 2
Overall Schedule

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GEOTHERMAL RESERVOIR TECHNOLOGY

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ABSTRACT

A status report on Lawrence Berkeley Laboratory's Reservoir Technology projects under DOE's Hydrothermal Research Subprogram is presented. During FY1985 significant accomplishments were made in developing and evaluating methods for (1) describing geothermal systems and processes; (2) predicting reservoir changes; (3) mapping faults and fractures; and (4) field data analysis. In addition, LBL assisted DOE in establishing the research needs of the geothermal industry in the area of Reservoir Technology. These activities, as well as plans for FY 1986 are outlined.

INTRODUCTION

Significant advances in the understanding of the characteristics and behavior of geothermal reservoirs have been made over the last ten years. However, several important issues have yet to be resolved (Table 1). That is, we need to: (1) develop better methods for mapping and characterizing fractures in geothermal systems; (2) identify and quantify the phenomena controlling two-phase fluid flow in geothermal reservoirs; (3) evaluate the effects of noncondensible gases and dissolved solids in reservoir fluids on geothermal system behavior; (4) develop methods for analyzing enthalpy transients and two-phase well tests; (5) upgrade existing high-temperature downhole instrumentation; and (6) enhance and verify modeling techniques to predict capabilities and longevities of geothermal systems.

Accordingly, the purpose of Lawrence Berkeley Laboratory's (LBL) Geothermal Reservoir Technology Project, funded by the Department of Energy's (DOE) Geothermal Technology Division (GTD), has been to reduce uncertainties in predicting the productive capabilities and longevities of geothermal reservoirs by developing and verifying reliable and practical techniques for mapping reservoir parameters, for understanding and monitoring reservoir processes, and for modeling reservoir conditions before and during the exploitation stage.

This project involves the development of methodologies and instrumentation for: (1) characterizing and mapping reservoir parameters, processes, and spatial dimensions; (2) monitoring and predicting reservoir behavior during production; (3) fault and fracture mapping; and (4) surface and downhole measurements. The project includes field case studies in which developments are tested and vertified for transfer to industry. LBL is also identifying new research areas and providing general guidance to DOE as cognizant laboratory for its Geothermal Reservoir Technology Program.

DESCRIPTION OF MOST IMPORTANT FY1985 ACTIVITIES

Fracture detection and mapping. To summarize existing technology, a "White Paper" was published describing the state-of-the-art in the U.S. and assessing the research needs in this area (Goldstein, 1984). In addition, a one-day workshop for industry was hosted by LBL on July 11, 1985 to review DOE-supported fracture research activities. A summary report on the workshop was recently issued (Goldstein and Cox, 1985).

As far as research is concerned, a variety of numerical modeling, laboratory and field studies were carried out. Electromagnetic (EM) techniques for fracture detection and mapping are being evaluated by means of numerical modeling, laboratory experiments based on metal scale model analogs, and field surveys. Specifically, surface-to-borehole and cross-hole methods for detecting major conductors and hydraulic paths between wells are being studied.

Table 1.
Geothermal Reservoir Technology
Important Issues Yet To Be Resolved

FRACTURES
- Detection and Characterization
- Fractures and Permeability

TWO-PHASE FLOW
- Relative Permeability Functions
- Two-Phase Flow in Fractures (Deviation from Darcy's Law)
- Capillary and Adsorption Effects
- Two-Phase Flow in Wellbores (Coupling Between Wellbore and Reservoir through Multiple Feed Points)

COMPOSITIONAL EFFECTS
- Noncondensible Gases
- Dissolved Solids

RESERVOIR DIAGNOSTIC METHODS
- Enthalpy Transients (Determination of Cold Water Fronts, Reservoir Properties, Natural Recharge, etc.)
- Temporal and Spatial Variations in Concentrations of Noncondensible Gases and Dissolved Solids

DOWNHOLE MEASUREMENTS
- Upgrade of Downhole Instrumentation

MODELING
- Efficient Methods for Three-Dimensional Flow
- Enhanced Capabilities for Front Tracking and Tracer Transport
- Verification of Techniques by Applications to Field Data

In November 1984, a P- and S-wave vertical seismic profiling (VSP) survey was carried out at The Geysers in a joint project with Geothermal Resources International, Inc. The survey mapped (a) fracture density as function of depth, and (b) dominant fractured direction (Figure 1). The field data clearly show that shear wave velocity is highly sensitive to the density and orientation of fractures. Theoretical and laboratory work is being done to verify the field results, and it seems that the shear wave velocity ratios are related to several factors, including the dominant fracture direction relative to the S-wave displacement vector, the average spacing between fractures, and a function called fracture stiffness (Majer et. al., 1985).

During August 1985, LBL along with Seismographic Services Corp., Geophysical Services Corp., and Japan Metals and Chemical Corp. conducted a shear-wave VSP survey in a well at the Nigorikawa geothermal field in Hokkaido, Japan. There were two objectives: (1) to define a deep fracture zone (2000 to 2500 m depth) and its extent by utilizing reflected shear waves; and (2) to define the extent of a shallow (600 m) fracture zone using tomographic techniques. The data are now being processed at LBL's Center of Computational Seismology, with results of the tomographic study expected by early November 1985.

Analysis of Vapor-Dominated Systems. Pruess (1985) developed a quantitative model for the natural state and evolution of these systems. Computer simulations showed that upon heat recharge at the base, a single-phase liquid-dominated geothermal reservoir in fractured rock with low matrix permeability will evolve into a two-phase reservoir with boiling-point-for-depth pressure and temperature profiles. The study also indicated that a rather limited discharge event through cracks in the caprock, involving loss of only a few percent of fluids in place, is sufficient to set the system off to evolve into a vapor-dominated reservoir.

Various analyses of reservoir data from Lardarello, Italy, were performed by D'Amore and Pruess (1985), and Pruess et al. (1985). The key findings were: (1) most CO_2 in well discharges originates from mineral buffers; (2) released CO_2 equilibrates only partially with other gaseous constituents; and (3) long-term trends of vapor fraction support the three-source model of D'Amore and Truesdell (1979).

Bodvarsson and Witherspoon (1985) developed theoretical decline curves for vapor-dominated systems using a multiple-porosity technique (Pruess and Narasimhan, 1985). They studied the parameters controlling the flow rate decline, the effects of well spacing on steam recovery (Figure 2), and the applicability of P/z analysis to estimate reserves of vapor-dominated systems.

Relative Permeability Studies. Combined experimental and numerical studies of two-phase steam-water flow through porous media were carried out by Verma et al. (1985), yielding information on relative permeability functions and capillary pressure curves at temperatures up to 120°C. The experimental setup is shown in Figure 3. The results indicated an enhancement of vapor relative permeability over that of non-wetting phases in two-component systems such as like oil and water, and gas and oil. It was hypothesized that this enhancement is the result of phase transformation effects at pore throats.

Analysis of data from different high-temperature (> 250°C) geothermal fields shows that the sum of liquid and vapor relative permeability values is equal to unity for all saturations (e.g., Bodvarsson et al., 1985a).

Modeling Studies of Olkaria. A fully three-dimensional well-by-well model of the East Olkaria field in Kenya was developed (Bodvarsson et al., 1985a, b). This detailed model is the first of its type to be applied to a geothermal system. A

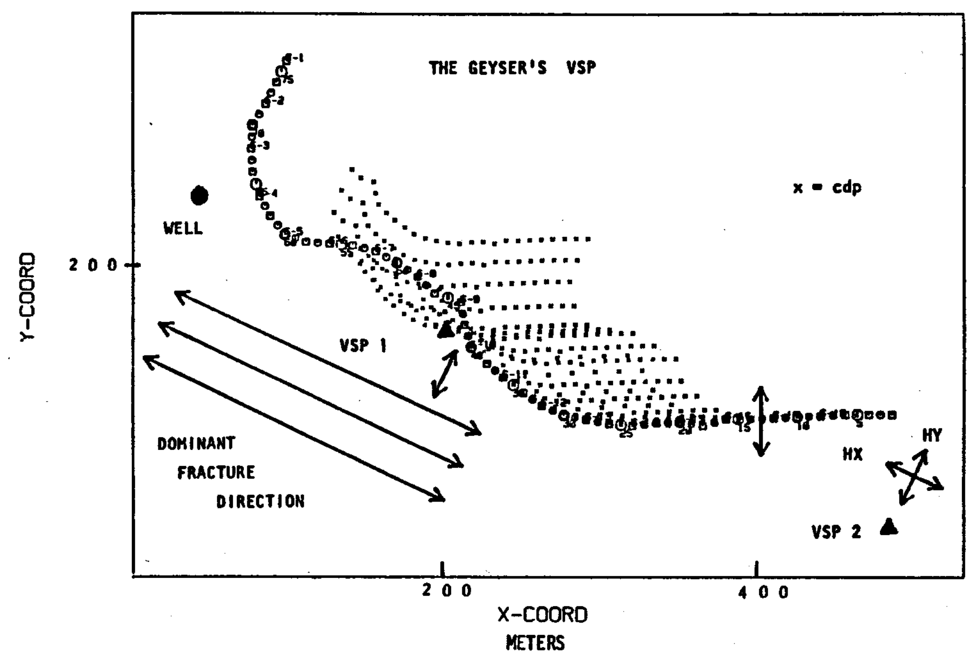

Figure 1. VSP survey layout at The Geysers. Triangles indicate vibrator positions; arrows indicate source polarization directions (Majer et al., 1985).

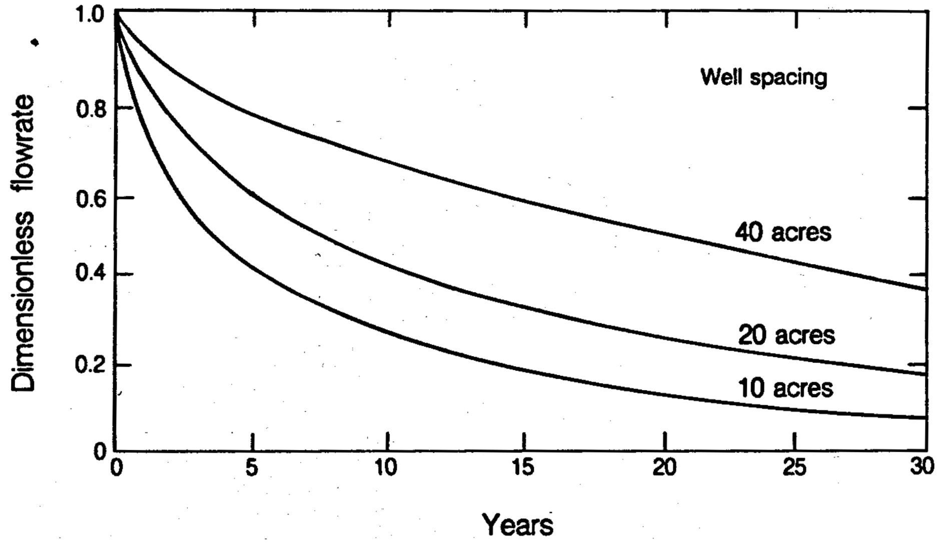

Figure 2. Effects of well spacing on flow rate decline in vapor-dominated fractured geothermal reservoirs (Bodvarsson and Witherspoon, 1985).

reasonable match with the flow rate and enthalpy history of all 25 production wells in the field was obtained. The model was used to determine the optimum well spacing, the overall generating capacity of the system, and the effect of brine reinjection on the behavior of individual wells and of the entire reservoir (Figure 4).

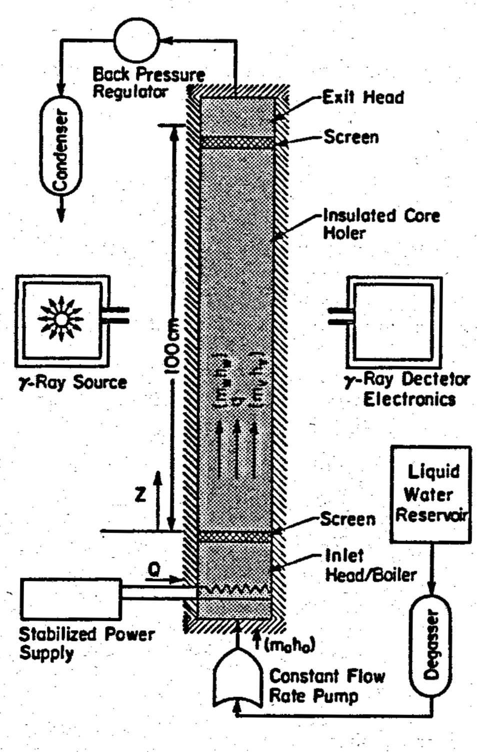

Figure 3. Schematic of the experimental setup to study two-phase steam/water flow in porous media (Verma et al., 1985).

Modeling Reservoir Changes at Cerro Prieto. During the period 1979-1983 repetitive high-precision dc resistivity measurements were made over the Cerro Prieto geothermal field at intervals of 6 to 24 months to study reservoir changes resulting from fluid production. This year Goldstein et al. (1985) performed two-dimensional iterative, least-square inversions of these data. The results of this analysis, supported by additional numerical experiments on artificial (simulated) data, have revealed that systematic, significant changes in resistivity have occurred within the Cerro Prieto area; e.g., (a) a slight increase in brine resistivity due to the recharge of cooler, less saline water from above and from the sides; (b) a possible slight reduction in bulk porosity due to calcite precipitation where cooler recharge waters come into contact with the hotter reservoir rocks; and (c) a slight two-phase condition around the production intervals.

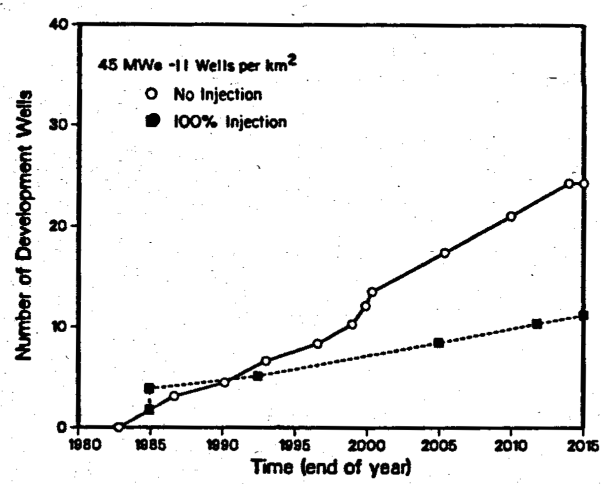

Figure 4. Effect of injection on the number of development wells needed to produce 45 MW_e at Olkaria using a density of 11 wells/km^2 (Bodvarsson et al., 1985b).

The study also showed that during 1981–1983 there was a reversal in the resistivity of the production region, which can be explained by the collapse of the two-phase region due to continued cooling of the reservoir. This hypothesis is supported by noted changes in the SiO_2 content of the produced brines as well as wellhead temperatures.

Hydrogeologic Model of Cerro Prieto. The hydrogeologic model of Cerro Prieto was updated based on data from recently completed wells. In the eastern region of the field a deeper reservoir (γ) was identifed at depths below 3100 m, that feeds a shallower reservoir (β) by fluid flow up a major normal fault (H) identified in earlier geologic studies (Halfman et al., 1985).

Enthalpy Transients in Two-Phase Geothermal Systems. A sensitivity study was carried out to determine the rock matrix and fracture parameters that control the enthalpy rise in fractured porous media under two-phase conditions (Lippmann and Bodvarsson, 1985). It was shown that the enthalpy transients are most sensitive to the characteristics of the relative permeability curves, matrix permeability and thermal conductivity, and fracture spacing and porosity. In contrast to porous media, in these fractured systems the effects of matrix porosity on enthalpy is small (Figure 5).

DOE-CFE Agreement on Geothermal Energy. LBL assisted DOE in the negotiations of a new three-year cooperative agreement with Comisión Federal de Electricidad (CFE). In February 1985 LBL organized a workshop between CFE and DOE-sponsored groups to review the latest data and results on the Cerro Prieto and Los Azufres fields, and to outline possible joint projects to be carried out under this agreement.

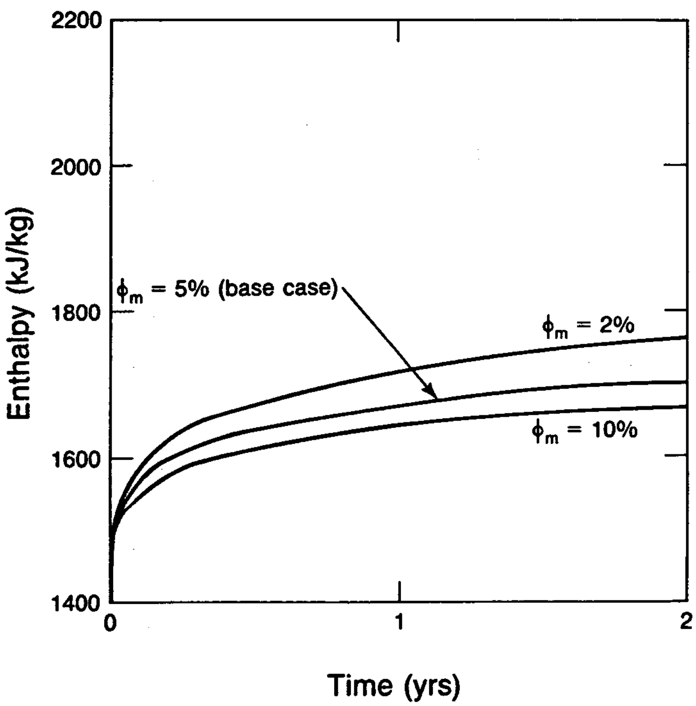

Figure 5. Effect of rock matrix porosity on flowing enthalpy transients in fractured two-phase geothermal systems (Lippmann and Bodvarsson, 1985).

Cognizant Laboratory Activities. As cognizant laboratory in Geothermal Reservoir Technology, LBL continued to assist DOE in formulating research plans for its Geothermal Reservoir Technology Program. To further determine the research needs of the geothermal industry and to review the appropriateness of DOE-funded projects to meet these needs, LBL organized and hosted on March 12, 1985 the second meeting of the Review Panel on Reservoir Technology (a third meeting is scheduled for September 30, 1985).

The results of the Panel meeting were reported to DOE for the consideration of GTD managers, and are available to the geothermal community (see Geothermal Resources Council Bulletin, July/August 1985, pp. 27–28).

PROPOSED PLANS FOR FY1986

An outline of LBL's FY1986 Geothermal Reservoir Technology activities as proposed to DOE is given below. The final program is being evaluated by GTD managers.

Subtask 1. Characterization and Mapping of Reservoir Parameters, Processes and Spatial Dimensions.

1A. Develop quantitative models of natural state and evolution of vapor-dominated geothermal reservoirs.

1B. Improve well testing techniques, especially for heterogeneous and fractured media systems.

1C. Explore applications of chemical data for reservoir diagnostics, using distributed-parameter models.

1D. Organize a joint industry-DOE/LBL workshop on instrumentation for wellhead and downhole measurements.

Subtask 2. Monitoring and Prediction of Reservoir Changes During the Production Lifetime.

2A. Demonstrate techniques for analyzing and predicting reservoir response to exploitation combining reservoir engineering, geophysical and chemical data.

2B. Study rock-fluid interactions and their impact on reservoir performance.

2C. Investigate effects of multiple feed zones on the behavior of geothermal wells.

Subtask 3. Improvement of Techniques for Modeling Reservoir Behavior.

3A. Develop capabilities for realistic modeling of brines and rock-fluid interactions at reservoir temperatures and pressures.

3B. Improve accuracy and efficiency of existing numerical codes.

Subtask 4. Fracture detection and mapping.

4A. Laboratory Studies.

4A-1. Seismic-acoustic modeling.

4A-2. Electromagnetic (EM) modeling.

4B. Numerical studies surface-borehole and cross-hole EM techniques.

4C. Field investigations.

4C-1. Vertical seismic profile survey.

4C-2. Electrical anisotropy.

4C-3. Well log analysis.

4C-4. Tectonics and fracture analysis.

Subtask 5. Laboratory Experiments.

5A. Perform and analyze laboratory experiments on "characteristic curves" (relative permeability and capillary pressure).

Subtask 6. Field Case Studies.

6A. Joint industry-LBL studies on U.S.fields.

6B. Analysis of Klamath Falls data.

6C. Field-demonstrate techniques developed under Subtasks 1 through 4.

Subtask 7. DOE-CFE Agreement.

7A. Assistance to DOE in technical coordination of the agreement.

7B. Delineation and descriptive studies of the Cerro Prieto and/or Los Azufres fields.

7C. Monitoring and modeling studies of the Cerro Prieto and Los Azufres fields.

7D. Data transfer between DOE and CFE.

Subtask 8. DOE-ENEL Agreement.

8A. Reservoir technology studies.

Subtask 9. Cascades Studies.

9A. Geophysical studies.

9B. Reservoir engineering studies.

Subtask 10. Cognizant Laboratory in Reservoir Technology.

10A. Assistance to DOE.

10B. LBL's Industry Review Panel.

ACKNOWLEDGEMENTS

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PAPER UNAVAILABLE

PRESSURE DISTRIBUTION AROUND A WELL PRODUCING AT CONSTANT PRESSURE IN A DOUBLE-POROSITY RESERVOIR

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ABSTRACT

This paper presents the characteristics of the pressure response of observation wells during a constant pressure test in a double-porosity bounded system. Wellbore skin in the constant pressure active well is considered negligible. The interacting effects of the exterior radius, r_{eD}, and the interporosity flow parameter, λ, are examined in pressure-radius and pressure-time responses. The pressure-radius semilog responses are semilog straight in the region around the well, indicating a constant rate in space. The shape of the fracture interference pressure response of the observation well is similar to the pressure response during constant rate tests in double-porosity systems. The dimensionless pressure response has a transition period where, for the pseudo steady state interporosity flow model, the pressure is constant. Interference fracture pressure responses for the pseudo steady state and the transient interporosity flow models are compared.

INTRODUCTION

The model for a well producing at a constant pressure is used for decline curve analysis. The mathematical solution for the rate decline of a single-porosity system was presented by *Carslaw and Jaeger* [1960] and *Van Everdingen and Hurst* [1949]. The interference pressure response to a constant pressure test was considered by *Uraiet and Raghavan* [1980], again in a single porosity-reservoir. They presented log-log type curves for various interference wells in an infinite reservoir.

In naturally fractured reservoirs, fluid flows both in the fractures and in the matrix blocks. *Barenblatt and Zeltov* [1960] and *Warren and Root* [1963] presented a mathematical model for double-porosity systems with pseudo steady state (PSS) matrix behavior. *Da Prat et al* [1981] and *Raghavan ad Ohaeri* [1980] considered the rate decline of a well producing at constant pressure in a bounded double-porosity system. *Da Prat et al* [1981] presented the Laplace solution for the rate decline of a well including wellbore skin, but presented type curves only for zero skin. Also, they did not present a single log-log type curve for various combinations of the three parameters that were considered, r_{eD}, ω, and λ.

Sageev et al [1985] presented a decline curve analysis method that extends the method presented by *Fetkovich* [1980] to double-porosity systems. They presented a single log-log type curve that describes the rate decline behavior as a function of four parameters: r_{eD}, S, ω, and λ. They used the PSS interporosity flow model for developing the type curve, but also considered the relation between the PSS and the transient interporosity flow model with fractured skin. The double-porosity model that includes transient matrix flow with fracture skin was presented by *Moench* [1983] and *Moench* [1984].

In this paper, we examine the pressure distribution around a well producing at a constant pressure, without wellbore skin, in a bounded double-porosity reservoir. Both pressure-radius profiles at fixed times, and pressure-time responses at fixed locations are presented. The effects of λ and r_{eD} on interference pressure responses are considered, as well as the practical aspects of interference constant pressure testing in double-porosity systems.

THEORY

The following presents a short description of the mathematical solution for a well producing at constant pressure in a double-porosity bounded reservoir. Reservoir and fluid properties are considered homogeneous, and gravity and inertial effects are neglected. *Deruyck et al* [1982] presented the fracture diffusivity equation:

$$\frac{k_f}{\mu} \nabla^2 p_f = \left[\phi \mu c_t\right]_f \frac{\partial p_f}{\partial t} - q^* \tag{1}$$

where q^* is the rate of flow between the matrix and the fractures. The initial and boundary conditions associated with the fracture diffusivity equations are:

$$p_f(r,0) = p_i \tag{2}$$

$$p_f(r_w,t) = p_{wf} \tag{3}$$

$$\left[\frac{\partial p_f}{\partial r}\right]_{r_e} = 0 \tag{4}$$

Making use of the initial condition, the Laplace transformation of the dimensionless form of equation (1) is, *Deruyck et al* [1982]:

$$\frac{d^2\bar{p}_{fD}}{dr_D^2} + \frac{1}{r_D}\frac{d\bar{p}_{fD}}{dr_D} - sf(s)\bar{p}_{fD} = 0 \tag{5}$$

where $\bar{p}_{fD}(r_D,s)$ is the Laplace transformations of $p_{fD}(r_D,t_D)$. The dimensionless groups are defined as:

$$p_{fD} = \frac{p_i - p_f}{p_i - p_{wf}} \tag{6}$$

$$q_D = \frac{qB\mu}{2\pi k_f h(p_i - p_{wf})} \tag{7}$$

$$t_D = \frac{k_f t}{\left[(\phi V c_t)_f + (\phi V c_t)_m\right] \mu r_w^2} \tag{8}$$

$$r_D = \frac{r}{r_w} \tag{9}$$

The variable $f(s)$ depends on the assumed interporosity flow model. For the pseudo steady state model:

$$f(s) = \frac{\omega(1-\omega)s + \lambda}{(1-\omega)s + \lambda} \tag{10}$$

For the transient interporosity flow model with slab-shaped matrix, $f(s)$ is:

$$f(s) = \omega + \frac{\lambda}{3s} a \tanh(a) \tag{11}$$

where: $a = \sqrt{\frac{3(1-\omega)s}{\lambda}}$

For the transient interporosity flow model with spherically-shaped matrix, $f(s)$ is:

$$f(s) = \omega + \frac{\lambda}{5s} b \coth(b) \tag{12}$$

where: $b = \sqrt{\frac{15(1-\omega)s}{\lambda}}$

The parameters ω and λ are defined as:

$$\omega = \frac{(\Phi Vc)_f}{(\Phi Vc)_f + (\Phi Vc)_m} \tag{13}$$

$$\lambda = \alpha \frac{k_m}{k_f} r_w^2 \tag{14}$$

and the other terms are defined in the Nomenclature.

The pressure solution for observation points away from the constant pressure active well in a bounded reservoir is:

$$\bar{p}_{fD} = \frac{I_1(r_{eD}g)K_0(r_Dg) + K_1(r_{eD}g)I_0(r_Dg)}{s\left[K_1(r_{eD}g)I_0(g) + I_1(r_{eD}g)K_0(g)\right]} \tag{15}$$

where $g = \sqrt{sf(s)}$

For an infinite system, the interference pressure solution is:

$$\bar{p}_{fD} = \frac{K_0(r_D\sqrt{sf(s)})}{sK_0(\sqrt{sf(s)})} \tag{16}$$

The matrix pressure for the PSS interporosity flow model is related to the fracture pressure by *Deruyck et al* [1982]:

$$\bar{p}_{mD} = \bar{p}_{fD}\left[\frac{\lambda}{(1-\omega)s + \lambda}\right] \tag{17}$$

PRESSURE DISTRIBUTION

As discussed by *Sageev et al* [1985], the dimensionless rate response of a double-porosity bounded system depends on the values of r_{eD}, ω, and λ. All the presented curves are evaluated using a numerical inversion method of the Laplace transformation developed by *Stehfest* [1970]. The dimensionless rate response of a double-porosity bounded reservoir is presented in **Figure 1**. The thin curve in the middle represents the response of an infinite homogeneous system. There are two curves for double-porosity bounded systems with a fixed value of the storage coefficient, $\omega = 0.01$, and a fixed value of the dimensionless radius, $r_{eD} = 10^4$. In the uppermost curve, the value of λ is relatively large (10^{-4}), and the double-porosity effects take place prior to the effects of the exterior no-flow boundary. Hence, the rate response is infinite acting at early time controlled by the fractured system, then flattens out for about two log cycles when the rate is almost constant, to be followed by an exponential rate decline of the combined fracture-matrix system.

In the lowermost curve in **Figure 1** the value of λ is small (10^{-9}), and the effects of the no-flow exterior boundary take place prior to the double-porosity effects. in this case, the infinite acting flow period is followed by an exponential decline of the rate, controlled by the fractured portion of the reservoir. The first exponential decline is followed by the double-porosity effects, yielding almost a constant wellbore rate, as the matrix pressure approaches the fracture pressure. After the flattening flow period, the rate declines exponentially, representing the depletion of the combined fracture-matrix system.

Figure 2 presents the dimensionless rate decline curve when the double-porosity effects take place before the effect of the exterior boundary. Also, six dimensionless times are marked on **Figure 2**, denoted by 1 through 6. Dimensionless pressure profiles for both the matrix and the fractures are presented in **Figure 3**. The first profile, for $t_D/\omega = 10^4$ represents the end of the infinite acting flow period of the fractured system. Hence, the matrix dimensionless pressure is negligible, and the fracture dimensionless pressure is negligible at the boundary, $r_{eD} = 10^4$. The pressure profiles marked 2 and 3 represent the intermediate flow period, when the fluid flow from the matrix supports a constant wellbore rate. During this flow period the matrix is depleting, as suggested by curves 2 and 3, yet, the fracture pressure is almost constant as a result of the flow from the matrix to the fracture. The forth pressure profile represents the end of the infinite acting flow period of the combined matrix-fracture system. Hence, the pressure in the matrix is slightly higher than the fracture pressure, but cannot be distinguished in the figure. The fifth and sixth profiles denote the exponential depletion of the combined matrix-fracture system, as the pressure profiles approach the value of 1.

Figure 4 presents the dimensionless rate decline curve when the effects of the exterior boundary take place prior to the double-porosity effects. The same six dimensionless times as in **Figure 2** are marked on **Figure 4**, denoted by 1 through 6. The pressure profiles for the dimensionless rate response described in **Figure 4** are presented in **Figure 5**. The first three pressure profiles describe the infinite acting flow period of the fractured system. The fracture pressure is declining throughout the reservoir, while the matrix pressure is constant at the initial pressure, p_D=0. The forth pressure profile describes the exponential decline of the fractured system caused by the presence of the no-flow exterior boundary. The fifth profile represents the double-porosity effects, resulting in a flattening of the wellbore rate, see **Figure 4**. The pressure depletion of the matrix is noticeable, while the fracture pressure is almost constant, indicated by the slow upward movement of the pressure profiles. The sixth pressure profile represents the end of the transition flow period when the rate response changes from being dominated by the fractured system, to the combined matrix-fracture system. The matrix pressure approaches the fracture pressure and eventually, the complete reservoir depletes exponentially.

The Semi-log pressure profiles presented in **Figures 3** and **5** are straight lines in the region surrounding the wellbore. This indicates a constant rate in space. The slope of the semi-log pressure profiles is proportional to the fracture flow rate that decreases with time. The constant rate flow period at the well is accompanied by a period when the slope of the pressure profiles is almost constant.

INTERFERENCE RESPONSES

In this section we examine the pressure-time responses at various locations away from the active constant pressure well. The double-porosity effects and the exterior boundary effects on interference pressure responses are examined for the PSS interporosity flow model, followed by a short discussion of transient interporosity flow models. We assume that wellbore storage is negligible at interference wells.

Interference pressure responses when the double-porosity effects take place prior to the effects of the exterior boundary are presented in Figure 6. Four dimensionless radii are considered for a fixed value of the dimensionless exterior radius, $r_{eD} = 10^4$. The thick family of curves represents the dimensionless pressure response of the fractures and the other family of curves represents the dimensionless pressure response of the matrix blocks. The interference response of the fractures increases initially, in this case up to $t_D/\omega = 10^4$. Then, the dimensionless pressure becomes practically constant for about two log cycles. The length of the constant pressure period is proportional to the log of $1/\omega$. After $t_D/\omega=5*10^5$, the pressure response of the combined matrix-fracture system increases, and is infinite acting up to $t_D/\omega = 10^{10}$ (as can also be seen in Figure 1). At $t_D/\omega = 10^{10}$ the system depletes exponentially, and the dimensionless pressure approaches the value of 1.

The matrix pressure response is smoother than the fracture pressure response. The matrix and fracture pressure responses join to a single curve at $t_D/\omega = 5*10^6$ for this case, indicating a combined depletion of the total system. The constant pressure period of the interference fracture pressure response is significant. This is similar to the dimensionless pressure response of a well producing at a constant rate, as presented by *Deruyck et al* [1982]. The flattening of the pressure response is indicative of double-porosity behavior of fissured systems. The derivative of the interference pressure response has a double hump that is similar to the pressure derivative presented by *Bourdet et al* [1984].

Interference pressure responses when the exterior boundary effects occur prior to the double-porosity effects are presented in Figure 7. In this case, the system behaves like a single porosity system up to $t_D/\omega = 5*10^7$. This is a much longer time in comparison to the case when the double-porosity effects take place prior to the boundary effects, that was at $t_D/\omega = 10^4$. The matrix pressures for the various dimensionless radii are practically the same , as indicated in Figure 7, and can be seen in the fifth and sixth matrix pressure responses in Figure 5. Figure 8 presents the responses of the same system described in Figure 7, except that $1 - p_D$ is used instead of p_D. Here, the constant pressure period is present, but occurs late into the test, starting at $t_D/\omega=10^9$. Also, the difference between the responses at various radii is much smaller in comparison to the responses described in Figure 6. When $t_D/\omega > 10^{11}$, the dimensionless rate of the combined matrix-fracture system declines exponentially, and $1-p_D$ approaches 0.

Interference fracture responses for the PSS and transient interporosity flow models are presented in Figure 9. Here, the double-porosity effects take place prior to the boundary effects, $r_{eD}=10^4$, $r_D=100$, $\omega=0.01$, and $\lambda=10^{-4}$. Slab and spherically shaped matrix blocks for the transient flow model are considered. The introduction of transient matrix flow reduces the pressure differences between the matrix and the fractures, and reduces flattening of the pressure response. In the responses presented in Figure 9, the PSS flow model has a significant constant pressure period, and the two transient flow models do not. The three fracture responses converge to a single curve at $t_D/\omega=5*10^5$, that is one log cycle earlier than when the PSS matrix pressure converges to the fracture response, see Figure 6. *Sageev et al* [1985] showed that transient matrix blocks with fracture skin greater than 1/3 yield a response similar to the PSS interporosity flow model.

CONCLUSIONS

1. The fracture pressure profiles in the region around the active constant pressure well are semi-log straight, indicating constant rate in space.
2. The slope of the fracture pressure profiles is nearly constant during the constant rate flow period at the active well.
3. The fracture pressure response at observation wells has a constant pressure period (PSS interporosity flow model) similar to the constant rate tests.
4. For a double-porosity reservoir with a small value of the interporosity flow parameter, λ, the double-porosity effects occur late into the test, and may be detected only if $(1-p_D)$ is used instead of p_D.
5. The magnitude of the interference pressure drops at observation wells increases as the distance between the observation well and the active well decreases.
6. For a given reservoir, the interference matrix pressure converges to the interference fracture pressure at the same time, and the double-porosity effects occur at the same time for all interference locations.
7. Transient interporosity matrix flow reduces the pressure difference between the matrix and the fractures, and reduces the flattening of the interference pressure response. The fracture interference pressure responses for double-porosity reservoirs with slab shaped or spherically shaped matrix blocks are similar.

ACKNOWLEDGEMENT

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NOMENCLATURE

B =	formation volume factor
I_0 =	modified Bessel function, first kind, zero order
I_1 =	modified Bessel function, first kind, first order
K_0 =	modified Bessel function, second kind, zero order
K_1 =	modified Bessel function, second kind, first order
V =	ratio of volume of one porous system to bulk volume
c =	compressibility
h =	formation thickness
k =	permeability
p =	pressure
p_D =	dimensionless pressure
$\bar{p}_D$ =	Laplace transform of p_D
q =	volumetric rate
q_D =	dimensionless rate
$\bar{q}_D$ =	Laplace transform of q_D
q^* =	matrix flow rate
r =	radius
s =	Laplace variable
t =	time
t_D =	dimensionless time
λ =	interporosity flow coefficient
μ =	viscosity
ϕ =	porosity
ω =	dimensionless fracture storage
α =	interporosity shape factor

Subscripts

D =	dimensionless
f =	fracture
m =	matrix
t =	total
w =	wellbore
e =	exterior

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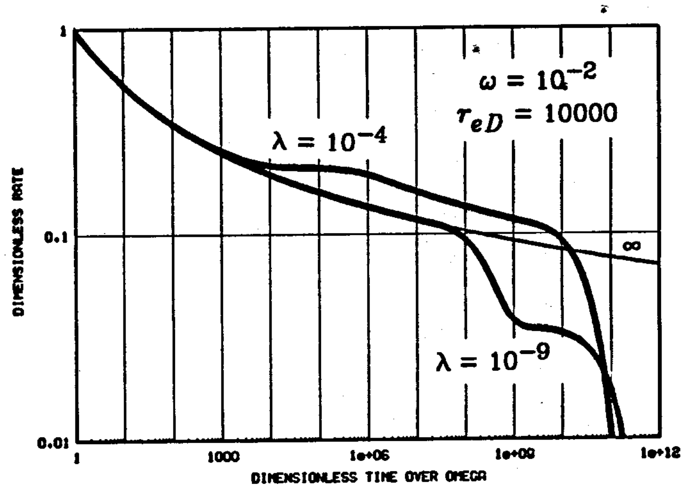

FIGURE 1: A typical response of an infinite and finite double-porosity system, PSS model, ω=0.01, λ=10^{-4}, 10^{-9}, and r_{eD}=10^4.

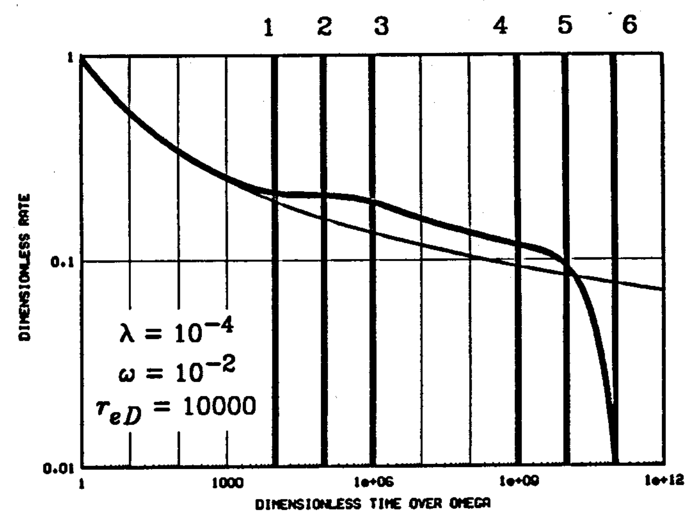

FIGURE 2: Log-log response for a finite double-porosity system, PSS model, ω=0.01, λ=10^{-4}, and r_{eD}=10^4.

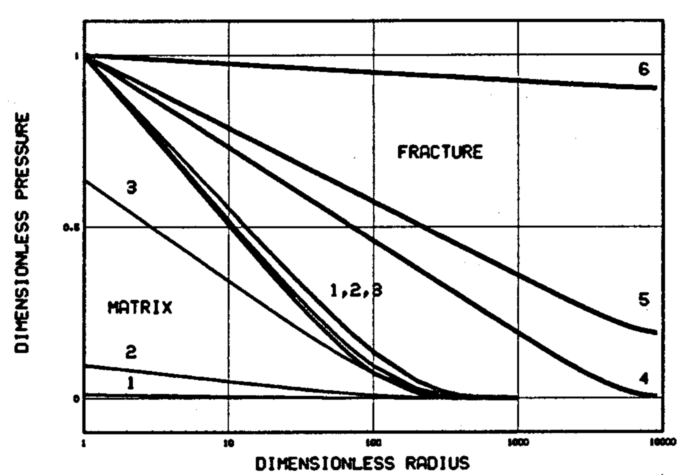

FIGURE 3: Dimensionless pressure profiles for a finite double-porosity system, PSS model, ω=0.01, λ=10^{-4}, and r_{eD}=10^4.

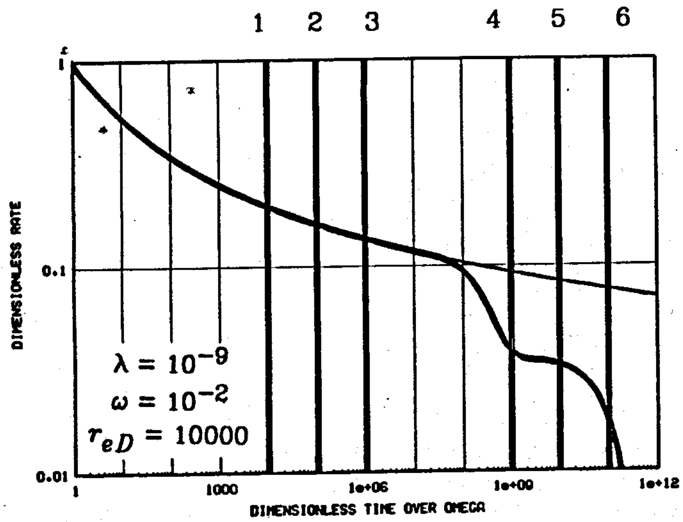

FIGURE 4: Log-log response for a finite double-porosity system, PSS model, ω=0.01, λ=10^{-9}, and r_{eD}=10^4.

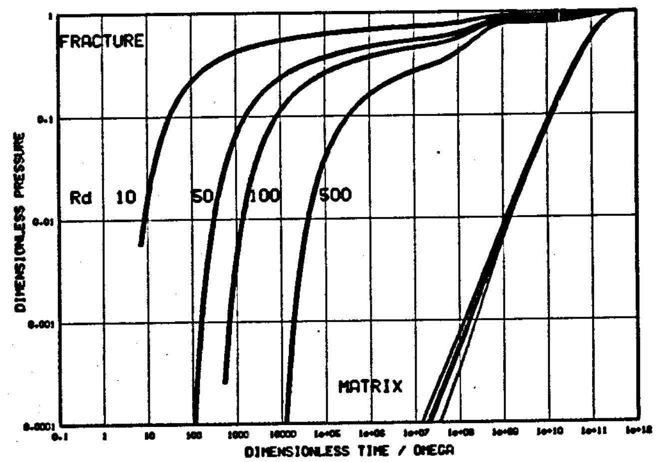

FIGURE 7: Interference responses for a finite double-porosity system, PSS model, ω=0.01, λ=10^{-9}, r_D=10,50,100,500, and r_{eD}=10^4.

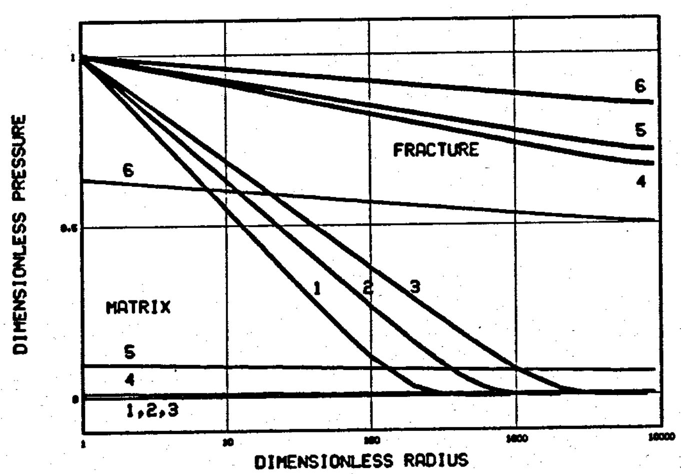

FIGURE 5: Dimensionless pressure profiles for a finite double-porosity system, PSS model, ω=0.01, λ=10^{-9}, and r_{eD}=10^4.

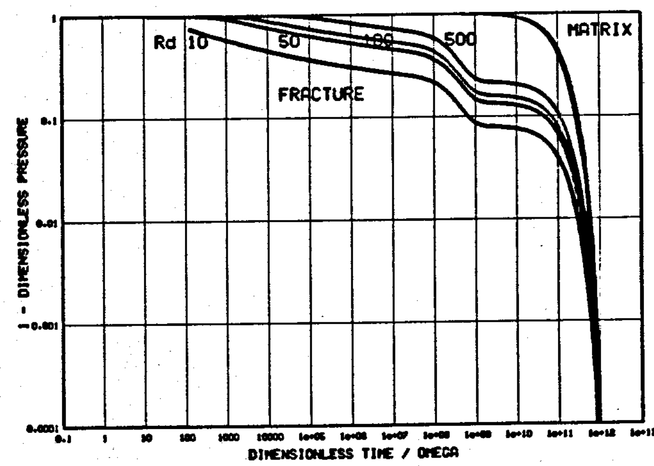

FIGURE 8: Interference responses for a finite double-porosity system, PSS model, using $1-p_D$ instead of p_D. ω=0.01, λ=10^{-9}, r_D=10,50,100,500, and r_{eD}=10^4.

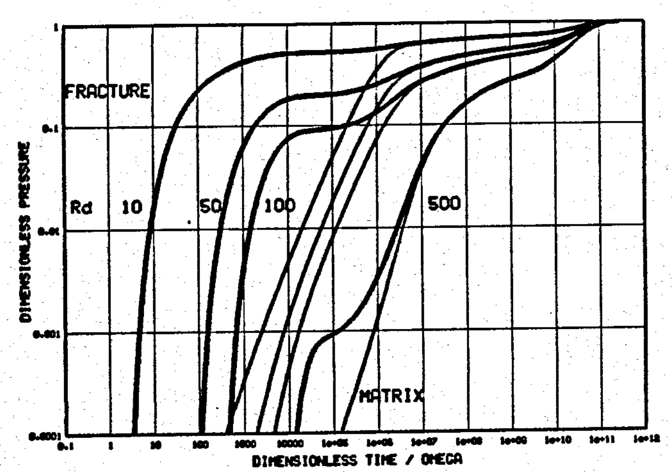

FIGURE 6: Interference responses for a finite double-porosity system, PSS model, ω=0.01, λ=10^{-4}, r_D=10,50,100,500, and r_{eD}=10^4.

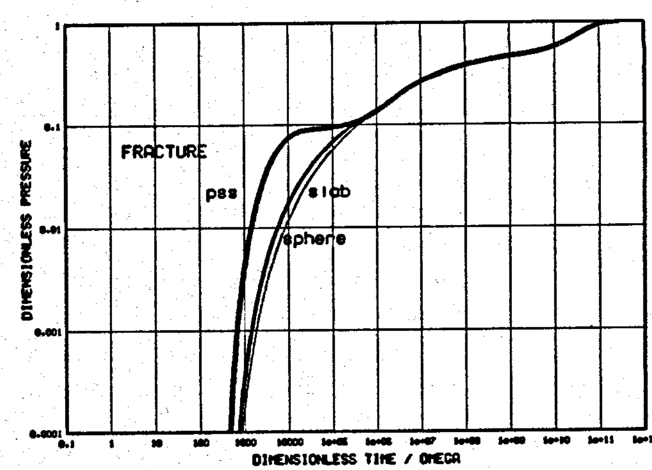

FIGURE 9: A comparison between interference fracture pressure response for PSS and transient interporosity flow models. ω=0.01, λ=10^{-4}, r_D=100, and r_{eD}=10^4.

ADVANCED MATERIALS FOR GEOTHERMAL ENERGY PROCESSES

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SUMMARY

The Geothermal Technology Division initiated the Geothermal Materials Program in 1976 to ensure that the private sector development of geothermal energy resources is not constrained by the availability of technologically and economically viable materials of construction. Since 1978 Brookhaven National Laboratory (BNL) has provided technical and managerial assistance in the implementation of the long-term high-risk effort. Major successes have been attained in the development of elastomers for high-temperature applications and in the use of polymer concrete liners for corrosion protection. Both technologies have been successfully transferred to industry.

In the case of the high temperature Y-267 EPDM (ethylene propylene, diene, methylene) elastomer, the operating limits for elastomeric parts were increased from the range 149°C-204°C to 260°C-316°C. Based upon extensive testing by L'Garde, Inc., and over 25 other organizations during the past 6 yr, no better elastomer for geothermal service is known. Reductions in cost up to several hundred times compared to those of other high temperature elastomers have been attained. Over 15 laboratory and 20 field case histories have been documented. Current uses include seals in logging tools, casing packers, gate valves, BOP rams, shock subs, and jars.

The materials program has also produced the most comprehensive and thorough examination of the geothermal cementing problem undertaken thus far. As part of the program, the first known downhole testing of cements in a flowing geothermal well was conducted. Nine cements satisfied the test criteria. Unfortunately the exposure temperature was only 214°C, and it is considered essential to have data at a temperature of at least 300°C before definitive conclusions can be made regarding the hydrothermal stability at economically attractive well conditions. Current budget constraints prevent the performance of these needed tests.

Research and development efforts aimed at further cost reductions and extension of service life are currently in progress. Tasks include high temprature elastomers for dynamic sealing applications, advanced materials for lost circulation control, waste utilization and disposal, corrosion resistant elastomeric liners for well casing, high temperature lightweight cements, and non-metallic materials for heat exchanger applications. The major thrusts of the FY 1985 efforts are summarized below.

1. High Temperature Elastomers for Dynamic Sealing Applications

   - Chemical modification of previously developed and tested Y-267 EPDM 260°C static seal material for use in dynamic sealing applications.

   - Optimization of EPDM formulations for use in critical high cost applications such as in downhole drill motors and open-hole packers.

2. Advanced Materials for Lost Circulation Control

   - Hydrothermally stable and pumpable chemical systems are being investigated for use as lost circulation control materials in geothermal well drilling operations.

3. Pitting Resistant Steels

   - Studies of the mechanism whereby high corrosion resistance is obtained through alloying of stainless steels with molybdenum combined with nitrogen.

4. Geothermal Waste Utilization and Disposal

   - Studies of methods for utilizing waste constituents as raw materials for cementitious binders or as nonleachable fillers in composites that can be used for general construction purposes.

- Analyses of biochemical techniques for concentration and subsequent removal of heavy metals from waste.

5. Materials for Non-Metallic Heat Exchangers

   - Development of corrosion resistant metallic and silicon carbide-filled composites which have thermal conductivities in the range of stainless steels.

6. Corrosion Resistant Elastomeric Liners for Well Casing

   - Investigation of high temperature chemical coupling systems for bonding elastomeric liners to carbon steel well casing.

   - Data on corrosion resistance of Y-267 EPDM-lined carbon steel casing for comparison with those for high chrome and nickel alloys.

7. High Temperature Geothermal Well Cements

   - Characterization of promising high temperature well cements under placement and downhole environmental conditions duplicating most of the well completion variables.

   - Preliminary screening tests on lightweight cement slurries.

8. Corrosion in Binary Geothermal Systems

   - Quantitative corrosion data from laboratory and plant tests for metals presently used in binary plants and other more potentially resistive metals and nonmetals.

9. High Temperature Cathodic Protection Systems

   - Testing and characterization of high temperature electrochemical processes designed to cathodically protect the external surfaces of well casing and heat exchangers.

Recent results from several of these efforts are given in the body of this paper. It is expected that Tasks 2, 4, 5, and 7 will continue in FY 1986.

INTRODUCTION

Among the most pressing problems constraining the development and expanded use of geothermal energy resources for electric power generation is the lack of satisfactory component and system reliability. This is due to the unavailability, on a commercial scale, of cost-effective materials that can function in a wide range of geothermal environments and to the unavailability of a comprehensive body of directly relevant test data or materials selection experience. Suitable materials are needed for service in geothermal wells and in process plant equipment. For both situations, this requires materials that can withstand high-temperature, highly-corrosive, and scale-forming geothermal fluids. In addition to requiring a high degree of chemical and thermal resistance, the downhole environment places demands on the physical/mechanical properties of materials for components utilized in well drilling, completion, pumping, and logging.

In 1976, the GHTD started the Geothermal Materials Program to address materials-related problems, and since 1978 Brookhaven National Laboratory has provided technical and managerial assistance in the implementation of the effort. Major successes have been attained in the development of elastomers for high-temperature applications[1] and in the use of polymer concrete liners for corrosion protection.[2] Both technologies have been successfully transferred to industry. Other outputs from the materials program being used by the geothermal industry include the characterization of well cements after downhole exposure to flowing brine,[3] and handbooks summarizing the performance of materials in above-ground and downhole geothermal environments.[4,5]

Achievement of the program goal requires the effective management of a wide range of technological and economic problems. The GHTD/BNL approach is to optimize the benefits of materials-related R and D through the resolution of selected problems. The program strategy concentrates on developing an optimum balance between 1) problems whose solutions have a short to moderate term impact on the operation of prototype plants, and 2) long-term R and D designed to have significant impacts on industrial viability and productivity through improvements in materials performance and costs. The program strategy is to conduct projects that 1) identify materials-related needs constraining commercialization, 2) evaluate the applicability of existing materials and technology to geothermal problems, 3) develop specific and generic solutions to materials problems that have major impacts on geothermal energy costs and productivity, and 4) provide appropriate and adequate incentives and mechanisms for the stimulation of industry-sponsored geothermal materials R, D and D.

RESULTS

1. High Temperature Elastomers For Dynamic Sealing Applications

This project performs applied research to optimize a Y-267 EPDM elastomer formulation, developed earlier by GHTD for static seal applications, for use in dynamic seal applications at temperatures up to 260°C. Elastomers for these conditions do not currently exist, and a successful development could substantially reduce drilling and completion costs. The effects of compositional changes on the properties of the elastomer are being determined, and the formulation optimized to yield the specific sealing requirements. Prototype and full-scale testing will be performed. Based upon the results from the generic research, a specific sealing application will be targeted for continued R and D.

The Y-267 EPDM elastomer compound was originally developed for geothermal casing packer applications. The primary requirements were to develop a thermochemically stable compound with excellent extrusion resistance. Consequently, the Y-267 EPDM compound contains no special consideration for dynamic seal applications. However, it is highly abrasion resistant, a characteristic that comes along with its excellent extrusion resistance which is partially provided by a small particle size black.

The current project is to modify the Y-267 EPDM compound for better dynamic seal characteristics while maintaining its excellent thermochemical resistance. The effort is centered around improving the lubricity and the lubricability of the compound. The effort evaluates developmental compounds in a simple rotating (300 rpm) shaft environment at 204°C with differential pressures up to 250 psi. Once the initial development is complete, the development will move into a phase devoted to a specific application, e.g., Moineau motor stator. The precise application will be selected based on the results of the initial development. The initial development is scheduled for completion towards the end of calendar year 1985.

2. Advanced Materials for Lost Circulation Control

This project is investigating hydrothermally stable and pumpable chemical systems for use as lost circulation control materials (LCM) at temperatures up to 300°C. Lost circulation problems directly and indirectly represent 20 to 30% of geothermal well costs, and high temperature materials that will yield permanent repairs that can be made without removal of the drill string in order to set casing and cement, do not exist. The investigations include laboratory studies of interactions between bentonite-based drilling muds, reactive solid additives, and chemical fluids. The pumpability characteristics of the slurries and the properties of the cured materials are also determined.

An interim report describing results through March 1985 has been published.[6] A formulation which appears to have high potential as a new cementitious lost circulation control material is composed of bentonite, ammonium polyphosphate (AmPP), borax, magnesium oxide, and water. The appropriate combination of these ingredients results in the formation of slurries with viscosities and thickening times adequate to allow placement. After curing at elevated hydrothermal temperatures, the cement produced was characterized by a compressive strength >500 psi at 2 hr age, a permeability to water $<2.0 \times 10^{-4}$ Darcy, and a linear expansion >15%. The reaction compound responsible for the strength development at 300°C was found to be an assemblage of interlocking crystals composed of a grown thin-plate crystal. It was inferred that this microcrystalline cluster is associated with montmorillonite and AmPP-based complex formations. Consistometer tests performed at Sandia confirmed the pumpability of the materials at high temperature and pressure.

Another promising high temperature LCM was recently identified.[7] In this work, it was found that the addition of a cement, borax and glass fiber mixture to bentonite slurries produces a LCM that is pumpable at high tempertures as a result of the retardation resulting from the hydrolysis of the borax. A series of slot tests were completed in July. A series of larger-scale tests in the Sandia National Laboratory Lost Circulation Test Facility are scheduled for FY 1986.

3. Corrosion Resistant Elastomeric Liners for Well Casing

The geothermal fluids in the Imperial Valley are characterized by brines with high levels of corrosive substances. This drives the operators to using super alloys for routine components such as tubing and piping. This can be extremely expensive, suggesting the use of the process industry practice of lining pipe to protect it from corrosion, a perfect application for Y-267 EPDM.

DOE/BNL formed a cost sharing project with a geothermal operator to adapt the Y-267 EPDM for this application. Processing and adhesion to steel pipe are the primary technologies to be developed to be in a position to test the feasibility of the concept. Currently, no known system to bond the Y-267 EPDM to steel exists which can withstand the 288°C postcure and the usually high temperatures associated with Y-267 EPDM applications. In addition, the uncured Y-267 EPDM is stiff and has no tack, making it difficult to lay up and mold onto the ID of pipe. The objective of this relatively small effort is to develop two (36 in.) lined prototype casing sections which can be field tested with actual brine flowing through them. The development of the prototypes is scheduled for completion in early 1986.

4. Geothermal Waste Utilization and Disposal

Before the large-scale development of geothermal energy can occur, environmentally and economically acceptable methods for the disposal of large quantities of waste must be developed. These wastes represent a large, low-grade domestic mineral resource. If economic methods for recovery are developed, the wastes could provide an important source of strategically important metals as well as revenues comparable to those from electric power generation.

The initial phase of the DOE/BNL program consists of an assessment in which data pertaining to the following questions are being compiled.

- What are the applicable environmental regulations at the state level for the states of interest?
- What are the applicable federal environmental regulations pertaining to geothermal resources and to what extent will they be involved?
- Are any of the exisiting regulations expected to change? If so, what are the timeframes for resolving these issues?
- Evaluate the regulations for definitions of waste classifications and for standard/proposed tests required. How are some of these required tests formulated and why?
- What are the near/far term requirements for the disposal of these waste?
- What is the current state-of-the-art disposal practices for these wastes?
- Can the operators of the geothermal projects meet the current regulation requirements and waste disposal standards? Are current disposal practices adequate? Will these companies need more time to develop additional or alternative disposal methods?
- What are the types of wastes generated from geothermal processes?

Two experimental approaches which are complementary are being used in attempts to develop methods which will economically meet the disposal regulations identified above.

The first is the use of biochemical techniques to concentrate and remove toxic metals from wastes, and the second is to develop processes for converting toxic constituents from the wastes into nonleachable forms which can be used as a construction material or disposed of in conventional landfill sites.

The initial results from the BNL studies on the biochemical treatment of wastes have recently been published.[8] These studies have demonstrated that certain microorganisms can grow in the presence of high concentrations of toxic metals in geothermal sludge and are able to bioaccumulate heavy metals. The bioaccumulation is selective and several microorganisms have been tested for selective adsorption of uranium, thorium, cobalt, chromium, manganese, tin, and platinum. The results have shown that under the experimental conditions used, P. aeruginosa SCU has a preference for uranium, while P. aeruginosa PAO-1 and P. fluorescens exhibit a preference for thorium, and Aspergillus niger is selective for chromium and thorium.[8] Currently the P. aeruginosa is being used as a model system to study mechanisms by which the toxic metal resistances are manifested at the molecular level. Concurrent studies address the bioaccumulation mechanisms. While the metal resistance is specific and plasmid mediated, the surface selectivity may be related to resistance, or may be due only to the chemical structure of the cell wall and cell membrane components. The results support the view that in the metal-microorganism interactions, several mechanisms may be operative, which involve specialized metabolites, such as exo-cellular chelators, specific cell surface sites, and transport agents.

With regard to the conversion of toxic wastes into nonleachable forms, several inorganic and organic encapsulants have been tested. Materials used include methylmethacrylate, polyester, sulfur, magnesium polyphosphate cement, and portland cement. Other variables included water content, particle size, and method of encapsulation. Preliminary results indicated that several systems had leach rates well below those specified in the State of California regulations. Work to optimize the processes and to estimate costs is in progress.

5. Materials for Nonmetallic Heat Exchangers

This project is investigating thermally conductive polymer-based composites for use as corrosion resistant materials of construction for shell and tube heat exchangers in binary geothermal processes. Corrosion of the brine side of tubing in shell and tube heat exchangers has been a major problem in the operation of binary geothermal processes. Compared to the cost of high alloy steels, a considerable economic benefit could result from the utilization of a proven corrosion resistant polymer concrete material if sufficient heat transfer properties can be derived. The work consists of determinations of the effects of compositional and processing variables on the thermal properties of the composite, and measurements of the physical and mechanical properties after exposure to hot brine and isobutane.

To date, the maximum thermal conductivity obtained is 3.5 BTU/hr-ft-^{o}F, compared to a value of 11.2 BTU/hr-ft-^{o}F for the AL 29-4C ferritic stainless steel used in the tubes of the Heber heat exchangers. Assuming all other design factors equal, direct substitution of the polymer composites for the metal tubes will reduce the rating of the exchangers by ~12%. However, anticipated reductions in the fouling resistance of the polymer composite tubing may compensate for the thermal conductivity differences.

For the Heber binary plant, it has been reported that the heat exchangers and condensers represent ~30% of the total investment in plant equipment.[9] Therefore, since the cost of the polymer composite tubing is estimated to be in the same range as that for carbon steel, substitution for the AL 29-4C could significantly reduce the cost of future binary plants.

6. Corrosion in Binary Geothermal Systems

This program yields corrosion data from laboratory and plant tests for metals presently used in binary plants and other more potentially resistive metals and nonmetals. In operating binary processes, brine leakage into the organic working fluid side of the plants has resulted in unanticipated corrosion problems. Data are not available on the effects of salt, oxygen, and water impurities in isobutane and/or isopentane on the corrosion rates of metals. The work involves the exposure of test coupons in operating plants and in a laboratory test loop in which the levels of water, oxygen and salt can be varied. When completed, the program will yield quantitative information regarding the extent of corrosion that will occur upon contamination of the binary side of a plant, thereby allowing designers materials options.

CONCLUSIONS

The DOE Geothermal Materials Program is addressing problems whose solutions have a short to moderate term impact on the operation of prototype plants as well as conducting long-term R and D designed to have significant impacts on industrial viability and productivity in materials performance. Active technology transfer linkages are established and maintained. To date, the program has resulted in the development of the best known high temperature elastomer for geothermal service, and several other outputs from the program are being used or tested by industry. Current R an D efforts on dynamic seals, lost circulation control materials, and lightweight well cements may be used by industry in the near future. Other efforts on elastomer-lined well casing, encapsulation or biochemical concentration and separation of wastes, and nonmetallic heat exchanger tubing will require considerably longer development times.

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GEOLOGICAL AND GEOCHEMICAL TECHNIQUES FOR FRACTURE DEFINITION IN GEOTHERMAL RESERVOIRS

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INTRODUCTION

Fracture definition and mapping has been a major research objective of the Department of Energy's Reservoir Definition Program for several years. This initiative reflects both the importance of fracturing in controlling fluid pathways and a need for research which is indicated by industry's problems in exploring for and developing fractured geothermal reservoirs. This point is further emphasized by industry's comments at the recent meeting of the Geothermal Resources Council that injection techniques in high-temperature fractured reservoirs are considered experimental. Geothermal energy will not be considered a truly renewable energy resource until the mysteries surrounding fracture geometry and fluid-rock interaction are solved.

Fluid flow is fracture controlled in essentially all high-temperature geothermal systems. Some data on the geometry of the fracture zones and on the chemical and physical conditions within the reservoir can be obtained directly through well logs and from the chemistry of sampled fluids. Other geological and geochemical investigations of reservoir rocks can frequently provide a great deal of additional information that cannot be obtained from these measurements. This information may be particularly important during the early stages of a geothermal program when it may be difficult to obtain data on temperatures and fluid chemistries through downhole measurements because the rocks have been cooled by drilling fluids, and flow tests are of insufficiently long duration to remove all drilling fluid from the reservoir. Later, during the development of a field, when the number of drill holes has increased, geological and geochemical studies of the reservoir rocks can provide information on the directions of fluid flow, and guide further development to areas of high permeabilities.

Our fracture investigations are based on detailed studies of high-temperature geothermal systems, largely through the use of lithologic samples from drill cuttings or core. These studies develop the models of fracture geometries, permeability, and alteration that must be addressed by any geophysical or reservoir engineering modeling. They also provide the basis for understanding the effects of geothermal injection, which is discussed in more detail in the accompanying paper by Adams and Moore (this volume). Although many of the techniques we have applied are well established, some have not previously been applied to the study of geothermal systems. The unique applications presented in this paper include the structural models from the Baca system, the fluid inclusion gas research from the Imperial Valley, and the stable isotope investigations from Meager Mountain.

FRACTURE FORMATION AND GEOMETRY

Fractures are formed in the field of brittle deformation in the earth's crust. This field is normally defined by the depth limit of earthquake activity and is as shallow as 2 km in parts of Yellowstone (Smith and Braile, 1982) and about 7 km beneath the Coso and Roosevelt Hot Springs geothermal systems (Walter and Weaver, 1980; Zandt and Nielson, in preparation). Below the depths where earthquakes occur, deformation is by ductile flow rather than brittle fracture, and it is unlikely that adequate permeability can be sustained to support geothermal systems. Within the zone of brittle fracture, the geometry and extent of fracture development is dependent on rock type, overburden pressure, strain rate, and stress orientation.

Fracture permeability at the Baca geothermal system in the Valles caldera, New Mexico has been defined largely through the study of 40,000 m of cuttings and cores (Hulen and Nielson, 1983; Nielson and Hulen, 1984). This stratigraphic data has then been used to develop a structural cross-section (Fig. 1) which can then be compared to production data to determine fluid flow paths. Structural permeability is developed in faults and fractures which were formed during the eruptions of the Valles caldera and by subsequent structural doming of the area of geothermal exploration (Redondo resurgent dome).

Nielson and Hulen (1984) modeled the development of this structural dome to help explain the permeability relationships found in the Baca project area. For instance, while many faults and fractures were geothermal producers, many showed no signs of fluid or of hydrothermal alteration, but their permeability was evidenced by large amounts of lost circulation during drilling.

As a result of the doming process, the affected strata are subjected to differential stresses. In the upper portions of the dome (Fig. 2), the rocks are under tension. This commonly results in normal faulting along the crest of the dome. Approximately halfway down through the dome, a surface called the neutral plane separates

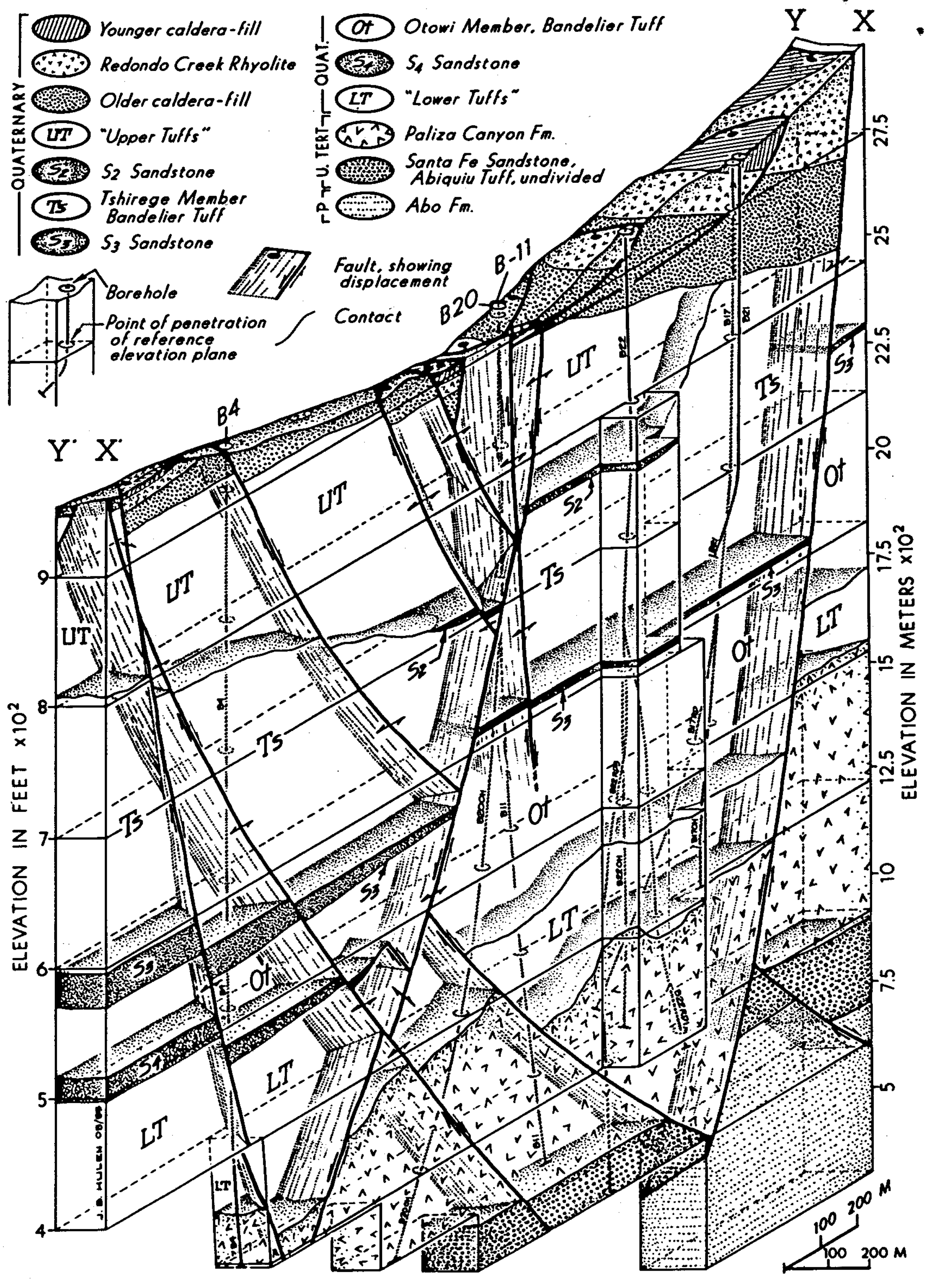

FIGURE 1
Three-dimensional geologic cross section of the Redondo Creek area (Nielson and Hulen, 1984).

the upper tensional environment from a lower region characterized by compression. In contrast to the normal faults above the neutral plane, the region below the neutral plane will be characterized by the development of conjugate shears. The amplitude of doming (ν_0) is related to the

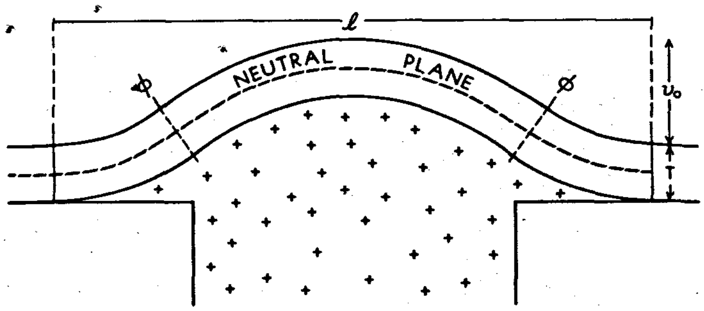

FIGURE 2
Idealized model of dome development.

diameter (ℓ) by the equation $\ell = [\frac{\nu_o T}{k(p-qT)}]$ where T is overburden thickness, q is unit weight of strata, p is magma pressure, and k is a constant (Johnson, 1970).

Nielson and Hulen (1984) concluded that the idealized model of dome development was modified by the reactivation of older structures associated with the Jemez fault. These structures were steep, throughgoing fault zones prior to the formation of the Redondo dome, and they have continued to maintain that character during and after the formation of the dome. It is our opinion that these reactivated faults are the principal conduits of upwelling hydrothermal fluids, and that successful wells in the field intersect these fractures, or fractures or stratigraphic horizons which communicate with these principal fluid conduits. The structural model developed is a predictive model in the sense that it in can be used to guide further exploration of fractures in this system (Nielson, 1985).

FLUID-FRACTURE INTERACTION

Geometry and distribution of fractures is only the first part of the equation in understanding the fracture controls on circulation in geothermal systems. Fluid interacts with fractures to either enhance permeability through dissolution or reduce permeability through alteration and precipitation. In the process of interaction between fluids and rocks, changes in mineralogy and physical trapping of fluid samples allow geochemical techniques to be used to quantify physical processes.

Data from Hydrothermal Minerals

The identification and distribution of the hydrothermal minerals occurring in the geothermal reservoir rocks must represent the first step in any program that will ultimately require geological or geochemical input. The recognition of "geothermal minerals" in fractured reservoirs that characterize the thermal systems outside of the Imperial Valley is frequently not simple. Detailed investigations of Roosevelt Hot Springs in Utah (Nielson et al., 1978; Capuano and Cole, 1982; Christensen et al., 1983) and Meager Mountain, British Columbia (Moore et al., 1985), among others, indicate that the reservoir rocks had been altered by several different unrelated thermal events. Thus, in many systems, particular care must be paid to the paragenetic sequences and detailed mineral relationships. Nevertheless, with care, a significant amount of information can be obtained.

Hulen and Nielson (1982, 1983, in press) utilized the distribution of secondary minerals at Baca to define permeable zones in reservoir rocks. Their investigations show that fluid flow has been confined principally to steeply dipping normal faults and subsidiary fractures associated with them. In addition, they demonstrated that thin sandstone lenses that interbedded with volcanic rocks at Baca could also act as thin stratigraphic aquifers when they were intersected by the steeply dipping faults. Permeability along many of these channels has been reduced or locally eliminated by hydrothermal self-sealing. Alteration from the surface through the base of geothermal production is of three distinctive types: argillic, propylitic and phyllic (Fig. 3). Strong phyllic

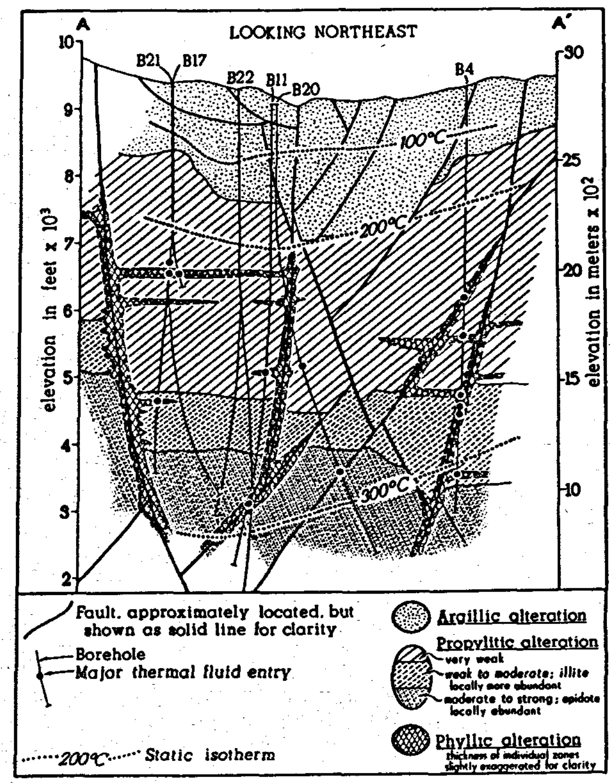

FIGURE 3
Hydrothermal alteration in the Baca geothermal system (Hulen and Nielson, in press).

alteration is typically associated with major active thermal fluid channels. Phyllic zones yielding no fluid were clearly once permeable, but now are hydrothermally sealed. The deepest well (B-12, 3423 m) in the dome may have penetrated the base of the active hydrothermal system. Below a depth of 2440 m in this well, hydrothermal veining

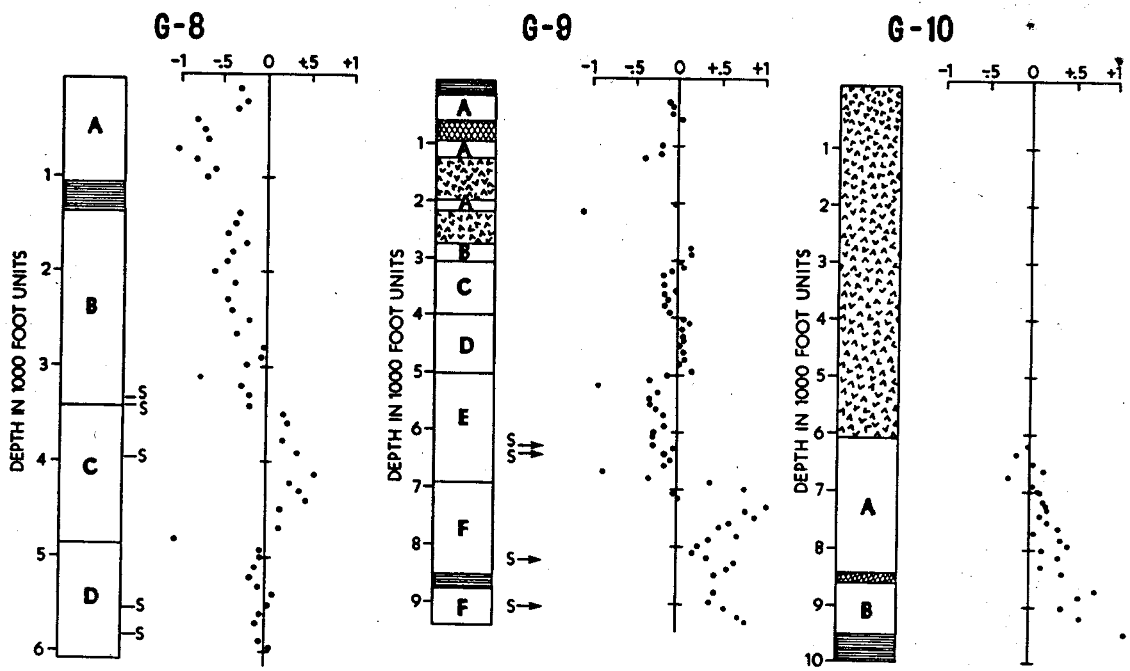

FIGURE 4
Stratigraphy within the greywackes from three wells in The Geysers. The greywacke is unshaded. Letters denote individual stratigraphic horizons which were differentiated on the basis of their chemical composition. A summary of the chemical variations is shown on the graph to the right of each lithologic log. Stratigraphic horizons between wells are not correlative. From Moore (1984).

disappears entirely and the rocks resemble those developed by isochemical thermal metamorphism. The transition is reflected by temperature logs, which show a conductive thermal gradient below 2440 m. This depth may mark the dome's neutral plane and indicates that exploration below this depth will be non-productive due to lack of permeability.

Moore et al. (1983, 1985) in a similar manner utilized the distribution of secondary minerals at Meager Mountain to locate zones of high permeabilities. This field appears to be similar to many of the Cascade stratovolcanoes currently being evaluated by the geothermal industry and by cooperative projects between DOE and industry. Meager Mountain is underlain by intrusive and metamorphic basement rocks that in places are intruded by young dikes related to recent volcanism. The basement rocks display evidence of at least three different and unrelated hydrothermal systems. Through careful petrographic and chemical studies, minerals related to each of the different events can be separated and their distributions mapped. Hydrothermal minerals related to the present geothermal system are also strongly zoned with respect to temperature. Here, three distinct hydrothermal alteration zones can be recognized. These include: 1) a low-temperature zone characterized by smectite and interlayered clays, 2) an intermediate temperature zone characterized by chlorite and illite, and 3) a high temperature zone containing epidote, actinolite and potassium feldspar. Data from other systems suggest that minerals of zone 1 probably formed at temperatures up to 225°C. The minerals of zone 2 are indicative of temperatures above 225°C but less than 300°C. Hydrothermal alteration in zone 3 probably occurred at temperatures above this range. The occurrence of these minerals and the general lack of significant veining of geothermal origin in the metamorphic and intrusive country rocks suggests that the dikes have been major conduits for the upwelling fluids.

Data from Rock Chemistry

During the past several years, UURI scientists have conducted significant new research on the role of rock chemistry as a tool for mapping rock types and permeable zones. This use of major element analyses to map lithologies has proven to be particularly useful for wells that are rotary drilled in sedimentary or metamorphic environments such as the Imperial Valley and The Geysers. For example, Moore (1984) showed that lithologically similar greywackes from The Geysers could be differentiated on the basis of their major and minor element contents (Fig. 4). Through this study, it was shown that many of the steam entries were associated with greywackes with a significant argillaceous component. The lack of widespread brecciation further suggested that these steam zones are associated with flat lying (thrust) faults and that a substantial amount of horizontal steam flow must occur in the reservoir.

We have determined the relative mobilities of various trace elements during alteration and are using this data to help map the distribution of permeable zones at depth. At Meager Mountain (Moore et al., 1983, 1985) the trace and minor element contents of 270 samples of the reservoir rocks from six wells were determined. Chemical analyses of the discharge precipitates from the well bores and springs were used to establish which trace elements are presently mobile at different depths within the system. Chemical analyses of travertine deposited at Carbonate Springs near Meager indicate that in the uppermost part of the system bismuth and to a much lesser extent arsenic and mercury are mobile. Trace elements that are mobile at deeper levels in the thermal system occur within calcium carbonate deposits formed by fluids that discharge from one of the wells located on the southeast edge of the field. These elements include mercury, arsenic, strontium, and bismuth and traces of zinc. Concentrations of arsenic up to 9000 ppm, zinc to 60 ppm, and lead to 25 ppm have been found in some samples. Discharge precipitates from the production well MC-1 provide information on trace metal mobilities in the deepest levels. Although the compositions of the scales are highly variable, chemical analyses indicate that silver, copper, nickel, and higher contents of zinc are available for precipitation. Silver contents as high as 115 ppm and zinc concentrations of 130 ppm were measured in the scale.

The trace element contents of the rocks sampled by the drill holes confirm the importance of dike rocks as conduits for the geothermal fluids in the reservoir at shallow depths. Dikes from the center of the thermal anomaly contain anomalous concentrations of Zn and in places Pb in addition to As and Hg (Fig. 5). These elements are crudely zoned with respect to the present temperatures. Dikes characterized by enrichments in Hg + Zn + As occur only in the highest temperatures whereas dikes enriched in Hg + Zn occur at somewhat lower temperatures (Moore et al., 1983).

Our current research in this area is being directed toward evaluating the chemical and physical conditions that result in the deposition of some of these generally mobile trace elements. Toward this goal, an extensive compilation of arsenic in geothermal waters has been conducted, the stabilities of various arsenic compounds at elevated temperatures have been calculated, and the arsenic contents of sulfide minerals from the Salton Sea geothermal system have been determined (Ballantyne et al., in prep.).

Data from Fluid Inclusions

Despite nearly four decades of deep drilling in high temperature geothermal fields our knowledge of the chemical properties and distributions of geothermal fluids is still far from complete. In part this reflects the reactivity and sensitivity of geothermal brines to changes in physical conditions and in part to the practical difficulties encountered in obtaining uncontaminated and representative samples. Geothermal fluids may be sampled in several ways; at the wellhead or from

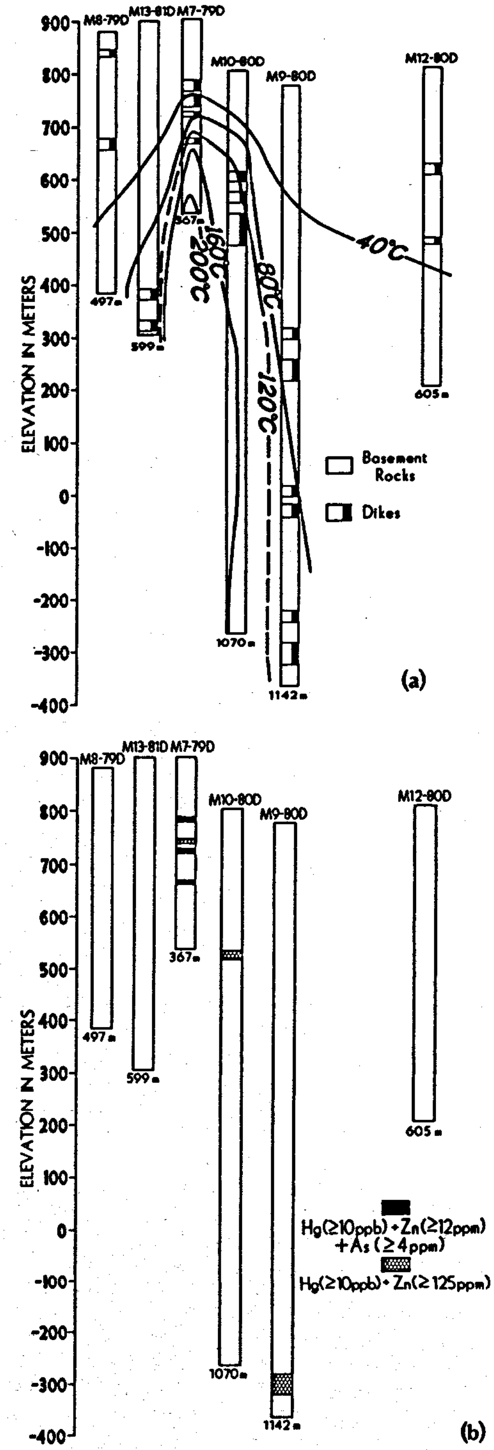

FIGURE 5
Distribution of temperatures, rock types and mercury, arsenic and zinc in the thermal anomaly at Meager Mountain, B.C. The dikes shown on the logs (Fig. 5a) were emplaced during recent volcanic activity. The trace element distributions indicate that the dikes have been the primary conduits for upwelling fluids in the anomaly (Fig. 5b). From Moore et al. (1983).

TABLE 1

FLUID INCLUSION DATA: IMPERIAL VALLEY, CALIFORNIA

Depth	Mineral	Homogenization Temp. (°C)	Salinity (wt.) % NaCl	CO_2/H_2O	CH_4/H_2O	Mde Ratios Ethane/H_2O	Propane/H_2O
850-880	An	206	12	.0139	.0006		
910-940	An	218	15	trace	.0005		
1000-1030	An	231	15	.0079	.0010	trace	
1000-1030	Qtz	217	13	.0024	.0064	.0002	trace
1000-1030	Sph	198	14				
1060-1090	An	244	19	.0028	.0005	trace	trace
1060-1090	Qtz	235	17	.0036	.0004	.0036	.0013
1120-1150	Qtz	224	15				
1120-1150	Sph	216	16				

An = anhydrite
Qtz = quartz
Sph = sphalerite

springs and fumaroles, through the use of a down hole sampler, or through the analysis of fluid inclusions. Fluid inclusions are samples of the geothermal brines that have been trapped in cavities in the hydrothermal minerals during their formation or during their subsequent fracturing and healing. Fluid inclusions typically contain a liquid and vapor phase at room temperature, and some may also contain crystals of daughter minerals precipitated from the fluids. The temperature of trapping of the inclusion is obtained by heating the inclusion until the vapor disappears and then adding a correction factor based on the depth of burial. The composition of the inclusion, in terms of equivalent weight percent sodium chloride, the major components of geothermal waters, is determined from the freezing point depression of the liquid.

These methods provide essentially no information on the quantity and type of gases present in the geothermal brines. This information is important both for predicting reservoir characteristics and assessing variations in fluid chemistry in space and time. Toward these goals, we are utilizing new techniques being developed at NASA under their lunar program to analyze the gas contents of individual fluid inclusions. Data has been obtained from samples collected from the Imperial Valley. The gas composition of the fluids may vary widely. Representative analytical data for inclusions from the Imperial Valley is given in Table 1. This finding is in sharp contrast with analyses of the gases discharged from the wells. These gases are enriched in methane compared to other hydrocarbons. The fluid inclusion data also indicate that salinities increase downward, confirming the suggestions that fluid flow is dominantly lateral.

Data from Isotopic Analyses

Estimates of the water to rock ratio and hence the overall permeability of a geothermal system can be obtained from mass balance equations based on the chemical composition of the fluids and rocks or from their isotopic compositions.

Little data is available from geothermal systems outside of the Imperial Valley and New Zealand. Recently we have applied this approach to the Meager Mountain thermal system. The isotopic compositions of the thermal fluids from this system are particularly unusual because of their wide range of deuterium values. The results indicate that the system has been rock-dominated and that it is characterized by extremely low water-rock ratios, perhaps in the range of .05 to .5 by volume. These values appear in general to be consistent with both the relatively high resistivities measured on the southern flank of Meager Mountain and with the low productivities of the geothermal wells.

CONCLUSIONS AND REQUIRED RESEARCH

The geothermal industry is plagued by high exploration expense due largely to the difficulties in exploring for fracture-controlled systems. For geothermal energy to become a truly renewable energy resource, injection techniques must be developed based on an intimate knowledge of the geometry of fractures, and the chemical and physical processes which take place along them.

Although a great deal of progress has been made, our knowledge of the internal structure of most active systems is still crude and much more work is required. Details of the reservoir properties ultimately must come from the rocks themselves. In this paper, we have described several approaches that had not previously been applied to active geothermal systems. The methods have yielded significant new insight into fracture formation at Baca and on the chemistry and compositional variations of the brines in the Imperial Valley.

Our current research objectives stem from the need for fundamental research into fracture permeability development in various rock types and of using fluid inclusion data to more accurately describe reservoir conditions. We feel that additional research into geological models of fractured geothermal reservoirs is needed. Detailed documentation of the structural complexity of active systems and the effect of interaction of fluids with these systems is in short supply. These types of data are fundamental for efficient exploration and production management. They also provide the ground truth necessary for the development of other mapping and interpretation techniques. Because the brine temperature and composition can be obtained from fluid inclusion measurements, the significance of this kind of fundamental data is far reaching. These data can, for example, be used in the development of new geothermometers as well as to provide pre-production chemical data needed in current reservoir simulation models and the basic data needed for development of evolutionary models of geothermal systems in space and time.

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GEOTHERMAL ASSESSMENT
in the
Bonneville Power Administration Service Area

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Abstract Bonneville Power Administration (BPA) has developed geothermal resource and engineering data bases to provide information and guidance in making generation planning decisions. Preliminary analysis indicates that different reservoir confirmation strategies may be appropriate depending on the geologic province being addressed. Future planning activities will address implementation mechanisms for confirming the region's geothermal resources.

Background The Bonneville Power Administration (BPA) is an agency in the Department of Energy. It was created by the Congress in 1937 to market power from Bonneville Dam, the first large dam to be completed by the U.S. Government on the Columbia River or its tributaries. As other Federal dams were built in the region, BPA was subsequently designated to market the power from them also. These multi-purpose projects are designed to provide flood control, recreation, navigation, and other benefits--in addition to generating electricity. They have a total generating capacity of about 20 million kilowatts from 30 large Federal projects. The Federal system supplies about half the power consumed in the Northwest with BPA acting as a wholesale energy broker.

BPA's service territory takes in 300,000 square miles in Washington, Oregon, Idaho, and western Montana, as well as small neighboring portions of Wyoming, Nevada, Utah, and California. The service area contains a population of approximately 9 million.

To distribute and market the power, BPA operates and maintains a region-wide grid. The grid also connects with utilities in the Pacific Southwest through the Pacific Northwest-Pacific Southwest Interties; with the power system in British Columbia to the north; and with systems to the east.

Besides wheeling power from the Federal dams, BPA delivers or exchanges large quantities of power for other utilities. The grid provides nearly 80 percent of the region's transmission capacity.

Federal legislation in 1980 gave added responsibilities to BPA and created the Northwest Planning Council to provide guidance to BPA in meeting these added responsibilities. The twofold task of the Council is to forecast the future electric energy demand of the Northwest and to develop plans to match future regional loads with conservation and new generating sources.

Overall generation resource planning strategy in the Northwest is accomplished by the Council in consultation and cooperation with BPA and other regional utilities. Translating these strategies into implementation plans, activities, and projects is the responsibility of the regional utilities who project the need for new generation resources within their respective service areas.

Completed Assessment Work Initial plans and projections by the Council indicated that geothermal generation could play a prominent role in the Northwest in the future, but that further assessment and knowledge would need to be developed. To address the Council's needs as well as our own, BPA undertook efforts in 1981 to develop geothermal engineering and resource data bases which would provide planning guidance for future work in geothermal resources.

Bonneville was immediately struck by the disparity of estimates prevailing among regional geothermal experts about the quantity of the resource and lack of knowledgeable information about the costs and types of technology necessary to commercially exploit the resource once it was found. Efforts were undertaken in two areas to remedy these deficiencies.

On the resource assessment side, the challenge was to, on a regional basis, systematically characterize known moderate to high temperature geothermal sites (resources greater than 90° C) within the BPA service area. The overall objective of the characterization was to consolidate and evaluate geologic, geophysical, environmental, and legal information currently available in existing records and files into a common data base for the Pacific Northwest Region (Washington, Oregon, Idaho, and that portion of Montana west of the Continental Divide).

Included in the assessment was development of: (1) consistent regional methodologies for the interpretation of geologic/geophysical data and estimating of resource potential, (2) a list of sites to be subsequently analyzed and ranked for degree of developability, (3) detailed site descriptions, (4) characterization of each specific site potential, (5) typical site configurations, (6) estimate of energy potential, development cost, and energy cost for each site, and (7) ranking criteria techniques to allow resource sites to be ranked one against the other.

The information derived from this recently completed work will be used by BPA along with other information to generate consistent forecasts of resource cost, timing, characteristics, and availability (MW). It also will be used to define and evaluate generation acquisition strategies and to assist in the evaluation of potential projects and feasibility studies.

The resource assessment work was conducted for BPA by the state Energy Offices of the four Northwest states and identified, characterized, and ranked 116 electric generation sites within the region in the manner described. These included 76 sites in the state of Oregon, 28 sites in Idaho, 8 sites in Montana, and 4 sites in Washington.

Simultaneously, BPA also launched efforts to develop engineering data bases to begin understanding the conversion technology issues associated with the resources characterized in the resource assessment study. BPA commissioned Kaiser Engineers and Southern California Edison (SCE) to develop sensitivity cost studies, conceptual plant designs, and generation comparative cost studies for the following conversion technologies.

<u>10 MW (approximately) Modular Plant</u> (flow from four wells)
Single-stage Flash
Binary Cycle
Rotary Separater Turbine

<u>Well Head</u> (flow from single well)
Single-stage Flash
Binary Cycle
Rotary Separator Turbine Gravity Head (Sperry Matthews System)

The detailed work developed estimates of the capital costs, annual costs, and cost of energy for both modular and "well head" size plants where power ratings would be on a more site-specific basis. The studies included a characterization of the geothermal fluid quantities, allowable salinities, and temperatures needed to support the plant concepts (177° C and 260° C).

Generic geothermal fluid delivery costs for fields capable of supplying fluid for the different plant concepts were also developed. Costs included allowances for appropriate return on investment values desired in high risk geothermal explorations. Two scenarios were developed: (1) for deep wells, 3000-10,000 feet deep in high Cascade-type environments, and (2) shallow, 500-3000 feet deep wells in a Basin and Range environment. Both scenarios included "take-across-the fence" type contracts wherein the resource (fuel) developer handles disposal (reinjection) of the exhausted fluid and includes those costs in resource contracts. Field development financing incorporated effects of Federal and state tax codes for depletion allowances, investment tax credits, energy investments credits, and accelerated cost recovery (ACR) methodologies. Results of the power plant study were reported by SCE in the EPRI 8th Annual Geothermal Conference proceedings.

<u>Future Activities</u> During our preliminary analysis of the data bases it was instructive for BPA to consider the resource on the basis of the two major geologic provinces which lie within the BPA service area--the Cascade Range and the Basin and Range. Little concerted attention had been paid to this second geologic province although the bulk of the BPA service area is within the Basin and Range province. A number of Basin and Range KGRA's were identified and categorized in the four-state assessment work mentioned earlier. Several "modest" sized fields (less than 100 MW) have been characterized and confirmed including Raft River, Idaho, and Beowae, Nevada. This characterization (shown in Table 1) suggests that separate and independent commercialization strategies for the Region's two distinct geologic provinces is required if future availability of these resources is desired. It also suggests a set of actions to confirm reservoirs in one geologic province may not be appropriate for the other.

Bonneville proposed to regional planners that they view the demonstration of geothermal reservoirs as a four-step process. The first step is development of a good scientific understanding of the geologic province coupled with scientific data gathered in regard to the

TABLE 1

Characteristic	Basin & Range	Cascades
Province Exploration Strategies Understood and Utilized.	Methology and techniques defined and successfully utilized.	Basic earth sciences work and understanding in early stage of development.
Industry Exploration Efforts	Extensive - especially in Southern Idaho and Northern Nevada.	Very little due to short field seasons, high costs and lack of scientific understanding.
Generic Reservoir Characteristics	Moderate size (less than 100 MW) 500-10,000 ft. depths, low salinity (less than 5000 ppm), Moderate temperature, hydrothermal systems (200° - 400° F).	Unknown - may be of substantial size.
Appropriate Conversion Technology for Expected Reservoir	Conversion technologies still evolving - optimization required on thermodynamic cycles, sizes, and plant costs.	Conversion technology may not exist if resource does not occur as a hydrothermal system.
Resource Integration to Utility Grid	Most KGRA's are distant from main grid and may have high per unit integration costs.	Could have either high or low per unit integration costs depending on reservoir size and location.
Plant Siting Factors	Some locations in environmentally sensi- areas, waste heat rejection could present problems due to lack of cooling water. Brine reinjection may be a problem.	Many locations in environmentally sensitive areas.
Reservoir Economics	Lower brine costs due to ease in drilling and modest drilling depths.	Unknown
Plant Economics	Higher per unit costs due to low enthalapy systems.	Unknown

geology, geochemistry, geophysics, and hydrology of the system studied. The second step, as BPA views it, is development of conceptual resource models as represented by maps, cross sections, and computer documents. Development of these conceptual models drive the industry exploration processes which we view as the third step and appear to have been successfully utilized by industry in locating commercial reservoirs in Basin and Range environments. It is BPA's understanding that such models do not exist for the Cascade Range geologic province; work funded by the U.S. Geological Survey (USGS) and U.S. Department of Energy's (DOE) geothermal program is ongoing but basic scientific understanding is still being developed.

Summing up, it appears that the necessary scientific understanding and reservoir exploration strategies are in place which would allow successful resource characterization work in the Basin and Range portions of the BPA service area, ignoring institutional constraints. However, until demonstrable scientific progress is made on development of conceptual models for Cascades geothermal resources, implementing demonstration confirmation drilling programs, which is one course of action being considered by regional planners, may be premature in the Cascades and have problematical chances for success.

To speak to some of the dilemmas suggested in Table 1, Bonneville has the following activities planned in their short-term two-year planning horizon:

- Address the "front-end" scientific unknowns of the Cascades geologic province geothermal resources. BPA is formalizing arrangements with USGS, USDOE, and the U.S. Forest Service to monitor, through an information exchange "forum," the scientific progress that lead Federal research and land management agencies are making in developing knowledge of geothermal potential of the Cascades' geologic province. As part of this activity, BPA plans to participate in and cosponsor yearly "High Cascades" geothermal reservoir definition workshops for the purpose of monitoring the scientific progress of the agencies conducting this work. Scientific forums and conference records suitable for dissemination to the public and industry would result from these efforts.

- Investigate and define (as scientific knowledge is developed) mechanisms which address the funding problems for early "high risk" scientific drilling. BPA will be monitoring the progress of DOE's Cascade Thermal Gradient Drilling Cofunding Program as a possible model for future regionally funded programs.

- Development in cooperation with other regional entities, of plans and implementation mechanisms to proceed with reservoir confirmation programs as appropriate and as the need is identified for reservoirs located in the BPA service area.

Conclusions BPA believes that geothermal power generation can play a prominent role in meeting future projected Northwest electric energy needs for the 21st century provided key concerns about the size characteristics and technical potential of the resource is addressed during the region's period of generating surplus. BPA's efforts to date have focused on developing engineering and resource data bases so that informed decisions can be made about the role of the resource in the future. The data base provides information which will give guidance in determining appropriate mechanisms to conduct identified field exploration work required for reservoir definition and characterization. The data bases have been developed so that they can be easily updated as new information and circumstances dictate. Early in 1986, the region's utilities will commence planning efforts to develop resource confirmation strategies and plans for geothermal resources which lie within the BPA service area. The pace of resource assessment, definition, and characterization work will be strongly influenced by forecasts of projected regional energy needs.

Acknowledgement The author is indebted to Michael J. Berger and John D. Geyer of BPA's Division of Power Resources Planning and Thomas J. White of BPA's Division of Resource Engineering for their aid and assistance in preparing this paper.

TECHNOLOGY TRANSFER

ON THE

HEBER GEOTHERMAL BINARY DEMONSTRATION POWER PLANT PROJECT

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ABSTRACT

Federal and DOE policy is to promote technological innovation and facilitate technology transfer to the public and private sectors. This paper describes the principal elements of the technology transfer plan and how it has been applied to the Heber Geothermal Binary Demonstration Power Plant project.

INTRODUCTION

Federal and DOE policy is to promote technological innovation and facilitate technology transfer to the public and private sectors. This policy is being implemented by all DOE laboratories.

To be effective, technology transfer (Table 1) must be a planned effort. It must identify the audience to whom the technology transfer is of interest. It must identify the information needs of the audience, collect and assemble this information and then make it accessible in usable form.

TABLE 1
EFFECTIVE TECHNOLOGY TRANSFER

- Planned Effort
- Identify the Audience
- Identify Information Needs
- Collect and Assemble Information
- Make Information Accessible

The purpose of this paper is to describe the technology transfer plan on the Heber Geothermal Demonstration Power Plant project.

HEBER GEOTHERMAL BINARY DEMONSTRATION POWER PLANT

Technology transfer is a contractual requirement of the Heber Geothermal Binary Demonstration Power Plant project. To focus on this requirement, the information in Table 2, which is in the statement of work, specifies the project goal and programmatic objectives. Let us examine how the Heber project and project objectives address the principal elements of effective technology transfer.

TABLE 2
PROJECT OBJECTIVES

The goal of the project is to stimulate commercial development of geothermal energy for the production of electric power. The following objectives are in support of those goals:

1) Demonstrate a binary conversion system technolgy at commercial scale.

2) Demonstrate reservoir performance characteristics of a specific liquid-dominated hydrothermal reservoir.

3) Demonstrate the validity of reservoir engineering estimates and of reservoir productivity (capability and longevity).

4) Provide Federal assistance required to initiate development at a resource of large potential.

5) Act as a "pathfinder" for the regulatory process and other legal and institutional aspects of geothermal development.

6) Provide a basis for the financial community to estimate the risks and benefits associated with geothermal investments.

7) Demonstrate environmental, social, and economic acceptability of the binary cycle technology for producing electric power from liquid-dominated hydrothermal resources.

8) Demonstrate the overall maturity of the technology and commercial readiness of the power plant.

PLANNED EFFORT

That technology transfer is a planned effort on the Heber project is implicit in the stated goal for the project which is to stimulate commercial development of geothermal energy for the production of electric power. The Heber plant is the first commercial scale binary power plant. As such, it will demonstrate the technical performance, reliability, and economic potential of an integrated geothermal power system. Successful demonstration will provide confidence needed by resource developers, utilities, and the financial community to make large scale commitments to a new technology.

To assure that technology transfer is not diluted or lost in implementing a project, the plan should include it as a distinct activity. This has been done on the Heber project where Data Acquisition and Dissemination is one of the four principal elements in the Work Breakdown Structure (Figure 1).

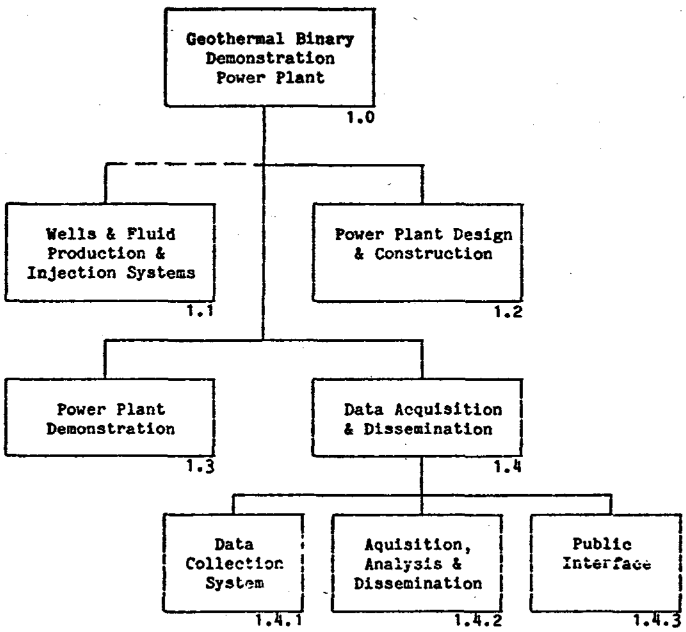

FIGURE 1
WORK BREAKDOWN STRUCTURE

IDENTIFY THE AUDIENCE

Identifying the audience for the proposed technology transfer is important to ascertain the audience's information needs and to address these needs. The principal groups interested in the Heber technology are potential users such as investor-owned utilities, public-owned utilities, and third-party developers. Third-party developers are an important group as they are eligible for tax credits and depreciation benefits. Tax credits and depreciation benefits may make a project viable that might not be under investor-owned or public-owned utility regulations. Also, if the power plant size is under 50 MWe, the third-party developer is not subject to utility regulations. Finally, PURPA regulations for the purchase of power from small producers make many projects viable only to third-party developers. Public-owned utilities may also justify the construction of alternative energy source power. Their principal advantages are the ability to borrow money over a long term at lower interest rates than investor-owned utilities and their investment and return may not be subject to taxes.

Additional groups in the audience are the financial community, public interest groups, and regulatory organizations. The financial community includes not only commercial banks and financial associations, but also insurance companies, pension funds, broker underwriters, corporations, partnerships, and special purpose limited partnerships that may provide funds to the developers. Public interest groups include those concerned with safety, environment, preservation of historical or archeological features, and protectionists of endangered wildlife and plants. Regulatory organizations include Federal, State and local resource management agencies, health and safety agencies.

IDENTIFICATION OF INFORMATION NEEDS AND DELIVERABLES

The principal information needs are delineated in the programmatic objectives, Table 2. Referring to this table, conversion system technology will be accomplished through the design, construction, and operation by San Diego Gas and Electric Company of a nominal 45 MWe net geothermal binary demonstration power plant.

Obtaining reservoir characteristics and productivity data will be accomplished by San Diego Gas and Electric Company through the location of the plant at Heber which is a typical liquid-dominated hydrothermal reservoir and by obtaining reservoir performance data that is planned to include fluid, production well, and injection well characteristics.

The Heber project had to comply with regulatory, legal, and institutional requirements of the Federal, State, and local governments. As such, the project acts as a "pathfinder."

Similarly, the needs of the environmental, social, and economic groups will be met by satisfying their needs through the regulatory process.

Information to establish financial risks and benefits of an enterprise is not a usual output from a demonstration project. In order to make the technical and cost information from the Heber project relevant to a commercial developer, ETEC is preparing a report describing a commercial version of the Heber project. The baseline commercial plant will consider the organizational, financial, and responsibilities arrangement among the participants, the project organization, and method of implementation and operation of the project. Many of the administrative practices, plans, and procedures applicable to the multiparty Heber plant will either be reduced in requirements or eliminated. In addition, ETEC will review the design of the Heber plant, incorporating recommendations made by San Diego Gas and Electric Company and Fluor Engineers, Inc. personnel and ETEC's own Engineering staff. Using costs on the Heber project as a reference, estimates will be made of the capital and operating cost of the baseline commercial plant.

Technecon Consulting Group, Inc. under contract to DOE, will perform economic and financial analyses. Specific Technecon tasks are:

1) Power plant performance and cost
2) Well field cost analysis
3) Well field cash flow analysis
4) Geothermal heat sales contract analysis
5) Power production economics
6) Public utility commission concerns
7) Public sector benefits
8) Technology transfer potential
9) Financial and investment decision analysis
10) Reporting.

Computer programs have been developed to perform these analyses.

Relative to the economic and financial analyses, three ownership cases will be analyzed: (1) financing, ownership, and operation by a regulated investor-owned electric utility; (2) financing, ownership, and operation by a tax-exempt municipal utility; and (3) financing, ownership, and operation by a non-regulated private sector enterprise.

COLLECT AND ASSEMBLE INFORMATION

The importance of data acquisition and dissemination is stressed by including these activities as major elements of the work breakdown structure (Figure 1).

It was originally contemplated to subcontract the Data Acquisition and Dissemination tasks, but these tasks will now be performed by San Diego Gas and Electric Company with assistance from other project participants and DOE contractors. The latter groups included EPRI, ETEC, Technecon, LBL, Battelle PNL, and Radian Corporation.

The detailed requirements of these activities are described in the Data Management Plan. The Data Management Plan summarizes the method by which data will be produced, evaluated, and transferred by the project (sponsors) to potential users.

Figure 2 depicts the data management activities logic. The plant operating records are processed by the data processor and summarized in final reports. The plant design and construction records are assembled as finished documents. These records include the engineering design package, reliability and availability reports, special studies and topical reports, and project control documents.

MAKE INFORMATION ACCESSIBLE

The Data Management Plan identifies and indicates the organization of the documents that will be produced and made available for dissemination. The two major groupings are the project documents and the demonstration test program documents.

Interim and final reports of these documents will be supplied to the DOE Technical Information Center where they will be available for dissemination to interested parties.

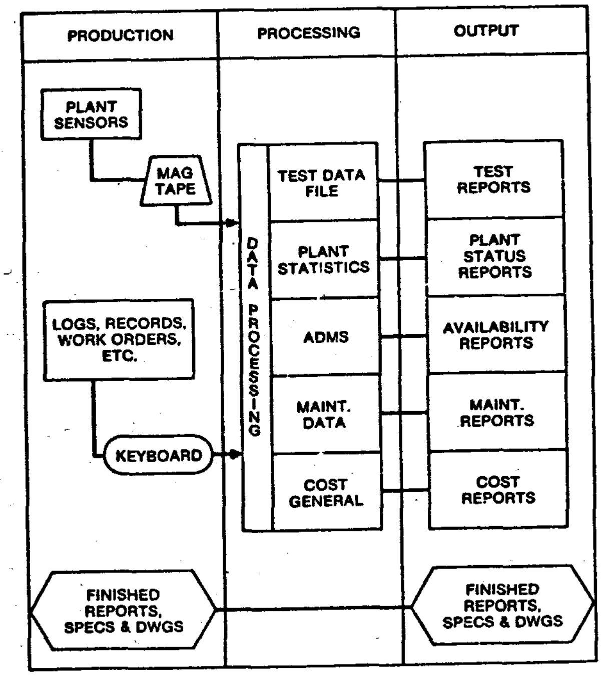

FIGURE 2
DATA MANAGEMENT ACTIVITIES SUMMARY

CONCLUSIONS

Technology transfer on an innovative concept such as the Heber Geothermal Binary Demonstration Power Plant project can be quite complex. The number of groups and organizations in the audience and their wide diversity of interests compounds the complexity. Successful technology transfer must identify the audience and its needs and assemble the information in usable form for dissemination. To achieve these results, a technology transfer plan should be included as an identifiable element at the start of a project.

FEDERAL GEOTHERMAL TECHNOLOGY TRANSFER ACTIVITIES

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ABSTRACT

GTD's FY-1985 explicit Technology Transfer budget was substantially higher than in previous years. This gave GTD the opportunity to pursue some important new initiatives. Those activities are described in terms of four generic technology transfer functions.

INTRODUCTION

Almost every facet of the GTD R&D program that is not directly on focused on the invention or development of new technology could be classified as "technology transfer". GTD's current technology transfer (T.T) activities address four related functions:

1. Adaptive Development - Support of R&D that is necessary to adapt technically-proven technology to fit into existing industrial engineering and technology settings. Most "field tests" and "verification experiments" on geothermal equipment and procedures fit into this category, or can be viewed as the bridges between GTD "R&D" efforts and GTD "T.T." efforts. Some examples are: (1) The completed project to transfer the EPDM high-temperature elastomer into commercial drilling devices; (2) Support of Geothermal Drilling Organization efforts to facilitate the commercial availability of drilling hardware developed by GTD; and (3) The Heber geothermal binary electric system verification experiment.

2. Technical Information Dissemination - Informational and educational efforts that enable industrial engineers to use the technical data that results from GTD R&D projects. Examples: (1) Technical report dissemination via the DOE Energy Technical Information Center at Oak Ridge; (2) Support of graduate seminars at Stanford University; and (3) Publication of highly specialized geothermal engineering handbooks, e.g., the Geothermal Materials Selection Guidelines.

3. Broadcasting - Providing information that encourages new actors to enter the geothermal energy arena, especially when those actors are likely to develop relatively untapped geothermal reservoirs or new geothermal energy applications. Examples: (1) The O.I.T. GeoHeat Center Technical Assistance Program; (2) The Cascades Deep Geothermal Gradient Drilling Program; and (3) The new "U.S. Geothermal Technologies" Digest.

4. System Improvement - Actions to enhance GTD's technology transfer program in generic ways.

The audiences for projects in functions 1 and 2 are mostly people who are already in the geothermal energy business. Function 3 projects are aimed at people who could enter the business, either as energy producers or energy users. Function 4 projects are aimed at GTD Headquarters and field managers.

TECHNOLOGY TRANSFER BUDGET FLUCTUATIONS

Federal program budgets for explicit T.T. activities often fluctuate much from year to year. GTD is going through such a fluctuation right now. The GTD budgets for technology transfer were $100 K in FY 1984 and about $900 K in FY 1985. The President's request for FY 1986 is $ 0 K. Since the D.O.E. appropriations bill for FY 1986 is not yet passed, GTD does not know how much explicit "technology transfer" money it will have in FY 1986.

Such fluctuations have been common over the last two decades, and an appropriate R&D management strategy for dealing with them has evolved. The strategy is based on the realization that the borderline between "advanced R&D" and "technology transfer" is not absolute. Two types of activity are appropriate to fund either implicitly as parts of R&D projects, or as explicit T.T projects: (1) Engineering work that adapts technically-proven technology to field conditions and industry needs; and (2) Information dissemination work that puts new technical information in the hands of private-sector engineers and decision makers.

When explicit technology transfer budgets are high, both of these activities are funded as T.T. When T.T. budgets are moderate, the first activity tends to be funded as R&D, and the second as T.T. When T.T. budgets are very low, it is legitimate to fund the second type of activity from R&D line items, since "No research is complete until its results are known to those who can use them."

In FY 1985, GTD found a little extra room to: (1) Support more broadcast efforts to enroll new private-sector technology producers and users into the geothermal energy business, and (2) Take a little harder look at the effectiveness of GTD's continuing T.T. efforts, to see if they can be improved.

SPECIFIC TECHNOLOGY TRANSFER ACTIVITIES

Table 1 describes most of the recently completed and ongoing GTD technology transfer activities. You can see from the Table that the four generic functions described above are covered pretty well by the current initiatives.

TABLE 1
GTD TECHNOLOGY TRANSFER ACTIVITIES

	PURPOSE				
	ADAPT TECHNOLOGY	DISSEMINATE TECH. INFO	BROADCAST INFORMATION	IMPROVE T.T. METHODS	BUDGET
F.Y. 85 ACCOMPLISHMENTS:					
Models & Databases Report		o	o		
G.T. Technology Digest		o	o	o	
GRC T.T. Poster Session		o	o	o	
T.T. Plan Guidance Manual				o	
T.T. Workshop Media				o	
F.Y. 85 IN PROGRESS (T.T. LINE FUNDING): $(K)					
INEL T.T. Projects	o	o			250
Italy Agreement	o	o			173
Nevada Leaching Project	o	o			119
U. Hawaii	o	o			75
Ascension Island	o	o			50
Mexico Agreement	o	o			
L.D.C. Effort		o	o		55
El Centro Conference		o	o		10
Program Review Printing		o	o		13
T.T. Support, Meridian		o	o	o	75
GRC Support		o	o	o	54
Sandia Telecomm. Project				o	15
(Total)					939
F.Y. 85 IN PROGRESS, (NOT T.T. LINE-FUNDED):					
Heber Binary Experiment	o	o			
Geothermal Drilling Org.	o	o			
Cascades Drilling	o	o			
OIT Technical Assistance	o	o	o		

FY 1985 Accomplishments

These recently completed activities were initiated either in FY 1984 or FY 1985.

Multi-Year T.T. Plan Guidance Manual. This manual was completed in November 1985. It describes major elements that are valuable to include in a programmatic T.T. plan. The manual is intended not only for GTD use, but for other D.O.E. Renewable Energy programs as well.

T.T. Workshop Proceedings. The Proceedings of the May 1984 GTD workshop, "A Synthesis of Technology Transfer Methodologies", were published in December 1985. They are a valuable compendium of lessons learned in the 1960s and 1970s, when many Federal T.T. programs were very active. Copies can be obtained from GTD Headquarters.

Geothermal Models and Databases Report. Reviews of many of the geothermally-related computer models and databases developed by GTD and its predecessor agencies during the 1975-1984 period have been collected in one report, "Update and Assessment of Geothermal Economic Models, Geothermal Fluid Flow and Heat Distribution Models, and Geothermal Data Bases". The purposes, general usefulness, and current availability of these tools are described. The intent of the report is to remind engineers and scientists of the availability of these resources. The report was prepared by Meridian, and published by GTD in May 1985.

T.T. Workshop Video Tapes. Three video tapes edited from presentations at the GTD 1984 T.T. workshop were completed in May 1985. Tape I is "An Overview of Technology Transfer Mechanisms", presented by Dr. John E. Mock of GTD. Tape II is "Technology Delivery Systems", by Dr. Arthur Ezra of the National Science Foundation. Tape III is "Practical Methods of Technology Transfer", and stars Roy Marlow of the Pennsylvania State technology transfer program, and Dick Traeger of Sandia. The tapes run for 28 to 45 minutes, and serve as interesting "refreshers" for T.T. agents and managers. They can be borrowed from GTD Headquarters.

Topics Review Meeting: The Geysers - A geothermal topical review meeting ("the Ogle Committee Meeting") on "Geothermal Development at The Geysers" was held in May at Santa Rosa, California. The latest technical developments at The Geysers were reviewed, and technical problems requiring more R&D were identified.

Geothermal Technology Digest. A digest of "U.S. Geothermal Technology: Equipment and Services for Worldwide Applications" was completed in August 1985. The illustrated fifty page digest is intended to help decision makers and engineers understand the current status of geothermal technologies, geothermal power development, and areas in which U.S. firms are well equipped to provide geothermal technology and services. The digest was written by Meridian, and designed and printed by INEL. It was distributed to the 650 attendees at the Geothermal Resources Council meeting in August 1985. It will be distributed further to U.S. industry and non-U.S. energy organizations.

T.T. Poster Session. The Geothermal Resources Council included a "Technology Transfer Opportunities Poster Session" at the GRC August 1985 International Symposium on Geothermal Energy. This enabled Federal and other technology developers to communicate essential details of new technologies to potential producers and users.

1985 Technology Transfer Current Activities

Activities funded under the FY 1985

Technology Transfer budget, about $ 900 K, and still in progress are described here.

INEL Technology Transfer. This program, budgeted at $ 250 K, consists of (1) the evaluation of condensation behavior in hydrocarbon turbine expansion processes, and (2) joint DOE and industry injection-backflow studies. Both of these studies are developing information that industry needs for its detailed design work with these technologies.

Italy Agreement. FY 1985 is the first year of the third 5-year agreement between the U.S. and Italy for joint investigation of geothermal energy production at Lardarello, Italy and nearby areas. The first agreement began in 1975. Stanford University, Lawrence Berkeley, and Lawrence Livermore will conduct studies of reservoir engineering, induced seismicity, fluid sampling, and other issues. The budget will be between $ 150 K and $180 K. Some details remain to be worked out.

Nevada Leaching Project. The University of Nevada is helping the mining industry understand the value of colocated geothermal resources in the solution leaching of metals from ores. The budget is $ 119 K.

University of Hawaii at Manoa. Three tasks to be performed at the Puna Geothermal Research Facility are budgeted at $ 75 K: (1) reservoir analysis, (2) sulfur abatement and recovery, and (3) the impact of hydrogen sulfide on plants. These projects are intended to pave the way for further geothermal development in Hawaii.

Ascension Island Project. The DOE-funded portion of this resource analysis project, $ 55 K for resisitivity measurements, was completed in the Spring of 1985. The U.S. Air Force plans to continue with this project, and GTD has agreed to continue monitoring it for the Air Force.

Mexico Agreement. In about a month, GTD anticipates completing negotiations with Mexico for joint technical studies of two fields in Mexico. Work at Cerro Prieto will extend the previous joint analyses of reservoir characteristics into the production areas next to the current field. Work at Los Azufres, a new undertaking for GTD, will measure reservoir characteristics preparatory to siting production wells. The wells will power the 50 MWe flash-steam power plant originally intended for D.O.E.'s "Baca" project, which Mexico has purchased from New Mexico Power and Light. Lawrence Berkeley, Stanford University, the University of Utah Research Institute, and possibly others will participate in the work. This agreement will be funded from GTD budgets of FY 1986 and later. Budgets for previous similar agreements ranged from $100 to $500 K per year.

Less-Developed Country Study. GTD is conducting a study of the geothermal resources and development opportunities in less-developed countries. The purpose is to clarify, for the U.S. geothermal industry, opportunities and pathways for marketing U.S. equipment and services abroad. $ 55 K is earmarked for this project, which is being conducted by Meridian. GTD is continuing to work to enlist support, both technical and financial, from the U.S. Agency for International Development, the Trade Development Program, and the Department of Commerce.

GTD Technology Transfer Support. Much of GTD's ongoing T.T. program support work has been contracted to Meridian. The following items are in progress, and budgeted at $90 K.

o GTD Technology Transfer Five-Year Plan. This is an update of the FY 1984 T.T. Plan. Now that we are near the end of FY 1985, it is nearly completed. This "Plan" serves mostly as an interim report of what was initiated in FY 1985 and what appears to be useful to do in later years.

o T.T. Guidebook for Federal Managers. This is an illustrated handbook on the design, planning, and management of Federal T.T. programs. It emphasizes strategies, tactics, and management approaches appropriate for R&D programs whose mission is to develop technologies for use by the private sector.

o Geothermal Technology Catalog. This catalog will describe about 200 technologies developed by GTD. The illustrated format is similar to that used in the DOE-ETIC "Energy-Grams" and the NASA "Tech Briefs". The catalog will alert and remind industry engineers of the availability of useful technologies, and point them to relevant contacts in the National Labs, R&D firms, and energy firms. Staff in National Labs and GTD-supported R&D firms are in process of writing most of the Catalog items.

GRC Support. The Geothermal Resources Council will develop an International Volume on geothermal energy. The grant of $54 K included the development of the T.T. poster session at the GRC August 1985 International Symposium on Geothermal Energy.

Sandia Technology Transfer Experiment. GTD is working with Dick Traeger at Sandia to acquire the equipment necessary for a teleconferencing and graphics communication experiment between GTD Headquarters and Sandia. The purpose is to explore the value of real-time communication of technical and management information.

Other GTD Technology Transfer Projects

GTD is conducting a number of projects, funded from budget lines other than Technology Transfer, which do or are expected to effect considerable transfer of geothermal technology to the private sector. These include:

Heber Binary Verification Experiment. A two-year instrumentated test period is just about to start, and will provide verification of the conversion technology, per se, two years of detailed process data, and verification of the process measurements and control technologies used in the plant. George Budney's paper in these proceedings describes the details of this project.

Geothermal Drilling Organization. FY 1985 is the second year in which GTD is jointly sponsoring with industry technology-specific actions to move important geothermal drilling technologies off the Federal R&D shselves into the hands of manufacturers. Current activities include:

- o Acoustic Borehole Televiewer: Squire-Water house is building two televiewers, which will be operated in the field for one year.
- o R.F.Q.s are out for using high temperature elastomers in drill pipe protectors, blowout preventers, and rotating-head seals.
- o GDO is preparing to monitor the use of foam as the drilling fluid in a geothermal well.

Cascades Drilling Experiments. The deep thermal gradient holes to be drilled in this GTD activity will assess the suitability of available exploration technology for detecting geothermal reservoirs in an unusual environment. This activity is attempting to transfer geothermal technology to an entire region of the country.

OIT Technical Assistance. The Oregon Institute of Technology's GeoHeat Center continues to provide information and technical assistance to new users of geothermal direct heat systems, and potential installers of wellhead electric generators.

Topical Review Meeting: Small Power Plants. A geothermal topical review meeting on "Geothermal Small Power Plants" will be held in November at Reno, Nevada. Technology status, R&D needs, and T.T. needs will be discussed.

OUT-YEAR TECHNOLOGY TRANSFER ACTIVITIES

FY 1986 and later are unlikely to produce any major surprises with respect to the routes and mechanisms that GTD uses to transfer Federally developed technology and technical data to industry. However, you can anticipate seeing a number of important "transfer" events coming out of GTD in the next few years. These include:

Heber Binary Experiment Results. Refined estimates of what Heber might cost if built as an "industryonly" rather than as a "research" plant should be available in 1986. The two year test should be completed in early 1988. The report on evaluation of performance and economics should appear in early 1989.

New Technical Handbooks. The following technical handbooks are scheduled to emerge from GTD projects during 1986 - 1988:

- o Well-Completion Handbook
- o Handbooks on new Reservoir Definition models
- o Brine Injection - Surface Treatment Handbook
- o Brine Injection - Fluid Mixing Handbook
- o Brine Injection - Fluid Migration Handbook
- o Detailed Analyses of advanced binary power plant technology options

Geopressure and Hot Dry Rock Evaluations. Both of these GTD advanced technology sub-programs are approaching major evaluation milestones within the next two or three years. Generic evaluation reports can be expected.

Technology Export Assistance Information. A moderate amount of GTD, DOE-wide, and Dept. of Commerce attention is being devoted to improving U.S. industry's ability to export equipment and technical services. Given America's current general weaknesses in international competition, this attention is likely to be maintained for the next few years. Reports that contain marketing intelligence and on how to thread your way through the network of Federal export assistance programs should appear soon.

SESSION III

Chairperson: George Tennyson, Albuquerque Operations Office
U.S. Department of Energy

HOT DRY ROCK PHASE II RESERVOIR ENGINEERING

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ABSTRACT

Early attempts to hydraulically fracture and connect two wells drilled at the Hot Dry Rock site at Fenton Hill in New Mexico failed. Microearthquakes triggered by hydraulic fracturing indicated that the fracture zones grew in unexpected directions. Consequently one of the wells was sidetracked at a depth of 2.9 km; was redrilled into the zones of most intense microseismic activity; and a flow connection was achieved. Hydraulic communication was improved by supplemental fracturing using recently developed high temperature and high pressure open hole packers. Preliminary testing indicates a reservoir with stimulated joint volume which already surpasses that attained in the earlier phase I reservoir after several years of development.

INTRODUCTION

Hot Dry Rock (HDR) geothermal energy reservoirs differ from the more familiar hydrothermal reservoirs in that in the former case, permeability and porosity must be induced, usually by the process of hydraulic fracturing, whereas in the hydrothermal reservoir these attributes are already present, and in fact the porosity is usually saturated with water or steam, which, after drilling, can be used as the working fluid for energy extraction and electricity production. In HDR reservoirs essentially no water exists in-situ, and so must be supplied from an extraneous source.

The technical challenges faced in HDR development are daunting. Wells must be drilled to depths where temperatures are likely to attain 200 to 300°C, suitable for electricity generation. Even in regions with favorable geothermal gradients such temperatures are found at great depths, 3 to 5 km, where the minimum component of the in-situ earth stress is likely to be 35 to 100 MPa (5000 to 15000 psi). One must then fracture the rock formation, and hold open the fractures so that the permeability remains high and flow resistance is low and such that large areas of hot rock are adequately bathed, resulting in high heat production. At the same time, since all water must be provided extraneously, one must avoid excessive water losses to the county rock surrounding the fractured reservoir. Furthermore, damaging earthquakes potentially could be caused by down hole accumulation of this water loss. One must also avoid potential geochemical problems, such as scaling of surface equipment with precipitated products of aqueous rock dissolution.

The incentive for meeting these challenges is the enormous resource base that HDR energy provides. Unlike hydrothermal reservoirs, which are rarely found, potential HDR reservoirs underlie much of the nation and world. Even if one considers just the high grade resources, i.e., regions with geothermal gradients greater than 40°C/km, where high temperatures can be attained at shallow depths, the HDR resource base represents a thermal energy equivalent to nearly 100 million Megawatt-centuries, about ten times that of coal deposits.

HDR research is underway in Britain, Federal Republic of Germany (FRG), France, Japan, and the United States. Supported by USDOE, FRG, and Japan, the largest in-situ demonstration project is being conducted by Los Alamos National Laboratory at the Fenton Hill, New Mexico site, located on the west flank of the dormant Valles Caldera.

Initial HDR feasibility was proven with the phase I reservoir. Two wells were drilled to 3 km, linked with fractures, and during intermittent testing from 1978 to 1980, 3 to 5 MW of thermal power were produced for periods as long as nine months. The flow resistance was low enough that the pumping power required to force the water down one well, though the fractures, and up the other well was less than 2% of the thermal power produced. The produced water was of high quality, essentially potable, and even during fracturing, the largest detected earthquake registered only 1.5 on the Richter scale. Further details are provided by Dash et. al. (1983).

RESERVOIR FRACTURING

The successes of the phase I reservoir led to the decision to create a deeper, hotter, and larger reservoir. The objective of this Phase II reservoir, also located at the Fenton Hill Site, is to establish the engineering practicality of HDR. Based upon Phase I experience, which indicated that fractures were nearly vertical, with roughly a North-South orientation , two new wells were drilled in segments. In the first segment, 0 to 2.5 km, both wells were nearly vertical, but in the deeper segment the boreholes were directional drilled towards the East, at an angle from vertical which eventually built up to 35°. Figure 1 shows a perspective view. The upper well, EE-3, which is the intended production well, lies 300 m above the lower injection well, EE-2, in the slanted interval. Also shown in Figure 1 is a phase I reservoir well which contains a geophone sonde. This sonde, and similar seismic sensors emplaced in other boreholes, detect and locate the microearthquakes triggered during hydraulic fracturing (House, Keppler and Kaieda, 1985).

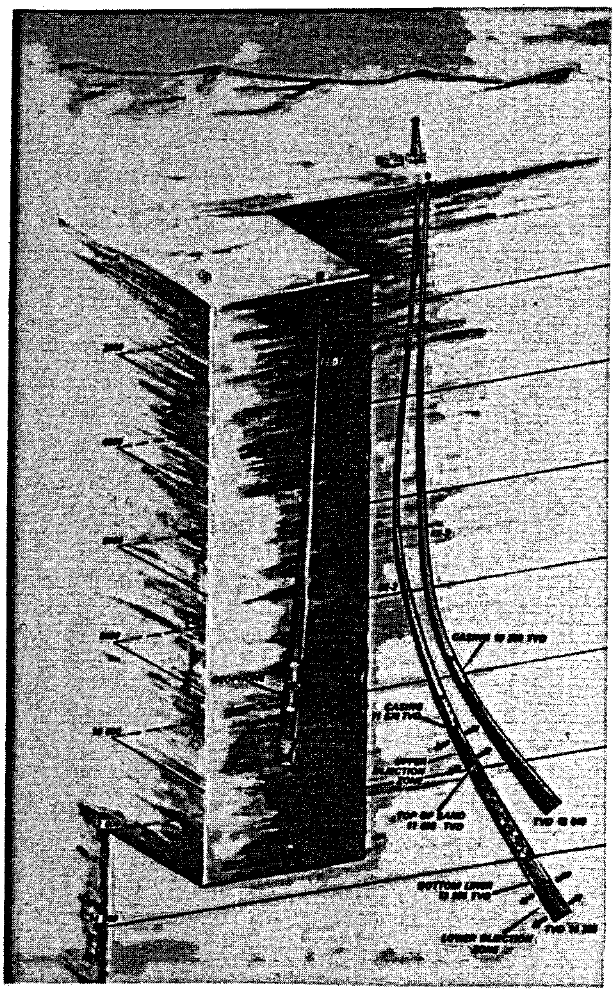

Figure 1. Perspective view of Phase II boreholes and typical geophone tool emplaced for microearthquake monitoring during fracturing.

First attempts to hydraulically connect the two new boreholes by fracturing were initiated near the bottom of the lower well. However the tubular goods in the well frequently failed due to the high downhole pressure (90 MPa or 13,000 psi), and stress corrosion in the high temperature environment (over 300°C). Attention shifted uphole, and in December 1983 a massive hydraulic fracturing operation was conducted in which 21,000 cubic meters (5,600,000 gal) of water were injected at 3.5 km in the lower well at downhole pressure and average flow rate of 83 MPa and 0.1 cubic m/s (40 barrels /min). Details are provided by Dreesen and Nicholson (1985), and House, Keppler and Kaieda (1985). Figure 2 shows the locations of the microearthquakes induced. The downhole seismic sensors are extraordinarily sensitive, which enabled detection of events with extrapolated Richter body wave magnitudes as low as -5, but Figure 2 shows only the 850 high quality events with magnitudes from -3 to 0. Note that seismicity is induced over a rock volume that is about 0.8 km high, 0.8 km wide in the N-S direction, and about 0.15 km thick. This rock volume is 3000 times greater than the water volume injected. House et al. (1985) concluded that:

1. First motions of the microearthquakes and fault plane solutions determined from the surface array of seismometers indicated a shear-slip motion, probably along existing rock joints. This suggests that any tensile or oscillatory source mechanism may only generate very weak seismic signals.

2. The finite thickness, 0.15 km, of the zone of seismicity and its spatial growth imply the creation of a zone of fracturing or joint stimulation, rather than a single classical fracture.

Fehler (unpublished work) performed spectral analysis of many of the microearthquake coda, and found power spectral densities consistent with usual earthquake mechanics, ie, shear-slippage. Corner frequencies were of the order of 300 Hz, and based upon the work of Brune (1970), Fehler found that the characteristic dimension of the rock surface mobilized for each shear-slip event was of the order of 10 m, comparable to the spacing of the major joints observed in well surveys.

The above results indicate a fracturing mechanism which is inconsistent with conventional theories of hydraulic fracturing (Hubbert and Willis, 1957; Daneshy, 1973) which predict the propagation of a single fracture caused by tensile failure of the rock. However, the HDR results are consistent with Lockner and Byerlee (1977), who observed a transition from tensile to shear fracturing when low flow rates were injected into laboratory rock specimens; and our observations were confirmed at the British Hot Dry Rock reservoir in Cornwall where it was observed (Pine and Batchlor, 1984) that fracturing occurred as a zone of multiple fractures, and that shear slippage along existing joints was the dominant mechanism. Because these joints are preexisting natural fractures, it is perhaps inappropriate to refer to the process of forcing water into them as "fracturing;" "stimulation" will be used instead.

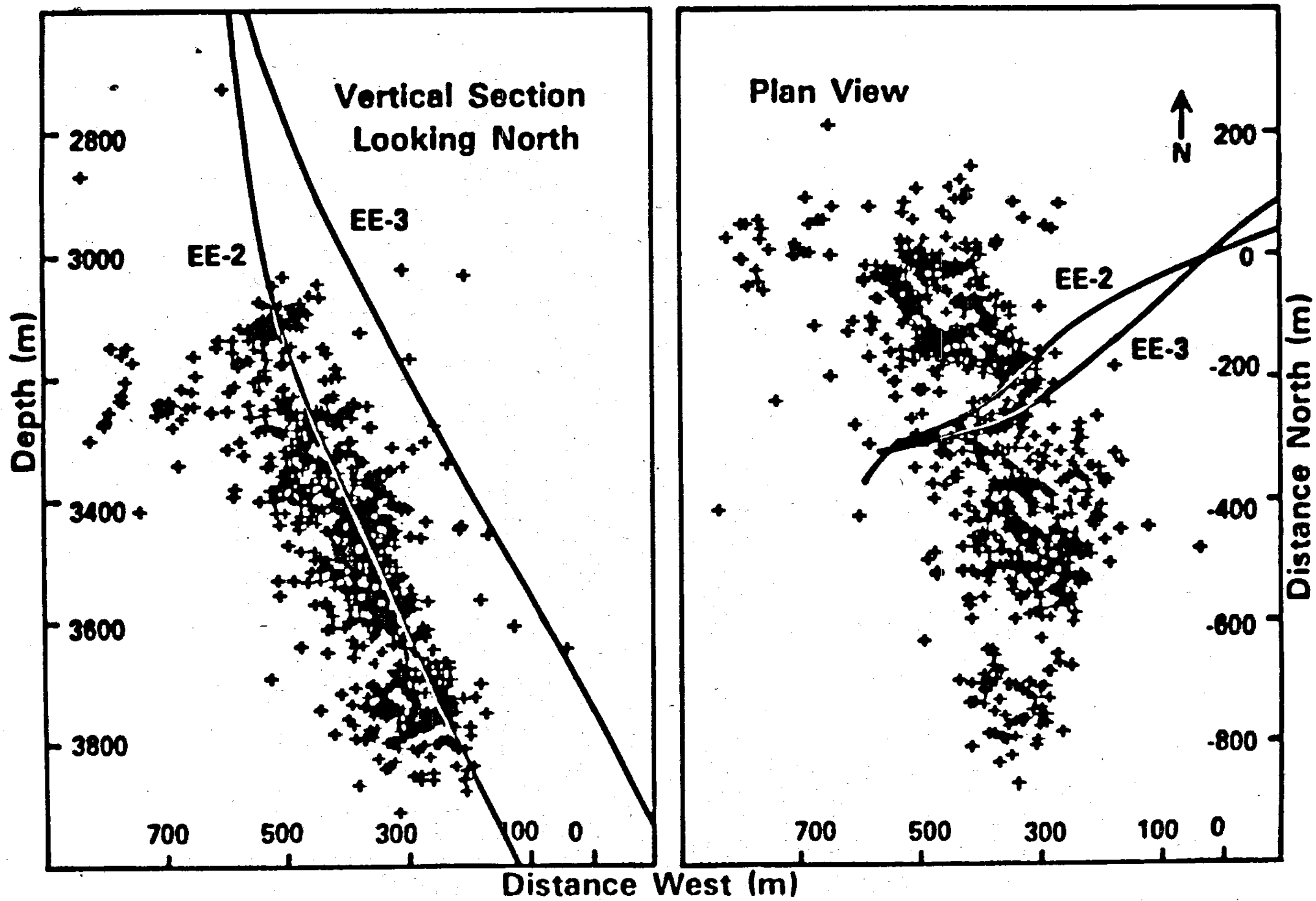

Figure 2. Hypocentral locations of microearthquakes induced by massive hydraulic fracturing in injection well EE-2. Left hand side presents elevation view, looking north, while right hand side is plan view, looking down. While it may appear in the elevation view that EE-2 and EE-3A intersect, in actuality EE-3A is 150 meters south of EE-2 at the cross-over depth.

Shear Stimulation Modeling. These unexpected results suggested that further study required a model incorporating detailed fluid dynamics and rock mechanics within jointed rock masses. The Fluid Rock Interaction Program, based upon the calculation method developed by Cundall and Marti (1978) was adapted for this use. The rock joints are on a regular rectangular grid and the code permits interactive coupling of fluid dynamics with rock stresses and deformations. For example, an excess of pressure on a block during one computational cycle will result in compression of the block and opening (dilation) of the joints next to it, resulting in additional permeability and changed pressure distribution.

When joints are aligned parallel to the principal earth stresses, a process equivalent to classical hydraulic fracturing (but without the necessity of accounting for rock strength) is predicted, in which a single joint begins to open at a pressure equal to the minimum earth stress, and the aperture and shape of the opened joint agree well with conventional hydraulic fracturing theory (Daneshy, 1973). However, when the joints are rotated 30° from the principal stress directions, and a low viscosity fluid like water is used for fracturing, two types of stimulation patterns can occur. In the first type, typified in Figure 3, which occurs when resistance to shear slippage is low or shear dilatancy is large, only a single joint is stimulated. In the second type, corresponding to high shear resistance or small dilatancy, multiple joint stimulation occurs as shown in Figure 4. Shear slippage along the joints is accompanied by shear-stress drops and the interaction of the stress drop with the acting earth stresses

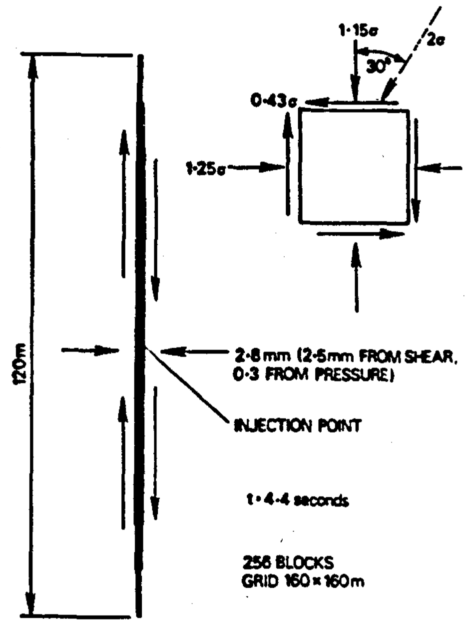

Figure 3. Single joint stimulation induced by shear slippage along natural joints. Stimulation of only a single joint occurs when resistance to shear slippage is low (low friction) or the dilatancy, i.e., the ability to open the joint due to shear, is high. The resolved stresses shown result from a principal earth stress of 2 σ applied at an angle of 30° to the joints. σ is the minimum principal earth stress and is perpendicular to the 2 σ stress.

results in opening of joints normal to the maximum stress, so that a dendritic, multiple joint pattern occurs. This pattern of stimulated joints, and the computed shear-stress drops, explain why microearthquake maps in water-fractured jointed-rock masses are usually not planar, but are ellipsoidal in shape, and why the observed first motions of microearthquakes indicate a shear mechanism.

To understand this stimulation behavior better, refer to Figure 5. The main joint has slipped in shear and separated contact. When the faces are no longer in contact there is no friction to support the initial shear stress, so the region midway between the center and the tip of the main joint has the y-stress profile shown on the top and bottom of Fig 5. The original normal stress, 1.75 σ, is reduced to as low as 1.25 σ in the upper right and lower left quadrants, precisely low enough for lift-off and stimulation of the lateral joints indicated. (As explained in Figure 3, σ is the minimum principal earth stress.) These x-direction joints then allow easy migration of the water into the y-direction joints immediately adjacent and parallel to the main one, so that these joints begin to open, and this cycle repeats itself, until eventually the fracture pattern appears as predicted in Figure 4, and observed in Figure 2.

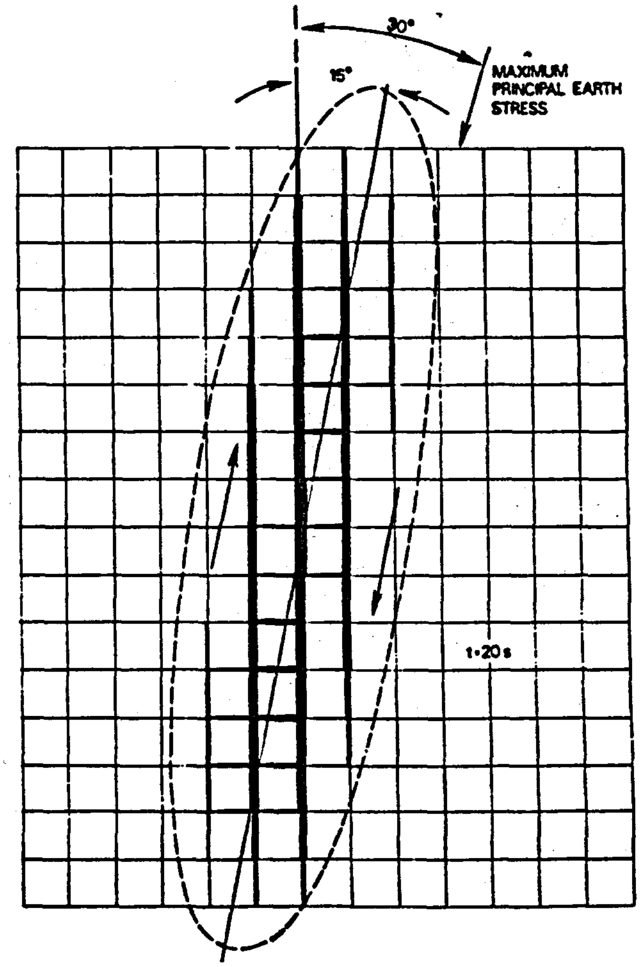

Figure 4. Multiple joint shear stimulation which occurs when shear resistance is high or dilatancy is low. Note geometrical similarity with microearthquake locations in Figure 2.

ACHIEVING HYDRAULIC COMMUNICATION

Despite the huge volume of water injected in the lower well during the massive hydraulic fracturing, the stimulated zone did not propagate into the vicinity of the upper well, as shown in Figure 2, and no hydraulic communication between the two wells was observed. Another large fracturing operation was conducted, this time in the upper well, but the two stimulated zones did not overlap sufficiently and again no

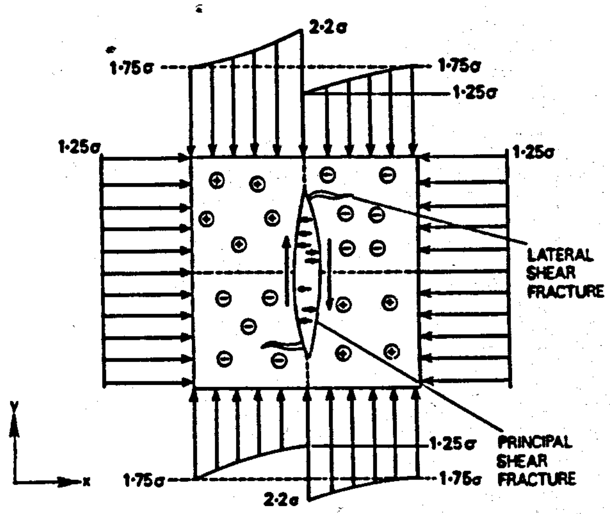

Figure 5. Stimulation of lateral joints.

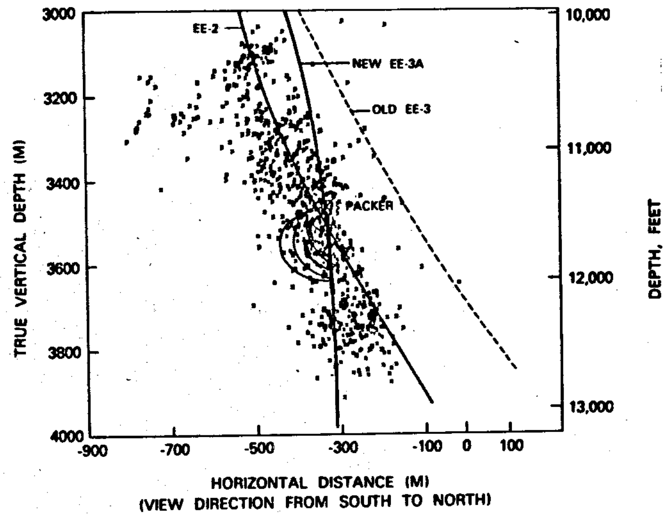

Figure 6. Elevation view of reservoir, looking North. Packer shown allowed supplementary stimulation of EE-3A, which resulted in low flow resistance connection between EE-2 and EE-3A. The flow paths indicated are not exact, but are inferred from joint locations determined from a temperature survey in EE-3A.

communication was observed. Consequently, in March of 1985 the upper well was sidetracked at a depth of 2.9 km, and directionally drilled as shown in Figure 6 through the fracture zone associated with the lower well. This sidetracked well is referred to as EE-3A.

Precursor signs of an impending connection were observed in May. Weak flows, 0.3 l/s, into the redrilled well were noted when the other well was pressurized to 12 MPa. After drilling ahead, another flow was observed, but this time the flow was much stronger and occurred at three joints intersecting EE-3A near 3.6 km. On May 20 it was noted that when the drill rig pumps were used to inject water into EE-3A, a sudden pressure rise was almost immediately observed in the other well.

With these increasing portents of success it was decided to improve the hydraulic communication quality of the joints near 3.6 km by stimulating them with high pressure. This was accomplished by setting a specially developed, high temperature packer (Dreesen and Miller, 1985) at a depth of 3.52 km, where the drill hole was reasonably smooth, and then pumping water into the entire open hole interval between the packer and the bottom of the hole, which was located at 3.72 km (12,200 feet) at this time. The physical situation is depicted in Figure 6. A volume of 1,670 cu. m (442,000 gallons) was injected, primarily at rates of 15 to 27 l/s (240 to 420 gpm), and at downhole pressures ranging from 66 to 75 MPa (9600-11,000 psi). A rapid rise in pressure was noted at EE-2, and two hours after the commencement of pumping in EE-3A, the EE-2 wellhead valve was opened, and water flowed out. At first the outflow rate was small, but by repetitively surging the well, i.e., by shutting it in for a while, then quickly venting it, the outflow rate was steadily increased, and at the test conclusion it attained a value of 10 l/s (160 gpm). The reservoir flow resistance was 3GPa s/cu m (30 psi/gpm), and with time and future stimulation, should reduce further. Even now, the impedance is only two times the low back-pressure impedance observed for the Phase I reservoir after several months of operation and several episodes of high pressure stimulation.

A post-connection temperature survey taken in EE-3A on May 30 showed that several new joints had been stimulated and also served as flow entries from EE-3A to the reservoir. Figure 6 portrays the potential flow paths, which appear short in this elevation view, but bear in mind that EE-2 and EE-3A are horizontally separated by 150 m at the depth where the two wells appear to intersect.

Following the successful connection the redrilled well was extended and two additional stimulations were conducted in it with open hole packers. The first stimulation was conducted very deep, and failed to result in significant communication. The second stimulation was attempted at a depth about midway between the successful and unsuccessful ones, and another hydraulic connection was achieved. The presence of an expensive drill rig over one well did not permit extensive flow testing, but a preliminary tracer test suggests that the reservoir has a stimulated joint volume of approximately 400 cubic m, which is 50 percent greater than that of the Phase I reservoir after years of operations and improvements.

In August 1985 the drill rig was furloughed after drilling EE-3A to its total design depth. In October the rig will be reactivated at EE-3A and detailed geophysical well surveys will be conducted. Two new stimulating operations, again using open hole packers, are planned for November, the goal being to enlarge the reservoir yet again. Following these stimulations the well will be temporarily completed with liners and tubulars, so that a drilling or workover rig will no longer be required, and then a 10 to 30 day long circulating flow test will be conducted to more fully evaluate the reservoir.

CONCLUSIONS

Seismic monitoring provides a view of fracture systems which is unobtainable by any other means at the depths of interest here. the seismic observations, supported by results in Britain as well as the rock mechanics lab, indicate that injecting with low viscosity fluid like water into jointed rock results in multiple joint stimulation caused by shear-slippage, not the single tensile fracture of conventional theory. Guided by microearthquake maps, an existing well was sidetracked and redrilled into the stimulated zone created by earlier massive hydraulic injections at EE-2. The redrilled well encountered zones of permeability induced by the early stimulation but it required supplementary stimulation before good flow communication could be established between the two wells. Two of the three supplementary stimulations have been successful, and it appears that future stimulations may be similarly successful, but already the new reservoir appears promising. It possesses a flow resistance and stimulated joint volume approaching that of, or superior to that attained by the earlier Phase I reservoir after prolonged heat extraction and permeability enhancing improvements.

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Inert and Reacting Tracers for Reservoir Sizing

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Abstract

Flow characterization and volumetric sizing techniques using tracers in fractured hot dry rock (HDR) reservoirs are discussed. Mathematical methods for analyzing the residence time distribution (RTD) are presented. Tracer modal volumes and RTD shape are correlated with reservoir performance parameters such as active heat transfer area and dispersion levels. Chemically reactive tracers are proposed for mapping advance rates of cooled regions in HDR reservoirs, providing early warning of thermal drawdown. Important reaction rate parameters are identified for screening potential tracers.

Nomenclature

A= effective heat transfer area

A_r= 1st order pre-exponential factor

$A_{r,2}$= 2nd order pre-exponential factor

C, C(t)= tracer concentration

C_p = fluid heat capacity

D = dispersion coefficient

E_a = 1st order activation energy

$E_{a,2}$ = 2nd order activation energy

E(v) or E(t) = exit RTD for a pulse

k = 1st order reaction rate constant

L = characteristic reservoir length

m_p = mass of tracer pulse

Pe = dispersional Peclet number = uL/D

Q = volumetric flowrate

t = time

T = fluid temperature

u = fluid velocity

V, <V> = modal and mean reservoir volume

x,y,z = reservoir postion coordinates

$w_{1/2}$ = width of the RTD at 1/2 height

ρ= fluid density

α= thermal diffusivity of rock

λ = thermal conductivity of rock

σ^2 = variance of the RTD

Introduction and Scope

This paper reviews the research and development work on tracers that has occurred in the last 11 years at Los Alamos and MIT. Details are contained in the following publications by the author and his co-workers (Tester, Bivins and Potter (1982), Robinson and Tester (1984), Robinson (1984), and Robinson, Tester, and Brown (1984)).

Tracers have become a reliable diagnostic tool for determining the size and fluid flow characteristics of geothermal reservoirs. They have been used in field tests of hot dry rock (HDR) geothermal reservoirs at the Fenton Hill site in New Mexico and at the Rosemanowes quarry in Cornwall, U.K. Model-independent information, such as fracture volumes and dispersive characteristics, obtained from inert tracer measurements has provided a means of quantifying the behavior of these fractured geothermal systems. Because, however, the information supplied by conventional inert tracers is insufficient to construct detailed reservoir models with extensive predictive capabilities, we are also developing new techniques that use temperature-sensitive, chemically reacting compounds as tracers. These reactive tracers will measure directly the cooldown rate of the rock between the two wellbores of a continuous flow geothermal reservoir. Reactive tracers should also be useful in measuring produced fluid thermal drawdown in some conventional geothermal reservoirs where reinjection has created this undesirable side effect.

To date theoretical modeling and bench-scale screening tests have been conducted to identify potential reactive tracers for field use and to explore the strengths and limitations of the reactive tracer concept for sizing HDR systems.

Inert Tracer Analysis

Definitions

1. Residence Time Distribution, E(t): E(t)dt is the fraction of th injected fluid which leaves the system between t and t + dt. An effective tracer follows the same flow paths as the reservoir fluid, and the concentration-time response measured at the outlet to a pulse injected at the

inlet is:

$$C(t)= m_p E(t)/Q \quad (1)$$

where m_p is the mass of tracer injected, and Q is the volumetric flow rate of fluid. The residence time distribution (RTD) curve can be also expressed as E(v), where E(v)dv is the fraction of the produced fluid which entered at t = 0 that emerges between v and v + dv. Thus, E(v) = E(t)/Q. This convention allows us to compare fracture volumes measured in tracer experiments at different flow rates.

2. Modal Volume, $\mathring{V}$: the volume corresponding to the peak of the RTD curve in $\mathring{V}$ most likely represents the volume of low impedance connections which follow a direct route from inlet to outlet.

3. Integral Mean Volume <V>:

$$\langle V\rangle = \int_0^{\infty} vE(v)dv \quad (2)$$

In fractured porous media, <V> is the void volume of all fractures which accept flow, regardless of their impedance. The calculated integral mean volume should be considered as an approximate estimate of the entire fracture system volume, since measurement of the tail of a distribution is inaccurate and the curve must be extended arbitrarily to infinite volume.

4. Width at 1/2 Height, $w_{1/2}$: the width between the two points on either side of the peak for which the tracer response is one-half its peak value. This parametrer, defined arbitarily, is a measure of the outlet dispersion of the main fracture flow paths. This approach circumvents the problem of defining the response curve's tail which decreases the usefulness of the variance as a measure of dispersion.

5. Effective Heat Transfer Surface Area, A: a single-parameter estimate of the heat transfer capacity of a fractured reservoir. Assuming plug flow up a single vertical, rectangular fracture of surface area A (on one face of the fracture), the fluid temperature within the fracture during long-term operation is given by a minor variation of a formula suggested by Murphy et al.: (1981)

$$\frac{T-T_i}{T_r-T_i} = \text{erf}\left[\frac{\lambda_r A(z/L)}{\rho C_p Q\sqrt{\alpha t_{op}}}\right] \quad (3)$$

in which T, T_i, and T_r are the temperatures of the fluid at point z, at the inlet, and throughout the rock initially. The parameters λ_r and α are the thermal conductivity and thermal diffusivity of the rock, ρ and c_p the average density and heat capacity of the fluid, and t_{op} the time of operation of the reservoir. The outlet fluid temperature is obtained by setting z/L = 1. Although simplistic, this model conveniently describes the long-term behavior of a fractured reservoir with a single adjustable parameter.

Dispersion Mechanisms

The dispersion in the outlet tracer response from a fractured geothermal reservoir results from a combination of three factors: (1) large-scale flow heterogeneities caused by the superposition of flows from fractures of different size and flow impedance, (2) crossflow between different fractures, and (3) dispersion within a single fracture.

The extent of dispersion in a single-fracture flow can be important. Four single-fracture dispersion sources have been identified: roughness of the fracture surface, holdup of tracer in dead-end pores or fractures branching off the one in which the flow is occurring (matrix diffusion), different arrival times of the fluid caused by multidimensional flow, and crossflow of a tracer between different flow streams. The last two can be treated separately or can be combined as Taylor dispersion. Horne and Rodriguez (1983) and Robinson and Tester (1984) have evaluated various single-fracture dispersion mechanisms for conditions likely in fractured geothermal reservoirs. Table 1 summarizes the results of these studies, using the axial dispersion Peclet number (Pe = uL/D) as the parameter characterizing dispersion. A large Peclet number indicates that the mechanism produces very little of the observed outlet dispersion. The table shows that the amount of dispersion produced within a single fracture is small compared with the overall level of dispersion measured in HDR reservoirs using tracers.

A number of models have been used to correlate the observed RTD to solutions of the convective-disperson equation. In these cases one or more adjustable parameters are used to fit the data. These parameters include fluid dispersivity (D), and individual fracture flow and volume fractions (Tester et al (1982)). Although these models usually can be adjusted to represent the data well mathematically, because of geometric and flow velocity uncertainties within the reservoir, their use in prediction of RTD's is limited.

The observed levels of dispersion in the Fenton Hill and Rosemanowes systems studied to date are dominated by multi-fracture flow. This conclusion was corroborated in some radioactive ^{82}Br tracer experiments at Fenton Hill using gamma logging in the production wellbore. As shown in Figure 1, distinct concentration-time curves were identified for three exit regions in the production wellbore (Robinson and Tester (1984)). Thus at least three different fractures were contributing to the observed total dispersion. Not only were the three fracture zones identified, but the dispersion from each individual fracture zone was too great to result from any combination of single-fracture dispersion mechanisms. Crossflow among the different fractures was occurring, perhaps in a highly-fractured region near the inlet to the reservoir as depicted in Figure 2.

Table 1. Magnitudes of Different Single-Fracture Dispersion Mechanisms

Sources: Horne and Rodriguez (1983), Robinson and Tester (1984).

Mechanism	Dispersional Peclet Number	Comments
Fracture Roughness	very large	scale of dispersion (fracture aperture) is very small compared to overall length scale (well-bore separation distance)
Matrix Diffusion	very large	large apertures and rapid flow velocities minimize matrix diffusion effect
Taylor Dispersion	$150 - 3 \times 10^4$	molecular diffusion coefficient varies strongly with temperature, causing wide range in Pe
Point Source-Point Sink Potential Flow	55	calculated assuming dispersion is caused solely by flow streamlines of different length and velocity
Actual Measured Dispersion in Fractured Geothermal Reservoirs	0.5-5	observed dispersion is much greater than can be explained by flow in a single fracture

Empirical Correlations

Despite the existence of detailed flow information from tracers, flow impedance measurements, and downhole logging, no adequate predictive reservoir model has been constructed for the latest Fenton Hill reservoir (Zyvoloski et al (1981)). At their present level of sophistication, tracer techniques are useful for measuring fracture volume and flow fractions, but cannot be used easily to determine the distribution and orientation of fractures in space. However, in analyzing past tracer experiments in the Fenton Hill and Rosemanowes systems, we have found an empirical approach to be very useful. The resulting correlations have led to general conclusions about the nature of flow and heat transfer in fractured geothermal reservoirs.

The large scale heterogeneities such as the superposition of flows from multiple fractures undoubtedly exert greater influence on heat transfer behavior, since the positioning of low impedance conduits effectively defines the accessible volume of rock. Indeed, the onset and subsequent rate of thermal drawdown is probably controlled by the surface area of the smallest low impedance connection. The modal volume $\hat{V}$ corresponds to the low impedance fracture connections, which should contribute most to the long term produced fluid temperature decline. These ideas are confirmed by Figure 3, where it is shown that $\hat{V}$ correlates with the reservoir's heat transfer capacity. The effective heat transfer surface area A was calculated by applying Eqn. (3), or similar numerical modeling results, to actual produced fluid thermal drawdown data for each reservoir. With Figure 3, a single inert tracer experiment can provide a crude estimate of the heat extraction capability of a fractured reservoir.

The Rosemanowes Phase II point in Figure 3 is not really a data point, as extensive energy extraction has not yet been carried out in this reservoir, so drawdown has not been observed. Only the modal volume has been plotted. We include it, however, to show that for this new reservoir and for commerically-sized systems, in general, use of the modal volume to estimate A is probably unjustified because of the large extrapolation required from smaller sized systems. A more legitimate approach for large systems with multiple entrance and exit regions perhaps would be to size individual fracture zones using preferential injection of a radioactive tracer and production well gamma logging (Tester, et al (1982)). These zones or subsystems are likely to be small enough to warrant the use of Figure 3. For example, the point on Figure 3 after the stress unlocking experiment (SUE) also is an estimate because the heat transfer area was not obtained by fitting it to drawdown data, but it is felt that this point represents a reasonable extrapolation from the original reservoir conditions.

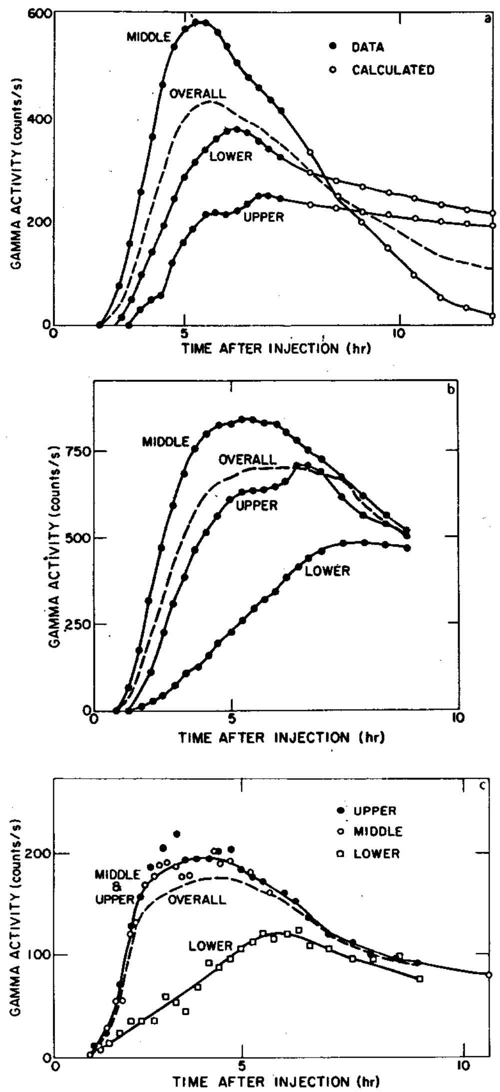

Figure 1 Individual fracture zone concentration-time curves obtained by ^{82}Br pulse injection followed by gamma logging in the production well bore. (a) Experiment 217-A5, December 12, 1980.

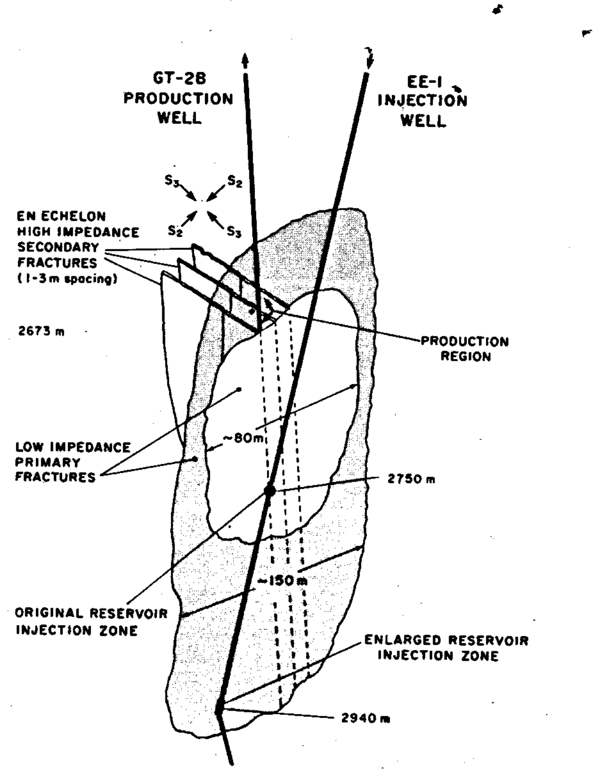

Figure 2 Conceptual schematic of the EE-1/GT-2 fracture system (adapted from Tester et al. (1982). Schematic of the fracture-well bore geometry.

This simple analysis ignores the fluid that does not flow through the low impedance fractures. Run Segment 5 tracer experiments at Fenton Hill (5/9/80 to 12/12/80) showed that in this reservoir roughly 30% of the injected fluid traveled through high impedance secondary joints. This result appears to be quite common in the HDR reservoirs tested to date: flow through several low impedance joints accounts for the early tracer resoponse, while a substantial secondary flow travels through a large volume of rock, probably at the periphery of the reservoir.

A comparison of the volumes of the low impedance primary flow paths and the high impedance secondary paths can be made. The modal volume represents the low impedance volume and the integral mean volume <Eqn. (2)> is the total fracture volume (main fractures plus secondary flow paths). As seen in Table 2, the integral mean volumes for the ^{82}Br tracer experiments of Run Segment 5 are much larger than the corresponding modal volumes. The enormous potential capacity of this reservoir appears to have gone largely unused due to the tendency of the fluid to short-circuit through low impedance joints. Total reservoir size estimates using microseismic mapping and geochemical information substantiate this conclusion.

In addition to the absolute sizes of the low-impedance fractures and the total reservoir, reservoir growth during energy extraction may be monitored using V and <V> from a series of tracer tests. Fracture volume growth may be caused either by thermal contraction and stress cracking of rock during cooldown, or through opening new fractures by water permeation into pre-exisitng joints in the rock matrix (hydraulic fracturing). For example, the increase in modal and integral mean volumes during the Run Segment 5 are plotted against total energy extracted in Figure 4. The maximum amount of new fracture volume possible via thermal contraction of rock is denoted by the free

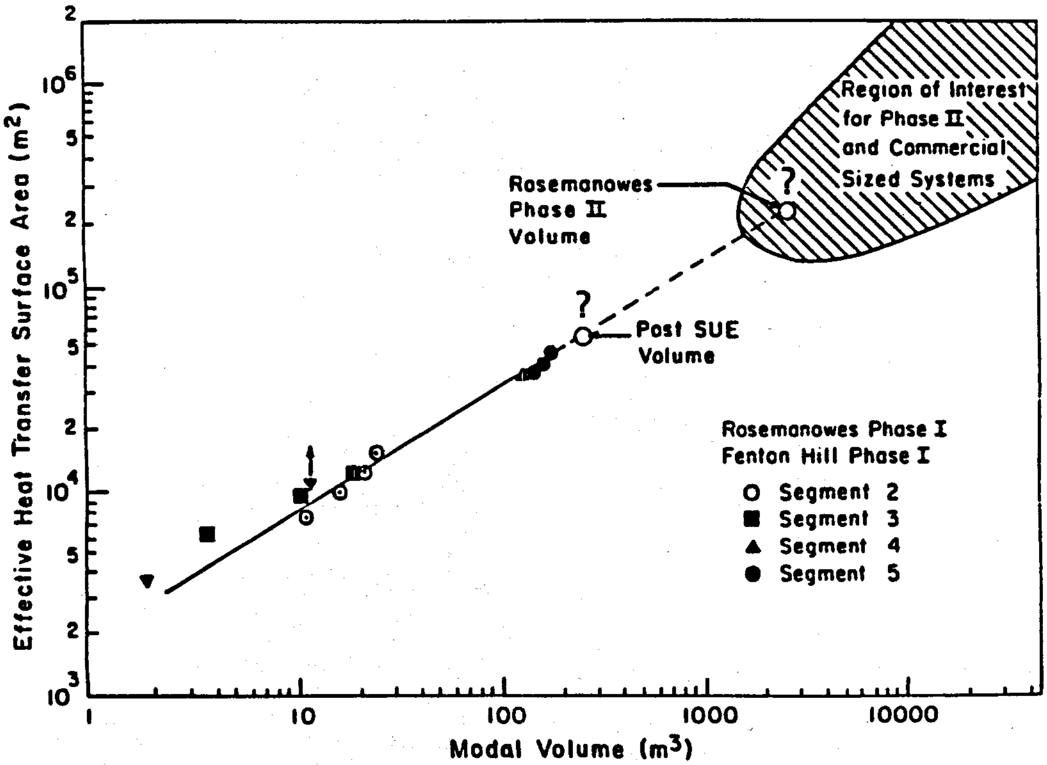

Figure 3 Effective heat transfer surface area vs. modal volume.

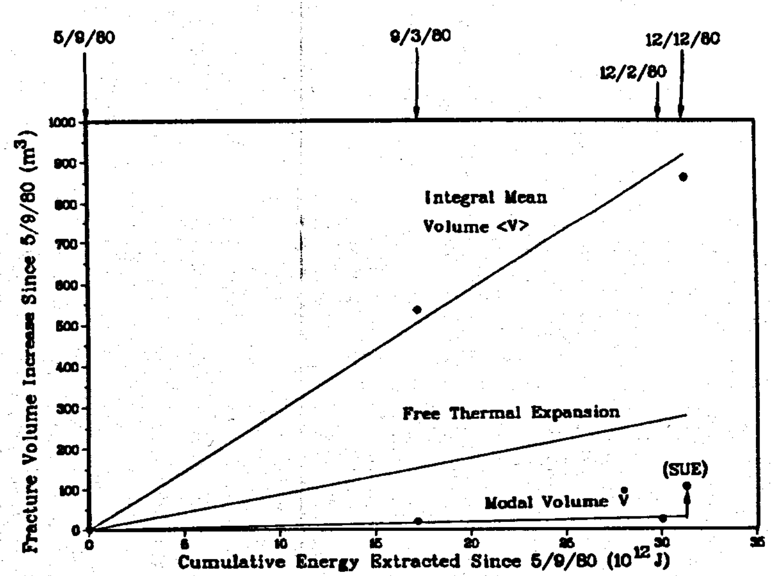

Figure 4 Fracture volume growth vs. cumulative energy extracted.

Table 2. Summary of Tracer Field Experiments

Date	V (m^3)	$\langle V \rangle$ (m^3)	$w_{1/2}$ (m3)	$w_{1/2}/V$
Fenton Hill Experiments				
2/9/78	11.4	-	18.1	1.59
3/1/78	17.0	-	40.3	2.3
3/23/78	22.7	-	62.5	2.75
4/7/78	26.5	-	70.8	2.67
5/9/80	161	1311	227	1.41
9/3/80	178	1845	323	1.81
12/2/80	187	-	303	1.62
12/12/80	266	2173	479	1.80
Rosemanowes Tracer Experiments (1982-1983)				
Rh6A	1.42		1.68	1.18
RH12	12.3		7.0	0.57
Fluor- escein #3	2390		4870	2.04

thermal expansion line. The large increase in integral mean volume suggest that hydraulic fracturing must have been occurring along with thermal contraction. However, much of this new volume was poorly utilized, as shown by the modest increase in modal volume.

For reservoirs operated with steady flow conditions, the need for low impedance fracture connections may be at odds with the goal of achieving an efficient volumetric sweep of fluid through a large number of fractures. Different operating strategies in future HDR reservoirs may allow us to utilize more efficiently the large fracture volumes which apparently possess only a relatively weak hydraulic connectivity with the main fractures. For example, in the SUE at Fenton Hill, rapid pressurization and depressurization of the reservoir from both injection and production wells after the system had been partially cooled resulted in a more even flow through a larger number of fractures. This is seen in the dramatic increase in modal volume caused by rapid pressurization in the SUE on 12/8/80 (Figure 4). A series of these high pressure experiments or possibly cyclical pressure transients, may bring more of the unused far-field fracture volume into the active heat exchange region of a fractured reservoir. Alternatively, huff-puff operation--injection into a shut-in reservoir, followed by production from the same well--might provide greater access to a larger volume of hot rock. Because tracer experiments measure fracture volumes, the beneficial results of the SUE were identified by tracer experiments, and they will be equally profitable when evaluating the success of future reservoir modification techniques.

RESERVOIR ANALYSIS USING REACTING TRACERS

Thermal drawdown analysis of small, prototype reservoirs has been made manageable by the ability to achieve produced fluid temperature decline after only a few months of operation. However, for larger systems, reservoir simulators will have to be used in a predictive way, since years could pass before produced fluid temperature measurements yield useful modeling information. More important, commercialization of the HDR concept requires that a method exist for predicting a priori the lifetime of a reservoir. The normal battery of diagnostic experiments (pressure transient, well logging, tracer, microseismic, and fluid geochemical) probably does not provide the information necessary to construct detailed reservoir models with predictive capability. Chemically reactive tracers, which are sensitive to internal changes to the reservoir's termperature field, may solve this problem in future HDR systems.

The kinetics of most chemical reactions are extremely temperature-sensitive. For first order reactions carried out in batch reactors, the following rate equation is often applicable:

$$dC/dt = -kC \qquad (4)$$

where C is the concentration of the reacting species and t is time. The rate constant k is the parameter which contains the temperature sensitivity. It normally can be described by the equation

$$k = A_r \exp(-E_a/RT) \qquad (5)$$

in which A_r is the pre-exponential factor, E_a the activation energy of the reaction, R the universal gas constant, and T the absolute temperature. For typical reactions in solution, k will vary by several orders of magnitude for the range of temperatures encountered in an HDR reservoir undergoing extensive energy extraction.

Suppose a tracer is injected into an initially hot reservoir, and the reaction proceeds about half way to completion during its stay in the system. Then, after some cooldown has been achieved, a second experiment should show less chemical reaction because of the shorter time the fluid spends in hot zone of rock. A series of reactive tracer experiments will, in theory, map the rate of progress of the cooled region as it approaches the exit well, giving an early warning of thermal drawdown.

The transient response of this reacting tracer experiment will be governed by both the temperature field and the dispersive nature of the fluid flow within the reservoir. For preliminary estimates, we assumed that the tracer behavior could be modeled using the one-dimensional axial dispersion equation with a first-order chemical reaction included:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial z^2}\right) - U\left(\frac{\partial C}{\partial z}\right) - kC \qquad (6)$$

Although objections have been raised against the applicability of Eqn. (6) for complex fractured porous media, we use it here to demonstrate the concept of reactive tracers and to perform parameter sensitivity studies. Since chemical reaction rates for first-order ractions depend on the time-temperature history of the fluid rather than on the specific dispersion mechanism, Eqn. (6) should be adequate for these preliminary calculations.

The other component of this reservoir model is the axial (z-direction) temperature field. The single-fracture temperature solution <Eqn. (3)> was used in these calculations. This uniform temperature field assumption is perhaps questionable given the explanation of tracer dispersion as flow through different sized fractures. These fractures are each likely to have unique temperature characteristics, e.g. the small ones (corresponding to short residence times) cooling down more rapidly than the large ones. Nonetheless, the model as formulated should be sufficient for parameter studies. Analysis of actual field experiments will have to address this question.

Our model system had the following characteristics: $A = 300000\ m^2$, $Q = 1.262 \times 10^{-2}\ m^3/s$ (200 gpm), and $T_{init} = 250\ °C$. The internal temperature field in a reservoir at various times is shown in Figure 5. To achieve 10°C of produced fluid thermal drawdown (a practical minimum for estimating reservoir size), five years of continuous operation are required.

The most important feature of the reactive tracer concept is its ability to identify thermal drawdown much more quickly than produced-fluid temperature measurements. For example, the reactive tracer response to a step change in inlet concentration is shown in Figure 6. Just 1 to 2 years of operation are required to obtain a sensitive estimate of heat exchange capacity.

Parameter studies using the axial dispersion model also support the following conclusions:

1) For thermal behavior such as that in Figure 3, reactions with higher activation energies are more sensitive to small levels of thermal drawdown.

2) Tracer dispersion affects the shape of the response curves, but not the sensitivity of the measurement. However, if dynamic shifts in reservoir size occur, inert tracers should also be used in conjunction with reactive tracers.

3) The reactive tracer response is sensitive to the extent of thermal drawdown, but not to the specific shape of the temperature field. Reactions which are moderately fast at the highest reservoir temperature are extremely slow at temperatures 100°C below this. Thus, the exact shape of the temperature field in the cooled region of the reservoir is unimportant. The conversion of a reacting tracer is essentially a measure of the amount of hot rock remaining between the two wellbores.

REACTIVE TRACER SCREENING STUDIES

A significant portion of our research efforts have been and are currently directed toward identifying appropriate reactive tracers for use in HDR systems with a range of mean residence times and rock temperatures. The desired kinetic parameter (A_r and E_a) should be such that the reaction time (1/k for a 1st order reaction) at the average reservoir temperature is approximately of the same order as the mean residence time. In addition, each reactive tracer must have the same characteristics required of an inert tracer in that it must be non-adsorbing and easily detectable in low concentrations.

In our early work, the kinetics of alkaline hydrolysis of a number of organic esters and amides were determined in aqueous solutions for temperatures varying from 100 to 300 °C (Robinson (1984) and Robinson, Tester, and Brown (1984)). For this system a pseudo-first order reaction was created by conducting the hydrolysis in excess OH^- or in a buffered solution. The results of these early studies are given in Table 3. Ethyl acetate, ethyl propionate and iso-pentyl acetate would be suitable for HDR systems at 70 to 125°C having mean residence times ranging from 10 to 200 hr. Ethyl pivalate and acetamide would work well for reservoirs between 150 to 200°C over the same residence time range. We are presently involved with identifying reactive tracers for hotter reservoirs at 200 to 300°C. A number of fluorinated low molecular weight hydrocarbons, peroxides, and organic dyes are currently under laboratory study with field tests planned for the near future.

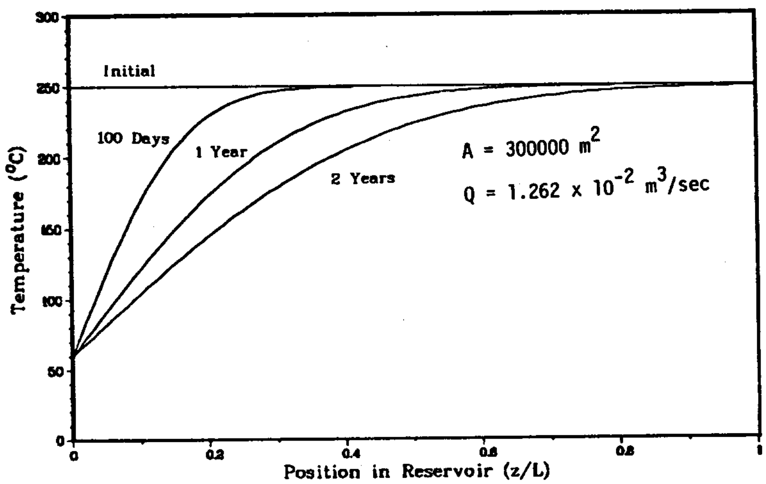

Figure 5 Internal temperature profiles during long-term energy extraction.

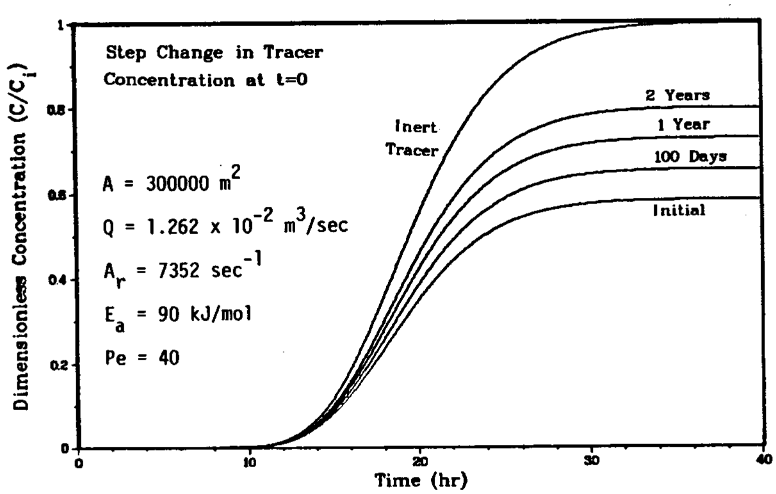

Figure 6 Reactive tracer behavior during long-term energy extraction.

Table 3. Results of Kinetic Experiments

$$A_r = (1.0457 \times 10^{-6})10^{ph}A_{r,2}$$

$$E_a = E_{a,2} + 45.8$$

Compound	$A_{r,2}$	$E_{a,2}$	$A_r/10^{pH}$	E_a
Ethyl Acetate	4.79×10^6	42.7	5.009	88.5
Ethyl Propionate	4.774×10^6	43.8	4.992	89.6
Iso-Pentyl Acetate	5.969×10^7	52.6	62.42	98.4
Ethyl Pivalate	1.473×10^{11}	98.3	1.54×10^5	144.1
Acetamide	1.519×10^8	73.5	1.59×10^2	119.3

CONCLUSIONS

1. Levels of tracer dispersion from field experiments in HDR reservoirs indicate that about 70% of flow is through a number of low impedance fractures. The remaining 30% of the flow travels through high impedance secondary flow paths of large volume.

2. Reservoir heat transfer capacity measured by effective heat transfer surface area A correlates with tracer modal volume V.

3. The volume of secondary flow paths grows substantially during long term energy extraction. More uniform flow and hence better utilization of high impedance joints was achieved by rapid pressurization of the Fenton Hill reservoir during the stress unlocking experiment.

4. Preliminary modeling suggests that the injection of chemically reactive tracers should be a sensitive reservoir test for measuring thermal drawdown far in advance of actual produced fluid temperature decline.

5. Laboratory kinetic studies have identified several chemically reacting tracers for use in geothermal reservoirs having temperatures ranging from 80 to 200°C).

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OPEN HOLE PACKER AND RUNNING PROCEDURE FOR HOT DRY ROCK RESERVOIR TESTING

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ABSTRACT

An acute need for open hole packers for high pressure, high temperature operations at the Fenton Hill, Hot Dry Rock (HDR) Geothermal Site has existed since 1981. Cemented-in-liners were used instead of packers while packer technology was brought up to HDR requirements. A reservoir development and evaluation program has just been completed with 5 successful open hole packer runs. These 5 successful runs were the result of: (1) R & D leading to improved packer materials and design, (2) an improved understanding of the interactions between the packer assembly and its hostile down hole environment, and (3), a carefully planned logging, sampling and coring program to locate packer setting depths (packer seats).

INTRODUCTION

After successfully extracting thermal energy from a small fracture system in the phase I system, a phase II system consisting of multiple fracture systems was proposed. After drilling and casing two wells (EE-2 and EE-3 on Figure 1)* reservoir development was begun. Both fracturing pressure and bottom-hole-temperature were much higher than projected. This combined with highly worn casing in EE-2 and a low fracturing pressure "leak off" zone at the EE-3 casing shoe severely limited the back up pressure that could be applied to minimize the differential pressure on an open hole packer. Two open hole inflatable packers were run after cooling the 575°F EE-2 wellbore with circulating water. One packer was set and 2000 psi differential pressure applied before packer failure occurred. The second packer, after substantially more wellbore cooling, failed at a lower differential pressure. Subsequent review of these packer runs failed to identify the failure mode. Oversized wellbore and insufficient self anchoring of the packer element probably contributed to the failures (Ref. 1).

Subsequently large fracture systems were created in EE-2 and EE-3 below a 4 1/2" cemented-in-liner and below the 9 5/8" casing shoes. Fracturing deep in the EE-3 open hole was proposed to attempt to intersect the upper fracture system in EE-2. An improved packer was run in and set in a 450°F region in EE-3 but it also failed before fracturing pressure was reached. The packer element had ruptured. It was apparent that it was set in an enlarged hole. A second cemented-in-liner was used to fracture deep in EE-3.

A connection to the EE-2 fracture system was not obtained. Massive hydraulic fracturing (MHF) in both EE-2 and EE-3 also failed to connect the wells. (Ref. 2 and 3.) Redrilling EE-3 into the EE-2 MHF zone, located using microseismic techniques, was to be the next approach used to try to connect the wells.

The blow down following the EE-2 MHF had left EE-2 damaged to the extent that it could not be used as an injection well. Budget constraints were expected to prevent a complete repair of EE-2 until much later and so EE-2 would be limited to low pressure service. Therefore EE-3A, the redrilled open hole bore in EE-3, was to be the injection well. It was expected that EE-3A would penetrate the low fracture pressure "leak off" zone before it encountered the EE-2 MHF reservoir. Zone isolation would be needed to by-pass the "leak off zone" and to selectively inject into the EE-3A open hole at phase II reservoir fracturing pressure. Cemented-in-liners could be used for zone isolation but were operationally unsuitable for reservoir testing because of their high installation cost and even higher removal cost. The possibility of damaging the reservoir with cement was also a concern.

A high priority was placed on developing equipment and procedures to achieve zone isolation with a retrievable open hole packer system. The initial performance specification called for service in an 8 1/2" to 9" diameter hole at 500° F with a 400°F cool down at 5000 psi differential pressure.

PACKER DEVELOPMENT

After the performance specification was determined, a list of potential problems and possible solutions was prepared and discussed with staff, consultants and several packer manufacturers. A revised list of problems and solutions was then prepared and is shown on Table I. The list was systematically approached. Engineering stress calculations, system analysis and simple hydraulic modeling were used, where appropriate, to determine which possible solutions could be ruled out on a technical basis. Discussions with packer designers and field specialists were used to identify realistic potential solutions and time and budget constraints eliminated some approaches. A

*References, Tables and Figures at end of text.

flexible equipment development plan evolved

1. Inflatable packers would receive primary effort and resources.

2. Autoclave tests would be used to assure that an inflatable element would meet the performance specification as a seal element but anchoring tests would be deferred until a down hole test could be conducted.

3. The tandem packer configuration or a single combination element (see Figure 2) would receive the main emphasis. An option to use the straddle configuration would be maintained if the anchor or combination element was not successful.

4. Contraction of fluid volume in the packer element during cooldown would have to be counteracted (Ref. 4). A fluid volume compensator was determined to be the most desirable method of maintaining proper packer element inflation. A tail pipe choke was less desirable.

5. The packer element would be protected with wear rings on the end pieces of the element.

6. A high strength down hole expansion joint would be designed compatible with the drill string and open hole packer.

Four autoclave tests of inflatable packer elements were conducted. Two tests were used to select the best element based on the performance specification and two additional tests were run at Baker Production Technology, formally Lynes Inc, to eliminate a design deficiency in the packer test mandrel which was detected in the first test. In the final test the packer element was heated to 500°F, inflated to 4500 psi in an 8-1/2" inside diameter casing and intermittently subjected to 5000 psi differential pressure through a 400°F cool down and heat up. The element was subjected to 5500 psi differential pressure at 500°F after heat up was achieved. Packer element deflation during cool down and pressure build up during heat up were observed.

The autoclave tests demonstrated that a short combination element could serve as the sealing element, but anchoring performance could not be demonstrated in any of the available autoclaves. With the need for an operational reservoir testing packer less than two months away a wellbore anchoring test of the combination packer element and test mandrel just below the leak off zone in of EE-3A was proposed.

PACKER RUNNING PROCEDURE

While the autoclave tests were being planned and performed, a simultaneous effort to prepare for running the packers was underway. As the drilling plan for EE-3A was prepared its impact on packer operations was considered. Where changes from past drilling practice were made, they benefitted both drilling and packer operations. The major exception was the proposal to drill with a sepiolite gel drilling fluid instead of water. The fluid was expected to improve overall drilling rate due to improved hole cleaning and reduced torque, drag, wear and corrosion of bottom hole assemblies and drill pipe. By lifting much larger drill cuttings than would be obtained with water sepiolite gel was expected to significantly improve the results from geological logging. Release and retrieval of the packer in a fluid with high gel strength was a great concern. Early attempts to run wireline logs in the high gel strength fluid were not successful. This dictated that the drilling fluid be displaced with water prior to wireline logging to select a packer seat. Packer operations were then completed before the water was replaced with sepiolite.

A conceptual model of the packer wellbore system was also developed (See Figure 3). The key elements in the model included heterogeneous rock, an out-of-gage wellbore and a packer assembly that interacted both thermally and hydraulically with the injection fluid and drill string. From this model the packer assembly, logging plan and running procedures evolved.

The basic packer running procedure is listed in Table II. Very high stress would be imposed on the rock in contact with the packer element (Ref. 5). Drilling parameters and geological logs were interpreted and a initial packer depth selected in order to avoid weaker rock. Temperature and caliper logs were run to select the exact packer setting depth (See Figure 4). The packer (Figure 2) was run with a shear-out-plug in the bottom of the packer mandrel. The plug was used to inflate the element through a port and check valve in the top sub in the packer. The drill pipe was filled with water using a fill up schedule during run in. An existing small fluid volume compensator was located below the bottom of the packer element. It was large enough to maintain packer element volume as the differential pressure was applied but was not large enough to maintain volume during the cool down of the packer that would occur at injection rates exceeding 1.5 BPM.

RESULTS

Seven EE-3A packer runs are listed on Table III. The first test was the anchoring and equipment shakedown test. A very short, apparently unfractured injection interval was isolated to expose the packer to a high differential pressure. The packer performed almost perfectly, but a design error prevented release of the expansion joint. This was corrected for the remaining packer runs.

On the second run the packer was exposed to sufficient pressure and cool down to fully stroke the volume compensator. The packer anchor released 2 1/2 hours later and the packer moved up hole rapidly slamming closed the expansion joint. The element resealed and injection was continued for 6 hours before leakage around the packer increased significantly. On subsequent packer runs a choke was run in the tail pipe below the packer. Injection caused a pressure drop across the choke. After the compensator stroked out the element was charged through the inflation port and check valve above the choke. Using this system packer anchoring was maintained through cool downs exceeding 300° F.

Well flow caused by an influx of carbon dioxide gas caused the packer element to partially inflate during the 3rd run. The element was damaged as it traversed the 2000 ft of the open hole and ruptured as it was inflated at the packer set depth. On the remaining packer runs a delayed drill pipe fill up schedule was used. The fluid level in the drill pipe had been kept above 2000 ft. It was subsequently maintained between 3000 to 5000 ft until the packer was at setting depth. There was no evidence of partial inflation on subsequent packer runs.

On the 4th packer run a reservoir connection between EE-3A and EE-2 was demonstrated while pumping 420,000 gallons of water into multiple fractures between 11,538 and 12,203 ft.

On the 5th packer run the element ruptured during inflation. After removing the packer a repeat caliper log showed a 9 3/4" diameter wash out on one side of the hole. The 6th packer was successfully set 30 ft shallower and a 1,400,000 gallon MHF injection was completed with no evidence of any leak around the packer. The packer continued to perform for another 32 hours after shut-in. The packer element finally ruptured due to stroke out of the compensator and continued heating of trapped fluid in the element.

The 7th packer was used to inject 1,500,000 gallons of water through multiple fractures between 11,977 and 12,550 ft depth in EE-3A. A second connection to EE-2 was demonstrated and evaluated during the test.

FUTURE PLANS

Two additional packer runs are planned this fall to complete the preliminary reservoir evaluation of EE-3A. Packer runs have also been proposed if redrilling to repair EE-2 is necessary and is funded.

The Hot Dry Rock Program is presently considering the use of a modified open hole packer to temporarily complete EE-3A. Commingled injection into all of connecting fractures below a "permanent" open hole packer would eliminate the need to cement-in a liner this fall and then have to washover and remove the liner in the future.

The use of multiple external casing packers in a "final completion" is also in an early planning stage.

CONCLUSION

With the cooperative efforts of Los Alamos and Baker Production Technology a packer and bottom hole assembly were designed and constructed. The equipment was able to meet and exceed the original objectives. Technical input and support from other packer manufacturers and consultants was invaluable during all phases of the effort.

Just as important as the equipment, were the carefully planned EE-3A drilling and logging programs; and the packer running procedures. Discussion with Baker Production Technology personnel provided input for the planning of each packer run. This planning achieved five successful packer runs out of seven attempts. In some respects even the two packer misruns were successes, because each failure mode was quickly identified and subsequently avoided by equipment and procedure changes. The critical components for a successful reservoir testing program using open hole packers included:

1. Packer seat selection based upon caliper logs, geological logs and temperature logs.
2. Accurate projection of bottom hole pressures and temperatures that would occur during the packer runs.
3. A understanding of how the packer equipment would function during the pressure and temperature changes.
4. A systematic approach to demonstrate and evaluate packer performance by increasing the operational goals gradually over a series of several packer runs.

Hopefully this successful demonstration of open hole packers in high temperature high pressure service will lead toward further developments including:

1. Geothermal open hole bridge plugs, both retrievable and drillable.
2. A commercial high pressure, open hole injection packer for high temperature service.
3. External casing packers for high temperature service.
4. High reliability drill stem testing tools for deep well, high pressure/temperature environments.

To further improve the reliability and performance of open hole packers the following technology development is needed:

1. Additional high temperature elastomer testing and development for both longer exposure and higher temperature applications.

2. Commercial gamma ray, temperature and caliper logging sondes coupled to a high temperature data transmission system designed specifically to support openhole packer operations.

3. Inflatable element modeling and simulation to improve our understanding of the sealing and anchoring mechanism.

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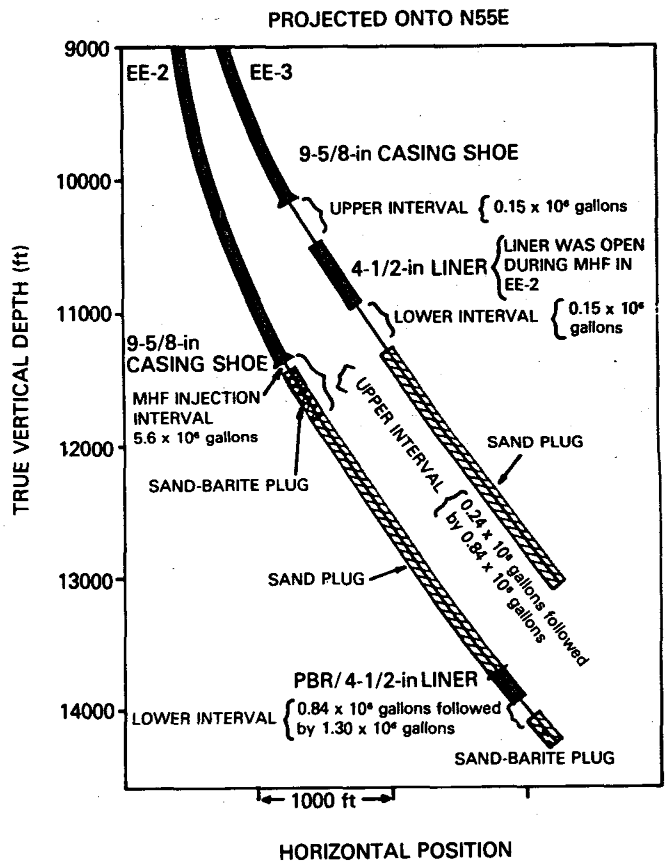

Figure 1. Phase II Reservoir Development.

TABLE I

Potential problems and possible solutions to meet the open hole packer performance specification

Potential Problem	Possible Solution
1. Adequately anchoring the packer to the bore at high differential pressures.	Balance forces with straddle packer configuration *Tandem packer with upper element modified to be an anchoring element. Hydraulic hold down modified from casing to open hole service.
2. Fluid contraction inside inflatable packer element, caused by cooling due to water injection. If excessive, packer inflation volume could diminish, and packer could be forced up well.	Compression type packer element. *Fluid volume compensator (pressure multiplier). *Choke below packer inflation port. Downhole pressure accumulator.
3. Oversized and elliptical wellbore.	*Inflatable packer element.
4. Excessive elastomer elongation in high temperature service.	Upgrade Y267 elastomer for higher elongation. *Larger run-in diameter packer elements.
5. Wear of packer elements in abrasive open hole wellbore.	Drill stabilizers above and below packer elements. *Wear gage rings on leading and tailing ends of packer elements.
6. Selecting a suitable packer seat by avoiding: a). Oversized wellbore b). Fractures c). Weak rock	*Open hole wireline logging a). Multiple arm caliper, b). Temperature c). Gamma ray correlation d). Televiewer. *Mud Logging a). Drilling parameters b). Drill cuttings-geological log c). Drill fluids chemistry and temperature
7. Frac string contraction during cool down.	Compensate by lowering frac string with rig. *Downhole expansion joint.
8. Potential high compressive loads in drill pipe.	*Large diameter heavy wall drill pipe. *Hevi-Wate drill pipe or drill collars just above packer.

* Possible solutions that were included in packer operations.

TABLE II

Basic Packer Running Procedure

1. Displace wellbore with water.

2. Wireline logging operations
   a). Temperature log
   b). 3 arm caliper log
   c). Other logs as required.

3. Packer assembly run-in
   a). Make up packer assembly (see Figure 2).
   b). Run and fill drill pipe with water per fill-up schedule.
   c). Space out packer, inflate element and shear out inflate plug.
   d). Release J latch and open expansion joint.

4. Pumping (injection) operations
   a). Maintain backside at maximum practical pressure.
   b). Inject down drill pipe to achieve objectives of reservoir test.

5. Shut down injection and wait for pressure to decay.

6. Close expansion joint and reconnect J latch.

7. Deflate packer element and retrieve packer.

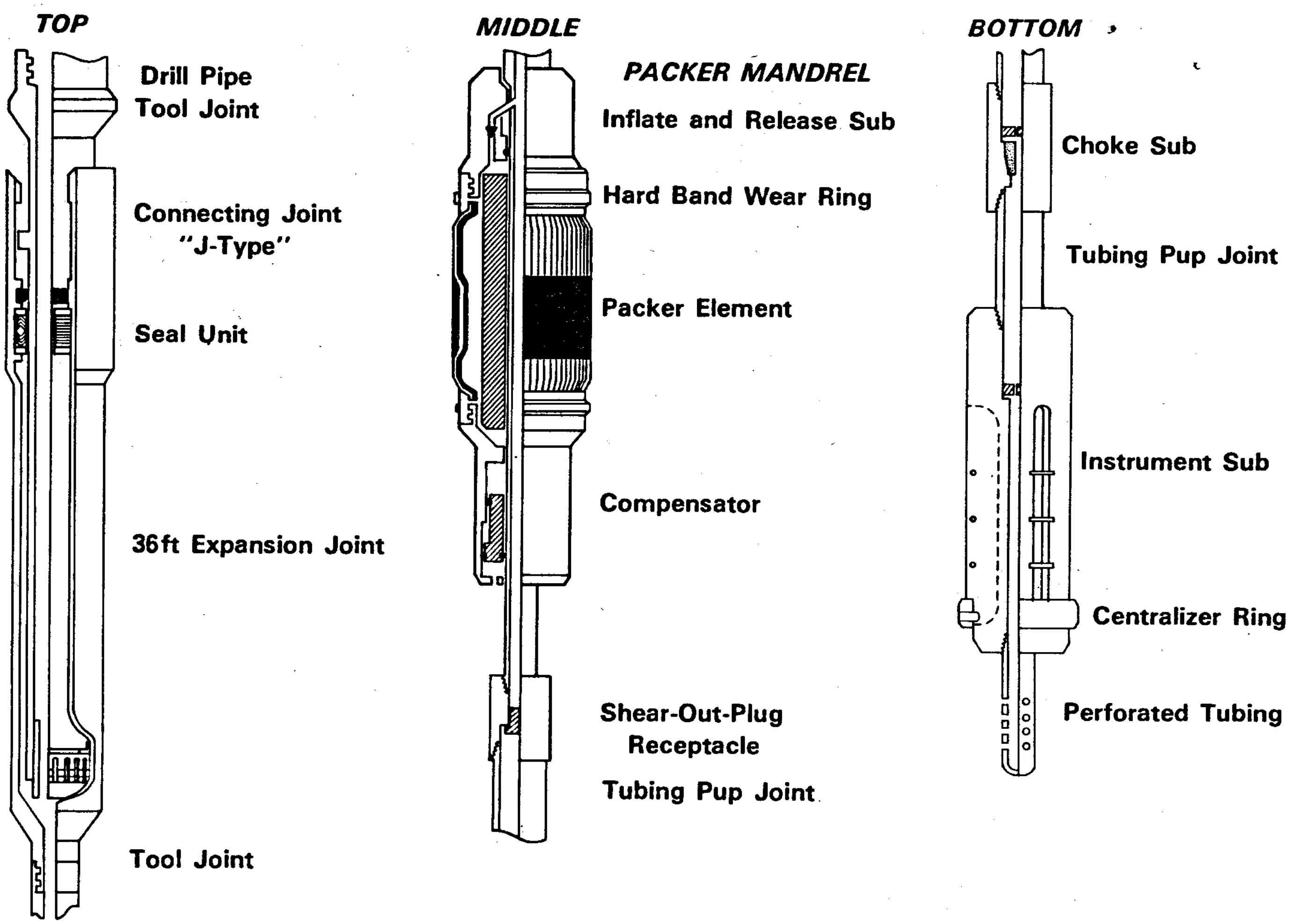

Figure 2. Packer Assembly.

TABLE III

Results of Open Hole Packer Runs in EE-3A

		Depths (ft)		Maximum Injection Parameters			
Run	Date	Packer	Injection	Packer Temp. (°F)	Diff Pressure (psi)	Rate (BPM)	Injected Volume (1000 gals)
1	4/19/85	10829	10830-10875	405°-360°	4700	6.0	6
2	5/02/85	10841	10842-11615	405°-178°	4530	8.6	140
3	5/15/85	11537	11538-12203	460°-120°	Packer damaged during run-in-hole		
4	5/27/85	11537	11528-12203	460°-120°	4325	10.0	420
5	6/20/85	12585	12586-13180	468°-407°	Packer element set in oversized borehole and ruptured.		
6	6/29/85	12555	12556-13180	462°-135°	5050	10.5	1386
7	7/16/85	11976	11977-12550	406°-154°	4800	12.0	1512

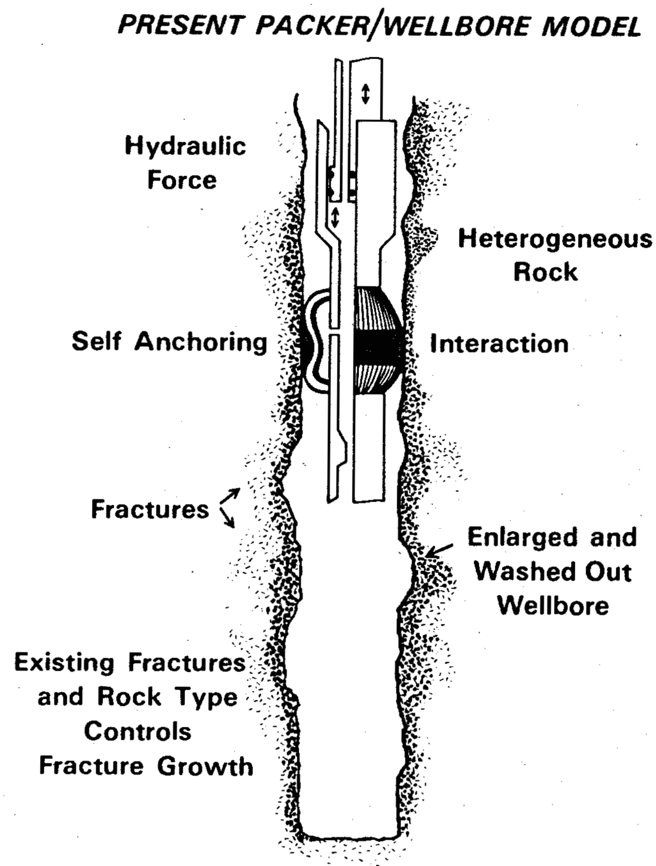

Figure 3. Conceptual Model of Packer-Wellbore System.

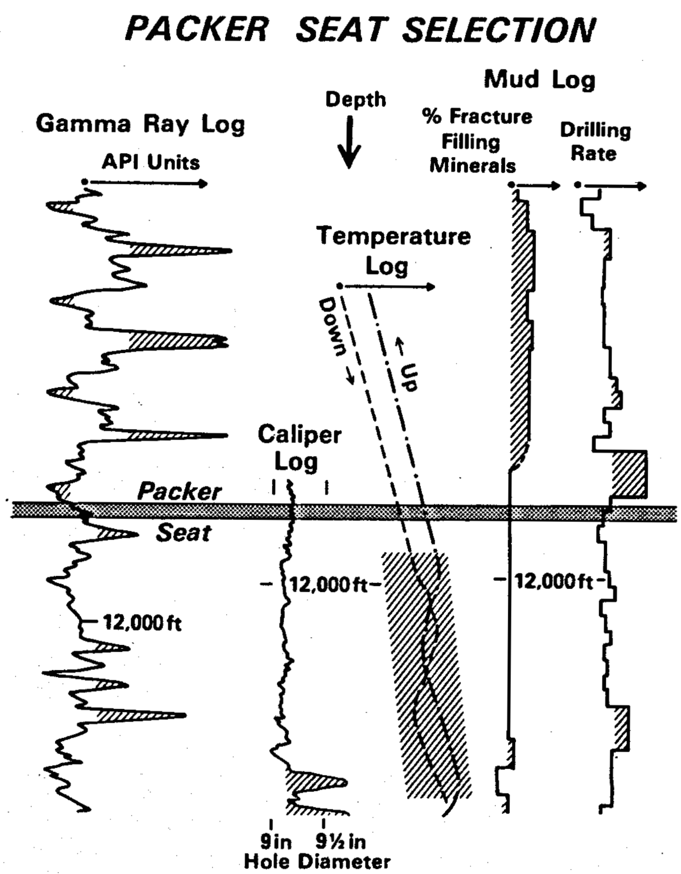

Figure 4. Technique Used To Select A Packer Seat.
(a) Correlate logs to common reference depth.
(b) Shade undesirable depths on each log.
(c) Find depth with no shading.

EARTH SCIENCE INSTRUMENTATION UPDATE
REVIEW FY1985

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INTRODUCTION

During this past year a very intense effort was concentrated on making a suitable reservoir connected to the injection and production wells at the Hot Dry Rock Fenton Hill Complex. This work included pressurization tests in both the EE-2 and EE-3 wellbores. The results of these experiments resulted in the sidetracking of EE-3 and drilling EE-3A into the previously mapped microseismic features. Numerous diagnostic logs and pressurization tests were performed during this redrilling phase. The successfully developed open hole packers were used to isolate zones of known hydraulic fractures culminating in successful reservoir communications. These experiments required the full blown array of surface instrumentation, surface seismic monitors, and deployment of the triaxial geophone detectors in the available adjacent wellbores. A total of 11 pressurization and hydraulic fracturing experiments were completed. In addition to the "standard" pre and post pressurization suite of logs for each experiment, 39 diagnostic and wellbore survey logs were run in the Fenton Hill wells. These logs used the high-temperature 3-arm caliper sonde, temperature with collar locator probe, gamma detector, fluid sampler, and string shot tool.

Several instrument development tests were performed using our logging equipment to run new tools in the geothermal wells in order to checkout their integrity and performance. Several tests were conducted on a new FM multiplex system installed in a downhole geophone package. Field tests were also run on a combination temperature/spinner/pressure sonde with a collar locator. Field tests were also conducted using the acoustic subassembly from the borehole acoustic televiewer to provide preliminary operational data.

HIGH-TEMPERATURE WELLBORE INSTRUMENT DEVELOPMENT

Several new downhole tool developments were pursued this past year. A combination temperature/spinner/pressure sonde including a collar locator was designed and fabricated (Fig. 1). The addition of the pressure sensors was the significant achievement for incorporation in this tool. Downhole pressure measurements are desirable

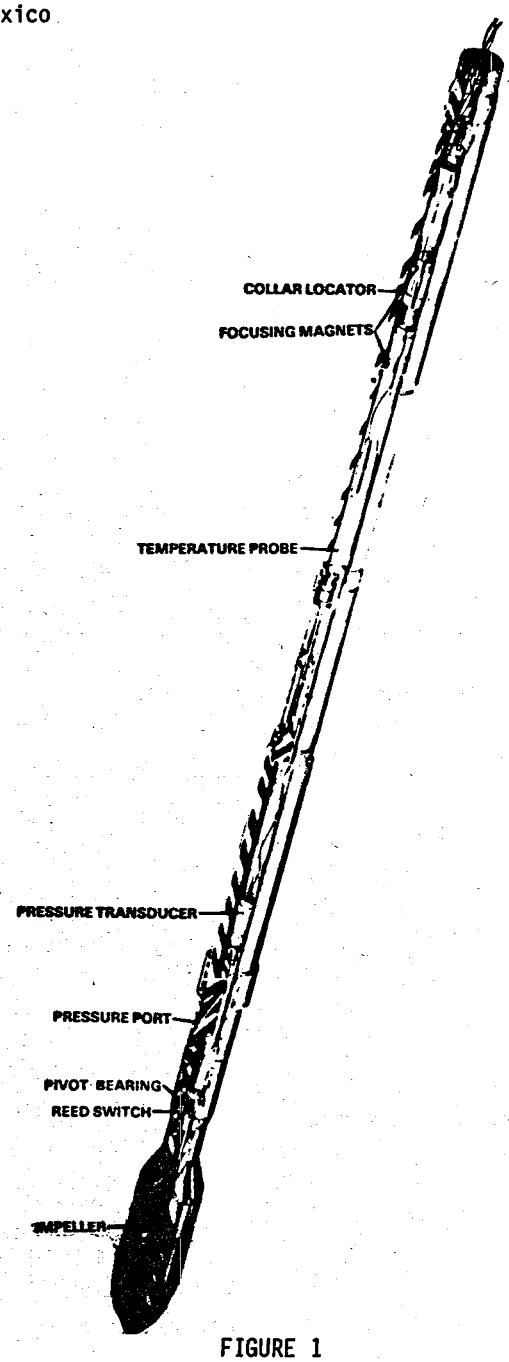

FIGURE 1
Temperature/Spinner/Pressure Tool

for several types of tests including pressurization and hydraulic fracturing diagnostics and well-to-well interference testing. There are very stringent specifications for the pressure transducers to meet the measurement requirements and are difficult to achieve in the geothermal environment. One major problem with the strain gage-type transducers is the extraneous effects of temperature on the pressure measurement. A combination of special temperature compensation and calibration techniques can eliminate drift, provide accurate data and still maintain infinite resolution. The desired detection of 1 psi differential with 5000 psi head pressure is certainly possible.

The slimline detonator tool used to calibrate the deployed geophone array was redesigned to allow detonation of up to 200 g of PBX (a high-temperature explosive) in a string shot configuration (Fig. 2). This much larger charge produces acoustic signatures that now can be used to calibrate the geophones deployed in outlying Precambrian boreholes and the surface seismic net as well. Fracture mapping can now be verified using both the hodogram technique and triangulation. This tool is immediately adaptable as a drill string backoff tool.

Another significant improvement in downhole instrument technology was the implementation of an FM multiplex system installed in the triaxial geophone sonde. Use of this wideband FM multiplex system was made possible primarily because of advances made in downhole thermal protection equipment to protect the electronics and enhanced frequency response in the TFE Teflon-insulated armored logging cable. Careful selection of appropriate conductors will allow carrier frequencies of at least 150 KHz to be transmitted over 20,000 ft of the 7-conductor TFE cable with only 20 db attenuation (Fig. 3). The improvement of the high-frequency response from the geophone excitation is shown in Fig. 4.

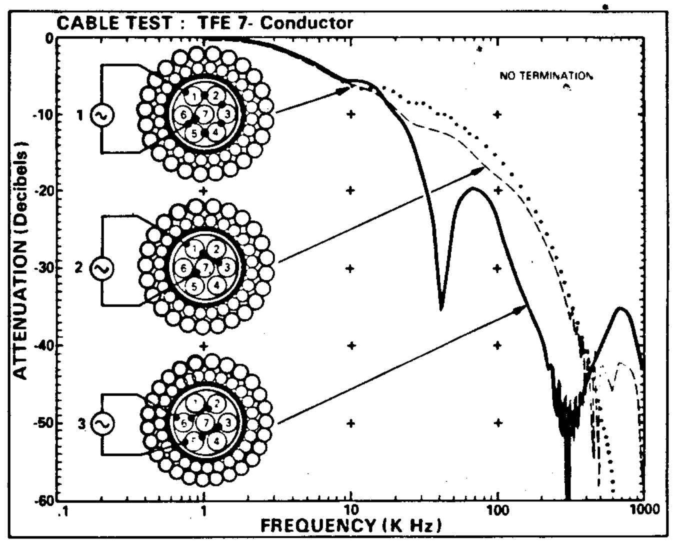

FIGURE 3
Frequency Response TFE Teflon Cable

The top trace is a geophone signal normally processed through a downhole amplifier with the high-frequency components attenuated by the cable. The second trace is the output of an adjacent geophone conditioned by the VCO (96 KHz ±8 KHz) and discriminated at the surface showing a much improved frequency response. The third trace is the output of an accelerometer used to compare response with the geophone and is also conditioned by the FM multiplex.

Our most intense effort this year has been the design and fabrication of a borehole acoustic televiewer for use in the Hot Dry Rock Program. This work has been a collaborative effort with the Westfalische Berggewerkschaftskasse (WBK) in West Germany. Los Alamos has primary responsibility for the acoustic assembly (Fig. 5) and the thermal protection systems for electronic circuits used in

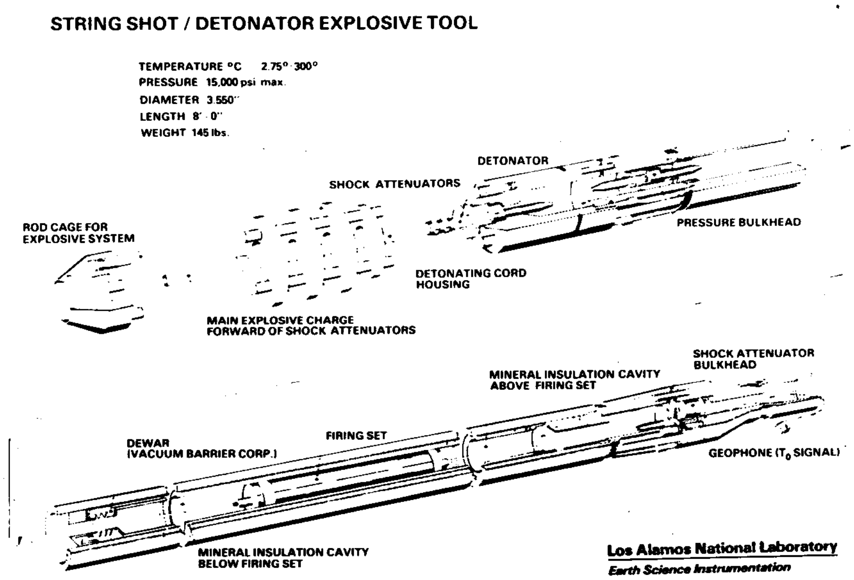

FIGURE 2
String Shot/Detonator Explosive Tool

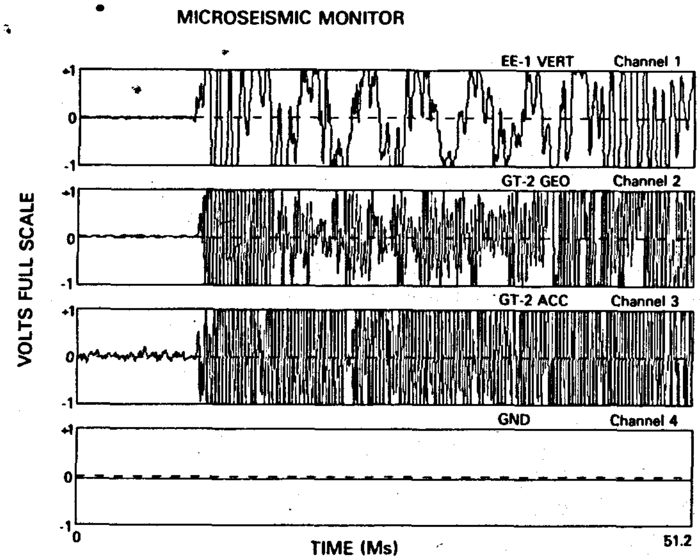

FIGURE 4
Comparison of Geophone Output Using FM Multiplex

the downhole instrument. WBK has responsibility for the downhole microprocessor and surface control, data acquisition, and on-line display. Unique features incorporated in the microprocessor and associated surface hardware allow a Δt measurement of transmitted reflected pulse which can be used to interpret depths of wellbore roughness. Unique features in the acoustic assembly include a "floating" window seal, piston-type pressure balance system, noise-free ceramic slip ring assembly, and a "front end" acoustic window. The floating window seal and piston balance system was developed at Los Alamos and used in the acoustic transceiver sondes (both transmitter and receiver). It has proven to be very successful in the field during numerous crosswell measurements. The first field test to checkout the borehole televiewer acoustic subassembly recently conducted at Fenton Hill confirmed operational integrity and reliability of this design at elevated temperatures.

The Los Alamos high-temperature downhole water sampler has been modified to accept a 2-ℓ sample bottle. Two new fluid samplers are presently being fabricated for the Salton Sea Drilling Project. The new samplers can be run from a 7-conductor cable or with a slickline using the high-temperature power supply and timer developed by Sandia National Laboratories.

FUTURE PLANS

Several areas of research and development are continuing. The work being done at Los Alamos with thermal protection equipment has gained wide-spread interest for use in high-temperature instrumentation. There have been significant improvements made in the development of downhole thermal systems but much more can be achieved to extend operating lifetime in the geothermal environment.

The next step for completing the borehole televiewer is the interfacing of the acoustic assembly to the downhole microprocessor and field testing the complete unit. This work is scheduled for early October. If all goes well we will interrogate the open-hole regions of EE-3A to evaluate the wellbore conditions and provide useful information for the well completion operations. We are looking forward to enhanced signal processing and software development that will enable caliper information.

The existing 3-arm caliper tool would yield considerably more information if it were extended to 6-arms and incorporated tool orientation. A conceptual design has been started that uses a high-temperature proximity gage made by Kaman Nuclear. The addition of three more caliper arms and orientation sensors would require a multiplex scheme in the downhole sonde.

Now is also the time to investigate the use of the high-temperature thermionic integrated circuits

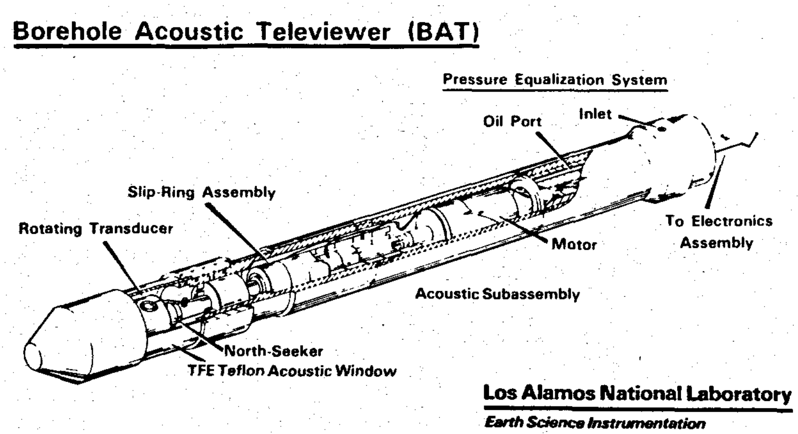

FIGURE 5
Borehole Acoustic Televiewer Downhole Acoustic Subassembly

for electronic circuitry in the well-logging tools. The circuits have been successfully tested for continuous operation at 500°C. Some circuits are ready for incorporation in downhole instrument packages to be tested over the 20,000 ft of TFE Teflon armored cable.

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SANDIA GEOTHERMAL TECHNOLOGY PROGRAM: INTERACTIONS WITH OTHER DOE RESEARCH AND CSDP*

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ABSTRACT

When the energy programs were initiated in the mid 70's, Sandia management made a conscious decision to apply existing Engineering expertise and capabilities in support of industry, government and university needs. A decision was made not to expend resources independently developing a panacea for the U.S. energy ills. Consequently, exchange of information and technology with others occurred from the start prior to the "Tech Transfer" buzz words of the 1980's.

The purpose of this paper is to briefly outline the Geothermal Technology Development (GTD)-supported Sandia programs; details will be given in subsequent papers by J. Kelsey and J. Dunn. Then, I will show how these programs interact with other energy programs at Sandia. Finally, I will discuss the overall Continental Scientific Drilling Program, its status (except for details on the GTD-run Salton Sea Experiment which is discussed elsewhere), and Sandia GTD interactions with CSDP.

GTD PROGRAMS AT SANDIA

The major programs run for GTD by Sandia are shown in Table I, along with some major accomplishments last year. As is evident from the listing, the work is oriented toward providing hardware to solve field problems with mathematical and laboratory modeling used to direct the R&D effort.

Past R&D has led to successful commercialization of PDC cutters on drill bits, high temperature drilling muds, hybridization of logging tool electronics, development of high temperature electronics, significant changes in the commercially available borehole televiewer, etc. We expect to see continued transfer of the current R&D into industry.

INTERACTIONS WITH OTHER DOE PROGRAMS

Sandia has major DOE Engineering responsibilities in both energy and weapon programs. Some of these are listed in Table II with notes of significant interaction with the GTD programs. The extensive use of weapons-developed codes (heat & mass transport, vibration, structural, ...) and facilities is not detailed in this summary.

Needless to say, the interactions are strong, to the point of at times being indistinguishable. For example, the Nevada Test Site contains a number of drifts bored into the mountains for nuclear testing. One of the tunnels, G-Tunnel, is used for insitu testing by a large number of nonweapon programs. The Fossil Energy-supported stimulation research includes tests in that tunnel wherein hydraulic fracturing is done at depth next to the tunnel, diagnostics for future field use are evaluated during the fracturing experiment and finally the actual fractured zone is mined out to verify the fracturing models and instruments. In the Geothermal Permeability Enhancement Program the G-Tunnel facilities were used; several boreholes were water filled and experiments performed in simulated geothermal environments. These later tests verified some theories and identified other problems; but most important, they provided a direct picture of insitu stimulation effects - the first ever obtained.

CONTINENTAL SCIENTIFIC DRILLING PROGRAM (CSDP)

The CSDP is a science-driven program to do fundamental research on the structures and processes in the continental crusts. The use of the drill to provide unique, high resolution information at depth can be traced in history back to the ill fated MOHO Project, followed by the immensely successful international Deep Sea Drilling Project (now the Ocean Drilling Program), the Ocean Margin Drilling Program (which never got started) on to the continent and the CSDP. This type of research has international interest as is shown in Table III.

The U.S. CSDP program has been discussed since initiated by the NAS/NRC Geodynamics Committee in 1973. A series of symposia, workshops and discussions resulted in a general program split as shown in Table IV with lead agencies identified. In any program all agencies have, and are expected to have significant scientific involvement. This interaction is defined in an approved Interagency Accord on CSDP. The majority of the CSDP general plans have been formulated by the Continental Scientific Drilling Committee of the National Research Council. The first active program with real drilling and research was initiated by George Kolstad of DOE/BES. Kolstad was also instrumental in developing the Interagency Accord and in fact, in catalyzing the entire U.S. CSDP program.

The U.S. program is currently sorting out its priorities and mode of operation. Congress has passed a resolution endorsing the activity and has a bill pending on specific actions. My version of the current structure is shown in Table V. Table VI summarizes past and planned U.S. research drilling. Many proposals to DOE and NSF are being considered for research drilling in areas as the Cascades, Alaska, Illinois, Kansas, Appalachia, Texas, New Mexico, etc. Sandia involvement in these activities is summarized in Table VII.

Since the DOE CSDP responsibilities are in Thermal Regimes, the DOE/GTD activities are obviously directly related. In fact, major portions of the Sandia-managed Magma Energy Program are indistinguishable from the CSDDP program since: (1) the CSDP understanding is a necessary base for evaluation of magma as an energy source; and (2) the GTD technology is needed for CSDP.

However, the end goals of the BES and GTD Programs are completely different - science for the sake of fundamental understanding versus geothermal heat as an energy resource. Mechanisms for attaining these goals extensively overlap and strong interaction of these programs is important.

The programs in CSDP and GTD at Sandia do overlap. Case in point is the recent work at Long Valley where in EOS (v. 66, no. 18, p. 194-200, Apr. 30, 1985) Rundle et al note: "Major funding for the experiment was provided by the Geothermal Research Program of the U.S.; Geological Survey (USGS) and by the Magma Energy Program of the U.S. Department of Energy (DOE),.... Additional funding came from DOE's office of Basic Energy Sciences and the National Science Foundation (NSF). The project was conducted partly under the auspices of the Continental Scientific Drilling Program." Authors on this publication included one each from Sandia, the USGS, LBL and four different universities. Specific interactions of the Sandia GTD and the CSDP programs are shown in Table VIII.

SUMMARY

The Sandia programs-supported GTD continue to develop technology and transfer that technology to industry for the purpose of reducing well costs and risks. An evaluation of the engineering feasibility of extracting high quality energy from molten magma bodies is looking to the future with the ultimate geothermal source.

Major accomplishments in the last year include:

- Establishment of the DOE-industry Geothermal Drilling Organization and initiation of the first cost-shared project.
- Commercialization of a lost circulation control system and a drilling mud viscometer.
- Identification of shallow ($\sim$5 km) magma bodies in Long Valley and Coso Hot Springs areas. Joint with scientific and financial support from the U.S.G.S. and DOE/BES.)

The GTD-funded research is closely tied to the Continental Scientific Drilling Programs. Instrumentation and drilling technologies developed for hydrothermal systems are directly supporting the CSDP/Thermal Regimes. The extensive industrial interface developed in the GTD Sandia programs is being effectively used in the CSDP studies and field activities.

*This work was supported by the U. S. Department of Energy at Sandia National Laboratories under Contract DE-AC04-76DP00789.

TABLE I: GTD PROGRAMS AT SANDIA FY85 ACCOMPLISHMENTS

Rock Penetration Mechanics

- Drill String Dynamics - Industry cost shared development completed Phase II modeling; planning a verification field test
- High Temperature Mud Viscometer in use at Texas Tech and several industries; marketed by Baroid/Fann

Borehole Mechanics

- Lost Circulation Test Facility in operation
  - Completed Tests of Conoco & Sandia Lost Circulation Materials
  - Comparison with Slot Tester Complete
  - Insitu Foam Tool Successfully Tested

Diagnostics

- Radar Fracture Mapping
  - Feasibility Verified by Field Test
  - Lab Prototype 60% complete (Southwest Research)
- Dewared Power & Controls for SSSDP Sampler
  - First Prototype Designed & Successfully Tested
- High Temperature Cement Bond Log
  - Design Complete & Prototype 80% Complete

Geothermal Drilling Organization

- Organization (DOE plus 18 companies) official
  Initial BHTV Project Underway

Magma Energy

- Long Valley & Coso Hot Spring Areas Identified as prime targets
- Geophysical Series Completed at Long Valley
- Vibraseis Profile Complete Over Shallow Magma Intrusion
- Seismic Data from Indian Wells Indicates Shallow Magma Intrusion
- Joint U.S. Navy-DOE workshop at China Lake

Permeability Enhancement

- Propellent Stimulation with Multi Fracs Verified in Water-Filled Wellbores
- Initial Sensitivity Analysis of Production Potential vs Frac Dimensions Complete

TABLE II: SANDIA PROGRAMS - GTD INTERACTIONS

Program	Technology	GTD Interaction: Limited	GTD Interaction: Nominal	GTD Interaction: Extensive
Fossil Energy				
Tight Gas	Stimulation			x
	Instrumentation			x
	Field Test		x	
Shale & Coal	Insitu Instrumentation	x		
	Fragmentation	x		
Sea Bed Stability	Self Contained Power & Instrumentation		x	
Strategic Petroleum Reserve	Wellbore Diagnostics			x
Drilling	Past R&D, No Current Active Program			x
Subsidence		x		
BES/Geosciences	Geochemistry			x
	Geophysics			x
	Geomechanics			x
Intelligent Machines	Decision Making		x	
Solar Energy	High Temperature Materials		x	
Weapons				
Testing	Containment		x	
	Verification		x	
	Field Test		x	
Components	Radiation Hard Devices			x
Materials	Foams, Corrosion			x
Analyses	Heat Transfer			x
	Mechanics			x
	Fluid Dynamics			x
Nuclear Waste	Geophysics			x
	Insitu Tests	x		

TABLE III: CONTINENTAL SCIENTIFIC DRILLING PROGRAMS

Country	Status	Future
U.S.S.R.	Kola Hole at 13 km Two others started	Kola to 15 km 50 deep holes planned
West Germany	Money legislated for first hole Extensive shallow drilling	Selecting final site for 14 km hole
Cyprus	2 holes drilled, 2300 & 770 m International program run by Dalhousie U/Canada	Need financing to continue
Iceland	Shallow holes drilled; international	No plans
Canada	Considering	Hope to tie to extensive lithosphere study
Czechoslovakia	5 boreholes over 6000 m	5 planned for Bohemian Massif
Australia	---	Several 1000 m
Sweden	---	5000 m, granite
U.S.A.	DOE/BES - At Valles and Inyo Domes	Salton Sea Off Shore - 20-30 heat flow holes Mammouth Lake - Fluid sampling Long Valley - Crustal Observation Fluid Valles Grande - Fracture & fluid circulation systems
	DOE/GTD - Salton Sea	10,000 ft. drilling to start
	USGS - Planning Creede	Preliminary drilling in FY86
	NSF - Screening Proposals through DOSECC; Appalachian site survey	Undefined

TABLE IV: U.S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Provide access to the third dimension into the earth's crust to understand structures and processes in:

Basement Structures	NSF
Thermal Regimes	DOE
Mineral Resources	USGS
Active Faults	USGS

TABLE V: CSDP RESPONSIBILITY LINES

COORDINATION	FUNDING	OPERATIONS	RESEARCH
NRC/CSDC & INTERAGENCY ACCORD	USGS		ALL AGENCIES PARTICIPATE
	Mineral Resources	(DOSECC)	
	Active Faults		
	NSF	DOSECC	
	Basement Structures		
	DOE		
	Thermal Regimes		
	BES	DATA BASE, LLNL CORE CURATION, LANL DRILLING & LOGISTICS, SANDIA SCIENCE PLANNING	
	GTD	TECHNOLOGY SAN, SSSDP	
	DOD Department of Navy		

TABLE VI: CSDP FIELD ACTIVITIES IN THE U.S.

Sponsoring Agency*	Completed	FY 86	Future Possibilities
DOE BES-Science GTD-Technology & Logistics	Inyo Domes - Conduit Inyo Domes - Dike Valles - Conduit	Mammoth Lakes Off Shore Salton Long Valley Observatory Valle Grande Salton Sea Scientific Drilling Program	Long Valley/Inyo Chain Katmai, Alaska Valles Grande
USGS	--	Creede	Tonopah, Red Mountain San Andreas
NSF	--	Being defined	
U.S. Navy	--	Being discussed	

*Agency supporting the drilling and field activities. All agencies have and are expected to support research in the areas.

TABLE VII: RESEARCH DRILLING ACTIVITIES - SANDIA PARTICIPATION

National Research Council		
Board of Earth Scientists	-	Bill Luth
Continental Scientific Drilling Committee	-	Dick Traeger (Chmn. Panel on Drilling & Instrumentation)
NSF/DOSECC		
Scientific Advisory Committee	-	James Kelsey
	-	Bill Luth
DOE/BES		
Geoscience Research Drilling Office	-	Dick Traeger
Inyo Research	-	John Echelberger
Long Valley Research	-	John Rundle
DOE/GTD		
Salton Sea Instrumentation	-	James Kelsey
Coring Study	-	Pete Lysne
Ocean Drilling Program		
Downhole Measurements Panel	-	Dick Traeger
Logging Scientist on Leg 104	-	Pete Lysne
German Program		
Measurements & Drilling Interactions with Ralph Haenel	-	Dick Traeger

TABLE VIII: SANDIA GTD - CSDP PROGRAM INTERACTIONS

CSDP Activity	GTD Direct Support	GTD Indirect Support
Deep Salton	Instrumentation Build USGS Logging Support Wellbore Cooling Analyses Consultants	Development of Logging Options
FY85 Long Valley	Magma Funding Wellbore Preparation Industry Sharing	Field Experience
FY85 INYO	Instrumentation Test Industry Approval	Drilling Experience Cable Testing
DOSECC	Kelsey's Time	Industry Contacts
NRC/CSDC	Drilling Costs Thermal Regimes Analysis Industry Info	Traeger Instrumentation Workshop
DOE/BES	Coring for Salton Sea Consultants	Contacts for Geoscience Research Drilling Office

DRILLING TECHNOLOGY/GDO

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Introduction

The Geothermal Technology Division of the U.S. Department of Energy is sponsoring two programs related to drilling technology. The first is a research and development program aimed at development of long term high-risk technology that will lead to reduced costs of drilling, completion, and logging of geothermal wells. The reduced well cost will in turn expand the geothermal resource base due to the improved economics. This program has the official title "Hard Rock Penetration Mechanics". The second program is intended to share with private industry the cost of development of technology that will result in solutions to the near term geothermal well problems. This program is referred to as the "Geothermal Drilling Organization" or "GDO". The Hard Rock Penetration Mechanics Program was funded at $2.65M in FY'85 and the GDO was funded at $1.0M in FY '85. The Hard Rock Penetration Program supported 15 FTE's at Sandia this year; no internal support was extracted from the GDO funds. This paper will detail the past year's activities and accomplishments and project the plans for FY86 for these two programs.

Hard Rock Penetration Mechanics

The Hard Rock Penetration Program consists of a number of distinct but related projects. Each project will be discussed separately.

Development of Improved Cavijet Nozzles

Project Objective: The objective of this project is to develop design procedures for cavitating jet nozzles that effectively cut rock at lower pressures than those required with conventional waterjet nozzles.

FY85 Activities: Analytic models were developed to better understand the dynamics of cavitating jets as the jet interacts with the rock. This model was used to design optimum nozzles for operating pressures of 2,000 and 7,000 psi. Rock cutting tests were performed at 7,000 psi and shown to be very effective in cutting both sandstone as well as granite.

Planned Activities: Cavijet designs for 2000 psi are to be built and tested by the contractor. If these nozzles are effective at this pressure, then we plan to pursue modeling and testing of nozzles in close proximity of a PDC cutter. This research will then support our advanced hybrid bit development.

Development of High-Temperature, High-Pressure Seals

Project Objective: The objective of this project is to design and test high-temperature, high-pressure piston plunger seals and check valves for application in a downhole pressure intensifier for use in geothermal waterjet drilling.

FY85 Activities: A zero clearance Ferratic CS-40 plunger seal was built and tested with a SiC rod. The first tests of this design were unsuccessful and modifications using a new electron beam welding scheme are in progress. The check valve design was built and successfully tested at 15,000 psi with water as a working fluid. The addition of grit to the water (to simulate drill cuttings) led to a failure of the seal after 4 hours.

Planned Activities: A detailed analysis of the failure mechanisms will be conducted. If a thorough understanding of these failures and in turn ideas for solutions are forthcoming, then this work may continue. If this is not the case, then this effort will be terminated.

Rock Mechanics for Polycrystalline Diamond Compact Cutters

Project Objective: The project objective is to understand the rock/cutter interaction well enough to predict and optimize the performance of PDC bits. The approach to this goal has been to conduct analytical and experimental investigations of a single drag cutter in virgin rock.

FY85 Activities: Tests at ambient pressure conditions of a single PDC cutter in rock have been conducted. Thin sections of the rock revealed that fractures are propagated downward in the rock as well as forward. These vertical fractures could be exploited with waterjets if they are indeed real.

Planned Activities: In order to evaluate the effects of ambient pressures on the generation of fractures, tests at Tulsa University of PDC cutters and rocks at confining pressures are planned. These tests will reveal the validity (or not) of testing at ambient conditions.

Improved Cutter Materials

Project Objective: The objective of this project is to develop a new cemented carbide suitable for application in geothermal drilling.

FY85 Activities: Samples of niobium carbide (NbC) were fabricated and tested for toughness and hardness. These samples were not as good as similar samples of tungsten carbide (WC), and examination of the NbC indicated that the fabrication process might be a major factor in their poor performance.

Planned Activities: A contract with Stanford Research Institute will be negotiated to further investigate cold-pressing and sintering techniques for producing NbC inserts. These samples will then be tested to determine their potential for increased hardness and toughness.

Drill String Dynamics

Project Objective: The objective of this project is to develop a computer program for use in solving the drill string dynamics problem, including the interaction of the drill bit and the formation. The wellbore/drill string simulation is being developed in order to specify the dynamic environment near the bit sufficiently for design of advanced downhole equipment.

FY85 Activities: Phase II of the code development was completed. This phase provides a model for the bit/rock interaction as well as a model for the downhole assembly (collars, stabilizers, etc.) Three additional industry members joined the funding consortium. The following companies each contributed $30,000/year toward the development costs: NL Industries, Mobil, SOHIO, Conoco, and ARCO.

Planned Activities: Phase III of the code will be developed in FY86. This phase will provide a complete drill string model including pipe to the surface and add enhanced user capabilities such as selective output and plotting functions. Four of the previous five sponsors are committed to continued support.

Thermal-Spallation Drilling System

Project Objective: The objective of this project is to assess the feasibility, economics, and technical problems of applying thermal spallation techniques to drilling deep holes in various types of rocks.

FY85 Activities: A systems analysis of a spallation drilling system was conducted. A conceptual rig was designed to allow comparison with conventional drilling and to identify components which would require further development. The major technical problems are: the umbilical, the winching mechanism, and the fishing tools. For shallow drilling in spallable rock, the system looks economically attractive, assuming that the aforesaid technical problems could be solved.

Planned Activities: Since spallation drilling is limited to shallow wells in spallable rock, it has no utility in hydrothermal wells for geothermal energy. No further work is planned on this project.

Thermal Studies of Polycrystalline Diamond Compact Drag Tools

Project Objective: The objective of this project was to develop a numerical-analytical model to predict temperatures in PDC drag bits under downhole conditions and to determine the effects of these temperatures on bit life.

FY85 Activities: Analytical and experimental models were developed to predict the thermal response of PDC cutters as a function of weight-on-bit, rotary speed, type of rock, and type of drilling fluid. These models indicate limited applicability of PDC bits in hard, abrasive rock at high rotary speeds.

Planned Activities: The majority of the work on this project has been completed and the major effort in FY'86 will be documentation of this information. The results of this study have led us to pursue the design and testing of a hybrid PDC/waterjet bit.

Aqueous Foam Drilling Fluids for Geothermal Applications

Project Objective: This project will identify or develop aqueous foams for use as drilling fluids in the underpressured formation characteristic of many geothermal areas. The foams will be capable of operating in elevated temperature environments and will exhibit chemical and foaming stability and anticorrosive and antioxidant properties.

FY85 Activities: We previously identified several surfactants with the potential of surviving the temperature and chemical environment expected in most geothermal wells. This year's activities concentrated on the evaluation of the fluid dynamics and heat transfer characteristics of aqueous foam. Preliminary test results indicate sufficient foam stability to function in a drilling operation.

Planned Activities: The bit hydraulics test facility is being reconfigured to permit testing with foam. These experiments will determine the ability of foam to cool the bit in a drilling operation. Following these tests, we hope to mount a field test to evaluate the foam's performance in a drilling environment.

Wellbore Thermal Code

Project Objective: The objective of this project was to correct, revise, and update the advanced Wellbore Thermal Code, GEOTEMP2.

FY85 Activities: Correction and revision of GEOTEMP2 has been completed. Documentation of this effort is also complete. The code has been used this past year to predict the temperature environment of the Salton Sea Scientific Drilling Project well in the Imperial Valley.

Planned Activities: The only modification of the code that remains undone is the incorporation of the models for aqueous foam. As the necessary information to build these models become available, they will be added to GEOTEMP2. The code will be used to support the prediction of wellbore temperatures expected in the Magma Program. This will involve adding several features such as insulated drill pipe as well as tables to determine water properties above the critical point.

Drilling Fluid/Cement Studies

Project Objective: The objective of this project was to study the formation of cement minerals in drilling fluids by observing the rheological changes in bentonite-based muds before cement formation.

FY85 Activities: Texas Tech University was awarded a contract to study the high temperature properties of bentonitic and saponitic fluids. These studies also included investigations of K_2CO_3, KCℓ, and several polymers as additives to the muds. Rheological and chemical characteristics of these fluids as a function of temperature and chemical additives have been documented.

Planned Activities: Plans to extend this work to include additional polymeric viscosifiers on the fluid properties are underway. We expect to again contract Texas Tech to do this work.

Lost Circulation Test Facility

Project Objective: The first objective of this project was to construct a facility having the capability to test lost circulation materials and techniques under simulated geothermal conditions. The subsequent objective is to use the facility to evaluate materials and techniques for use in solving problems associated with completion and lost circulation in geothermal wells. The final objective is to recommend the proposed solutions that stand the best chance for success in the field; thus, the facility will serve as a final screening facility before field testing.

FY85 Activities: The new test vessel designed for more rapid turnaround of LCM tests was finished and approximately 300 tests were conducted. Materials evaluated included battery casings rock wool, and the "paper" used to separate cells in an automobile battery. The battery materials were found to be temperature stable and capable of plugging small fractures. These data were reported at the GRC annual meeting in August.

Planned Activities: Further testing will continue next year. Specific tests will focus on finding a combination of particle, flake, and fiber that is temperature resistant and able to plug fractures on the order of an inch wide.

Lost Circulation Plugging Model

Project Objective: The objective of this program is to develop an increased understanding of wellbore fluid dynamics and to investigate particle orientation near fractures.

FY85 Activities: A viscometric flow model was developed to predict the required fluid properties to achieve a viscometric plug--i.e. due to the fluid viscosity alone. This mechanism is applicable to matrix permeable formations. A suspended particulate orientation model was also developed to predict the flow of particles into a fracture when suspended in the mud. This analysis is needed to design LCMs for large fracture plugging.

Planned Activities: The suspended particulate model will be expanded to determine the effects of particle geometry, weight, concentration, etc., as well as the effects of fluid and flow properties on the plugging mechanism. Also planned is the development of an incipient plugging model which can be used when the dilute suspension assumptions of the particulate model become invalid.

Lost Circulation Zone Mapping Tool

Project Objective: The objective of this project is to develop a wire-line tool capable of locating and defining features of fractures that intersect the borehole.

FY85 Activities: The mechanical and electrical design of the LCZMT is complete. Modifications include the addition of a downhole AGC circuit to alleviate operator dependence, a temperature probe to permit a temperature log while lowering the tool into the well, a variable rotation speed to permit logging speeds of 5, 10, and 15 ft./min., and a low frequency (~ 400KHz) transducer to determine the feasibility of using this tool for casing inspection.

Planned Activities: Mechanical and electrical parts will be built and the tool will be assembled and bench tested. Following these tests, field tests will be run to verify the operational capability. The tool will be used to map geothermal loss zones, so that our analytical and experimental models can be updated to better represent the insitu conditions.

Acoustic Cement-Bond Diagnostics

Project Objective: The objective of this project is to develop high-temperature technologies for use in the design and fabrication of an acoustic cement-bond logging instrument for operation at temperatures up to 250°C (482°F).

FY85 Activities: The CBL has been assembled and bench tested at conditions up to 200°C. These tests revealed the need for another amplifier stage in order to generate sufficient signal at the surface. This stage was built and tested and is now ready for final assembly.

Planned Activities: A full system bench test will be conducted to determine the tool performance. Once we are convinced that the tool operates properly we plan to test it in the API test wells at the University of Houston or Texas A&M University. A Geothermal well field test will follow these successful tests.

Radar Fracture Mapping

Project Objective: The objective of this project is to develop a high-frequency technique for the location of fractures in the vicinity of boreholes from downhole measurements in a single wellbore.

FY85 Activities: Feasibility tests of the radar concept were completed this year. Southwest Research Institute was contracted to fabricate a prototype tool for further lab testing at Sandia. Meanwhile we have been testing various rocks with various levels of water saturation to measure their dielectric constant. This will give us information to predict the depth of penetration of the EM signal. Software for data analysis is also being developed.

Planned Activities: Once the prototype tool is delivered, we plan extensive testing in a shallow borehole with known (implanted) targets. This will allow us to confirm the tool is operational in a more realistic environment and also to test some of our signal processing algorithms.

Geothermal Drilling Organization

Objective: To foster the development of technology aimed at reducing the cost of drilling and maintaining geothermal wells through cost-shared (50% from industry - 50% from DOE) projects.

FY85 Activities: Fiscal year 1985 was the first year of this project. A non-profit group of industry representatives, the Geothermal Drilling Organization (GDO), was established to prioritize projects and provide the industry portion of the shared development costs. Table I lists the current membership of the GDO. A formal contract between GDO and the DOE has been negotiated and signed. A preliminary list of projects has been identified and is shown in Table II. The first project, development of an acoustic borehole televiewer, has begun. Two GDO members, Union and GRI, have agreed to participate in the project and have provided funds for the contract which has been awarded (through competitive bid) to Squire-Whitehouse of San Diego, California. The contractor will build two complete systems and provide field service for at least one year. The total cost of this project is $950,000. The specifications for the development of rotating heads, BOP rubbers, and drill pipe protectors have been made and are being reviewed by the GDO members to determine interest in funding participation.

Planned Activities: Of first priority will be the continuation of the televiewer project ensuring that the tools meet specifications and survive laboratory and field testing. Contracts to develop the rotating heads, BOP rams, and drill pipe protectors will be placed. Other projects on the list shown in Table II will be pursued as monies and industry interest dictate.

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Table I

Geothermal Drilling Organization
Membership-August 1, 1985

Operators
- Union Geothermal - Del Pyle
- Geothermal Resources International - Jim Combs
- Phillips Geothermal - Tom Turner
- Chevron Geothermal - Dale Santti
- California Energy Co. - Bob Pryde
- MCR Geothermal - Jack Walton
- Steam Reserve Corp. - Bill Dolan
- Mono Power Co. - Bernard Perry
- Andarko Production Co. - Steve Adam

Service Companies
- Foamair Products - Dale Rannels
- Eastman Whipstock - Bob Coats
- NL Industries - John Olsen
- Dresser Industries - Ron Gardner
- H & H Tool Co. - Henry Rushing
- Dailey Directional - Alan Cassiano
- Smith International - Jack Knowlton
- Exlog-Smith - Bob Smith

Other
- Sandia National Laboratories - James Kelsey
- Pajarito Enterprises - John Rowley

Table II
GDO Project List

- Acoustic Borehole Televiewer
- High Temperature Rotating Head
- High Temperature Rubbers for BOP (Ram type)
- Aqueous Foam for Drilling
- Explosives for Backoff and Perforating
- Inert gas generator for "Air" Drilling
- Casing Thermal Stress Analysis
- Casing Liner Materials
- Subsurface Descaling Equipment
- Downhole Pumps
- Hardfacing for Downhole Tools
- Cavijets for Drill Bits
- High Temperature MWD
- Wireline Retrievable/Large Diameter Coring

THE MAGMA ENERGY AND GEOTHERMAL PERMEABILITY ENHANCEMENT PROGRAMS

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Introduction

The Magma Energy Extraction and Permeability Enhancement programs are both U.S. Department of Energy, Geothermal Technology Division, programs managed by Sandia National Laboratories. Project funding during FY85 was $1.4 M for magma energy and $650 K for permeability enhancement. Accomplishments during FY85 and project plans for FY86 are described for both programs.

Magma Energy

Thermal energy contained in magmatic systems represents a huge resource. In the U.S., useful energy contained in molten and partially-molten magma within the upper 10 km of the crust has been estimated at 50,000 to 500,000 Quads. The GTD magma energy program is a long-range, high-risk, large-payoff program directed at determining the engineering feasibility of extracting energy directly from crustal magma bodies. This program has a strong engineering emphasis and follows a DOE/OBES - funded Magma Energy Research Project that concluded scientific feasibility of the magma energy concept. A primary long range goal of the current program is to conduct an energy extraction experiment by drilling into a molten, crustal magma body. Critical to evaluating engineering feasibility are several key technology tasks: (1) geophysics - obtain detailed definition of potential magma targets, (2) geochemistry/materials - characterize the magma environment and select compatible engineering materials, (3) drilling - develop drilling and completion techniques for entry into a magma body, (4) energy extraction - develop heat extraction technology that will produce energy at high rates, and (5) system studies - develop first order analyses to evaluate the economic viability of magma energy. Project accomplishments and plans will be discussed in terms of these key tasks.

Geophysics

During FY84, twenty-one potential magma sites were evaluated in terms of suitability for conducting a long term magma energy extraction experiment. Early in FY85, this resulted in the selection of two primary sites, Long Valley caldera and the Coso Hot Springs area, both located in California. Accordingly, during FY85 our geophysical activities were concentrated in these two areas. Major accomplishments included completion of a coordinated suite of seismic experiments in Long Valley conducted by a consortium of institutions. Measurements were centered around a 1 km deep temperature gradient well previously drilled by Santa Fe Geothermal near the northwestern end of the resurgent dome. Experiments included downhole passive seismics using a triaxial geophone package coupled to the formation at the bottom of the well, vertical seismic profiling, a normal-incidence P- and S-wave reflection profile, and a wide angle P-wave reflection profile. Major funding was provided by the Magma Energy Program and the U.S. Geological Survey with additional funding support from DOE's Office of Basic Energy Sciences and the National Science Foundation. Geophysicists contributing to this cooperative effort are from Sandia National Laboratories, the U.S. Geological Survey, the University of California/Santa Barbara, Lawrence Berkeley Laboratory, the University of Wyoming, and the University of Southern California/Los Angeles. The data from this series of experiments when combined with earlier seismic data (primarily the refraction experiments of Hill and the passive shear wave measurements of Sanders) resulted in a preliminary composite view of the magma chamber underlying Long Valley caldera. The inferred chamber is large with dimensions on the order of the caldera diameter (20 km) and has two cupolas that extend toward the surface. The top surface of the northern cupola is at a depth of approximately 7 km and the southern body is at 5 km depth. During July 1985, the magma program organized and funded additional seismic profiling in the caldera in a region expected to image the southern cupola. Experiments included a common depth point P-wave reflection profile combined with wide angle recording for relatively deep interrogation of the crust and a small-scale refraction profile to obtain near-surface static corrections. The University of Wyoming fielded the CDP reflection experiment using four P-wave vibroseis trucks for energy sources. Wide angle recordings were made by the University of California/Santa Barbara. Preliminary results of this profiling show three reflectors at depths below the surface of approximately 4 to 5, 6 and 12 km.

In the Coso Hot Springs area, seismic tomography was used to invert P-wave travel times from local earthquakes for three-dimensional velocity structure of the upper crust. An inversion of 2,328 arrival times resulted in two areas of well-resolved, suspiciously low compressional velocity which may be related to small magma bodies. Beneath the Indian Wells Valley, 20 to 30 km south of

Coso Hot Springs, a very shallow (<5 km) low-velocity zone corresponds to an area of previously observed S-wave depletion. Low velocities under the hot springs area are deeper, from 5 to 10 km, in rough agreement with previous teleseismic data. The quality of the data is judged to be quite good since raypaths pass through the anomalies from almost all directions. Numerical experiments are underway to assess the variance and resolution of the inversion. Noise tests indicate that the Coso data contain significant information, well above the ambient noise level for a one-dimensional structure with superimposed random errors.

Thermopile heat flux gages were used to measure heat flow in the Devil's Kitchen area at Coso. A localized region of high heat flow, on the order of 42 w/m^2, was found near the geothermal wells. Three separate measurements taken from October 1984 to July 1985 showed a decrease in heat flow with time. In the near future, a few gages will be installed permanently to record the temporal nature of this high heat flow anomaly.

Geophysical studies during FY86 will concentrate on Long Valley caldera with a low level effort continuing at Coso in the Indian Wells Valley area. Early in FY86, the results of reflection profiling in Long Valley caldera near the expected southern cupola of magma will be reviewed by the Long Valley Geophysics Steering Group, geophysicists from several National Laboratories, the U.S. Geological Survey, and several universities. Recommendations will be made for additional geophysical surveys to be implemented during FY86 in order to locate a geophysical borehole. The geophysical well will be drilled over the "best" magma location to acquire downhole data above and anomaly determined primarily by surface techniques. This is an essential step in the process of selecting a drill site to conduct the full scale magma energy extraction experiment. In addition, we will develop an experimental plan for the geophysical borehole and begin engineering investigations of problems associated with implementing the plan. In the Coso area, three-component seismic stations will be installed through a cooperative effort involving Sandia, Cal. Tech., and the Naval Weapons Center. Three component data should lead to improved definition of the nature of the Indian Wells anomaly. Uncertainties related to the influence of low velocity valley fill on the seismic results should be resolved.

Geochemistry/Materials

Problem areas addressed during FY85 include: characterization of magma at the primary sites, investigation of rhyolitic magma/metal compatibility, characterization of rhyolite chillrind surrounding heat exchanger, and initial analysis of explosive volatile visiculation and venting. Compositions of the Long Valley and Coso magma chambers were estimated from analyses of rhyolite glass at the surface. Volatile concentrations were obtained by analyzing glass inclusions in rapidly quenched tephra. The rhyolite compositions at Long Valley and Coso are very similar with Coso having a slightly higher silica content (77.5 wt. % vs. 73.1 wt. %). Expected in situ magmatic volatile concentrations are also similar with the Coso magma lower in water content but higher in sulfur, chlorine and fluorine. An experimental magma was developed for materials compatibility tests with composition and volatile content intermediate between the Coso and Long Valley rhyolites. The melt is prepared using ground rhyolite glass from Panum Crater (Mono Craters) to which the correct amount of H_2O, S, Cl, and F are added.

An experimental procedure for testing magma/metal compatibilities was developed. The metal alloy test specimen is sealed with a volatile-bearing rhyolite glass in a gold tube. This tube is then subjected to the desired pressure and temperature conditions by using a heated pressure vessel for lower temperature, small quantity runs or by using the magma high temperature/high pressure facility for severe conditions and large batch runs. The complete experimental matrix was defined by choosing 19 test materials (including a carbon steel, stainless steels, alloys, and superalloys) and two magma temperatures (850 and 500°C).

Preliminary experiments to test experimental procedures and analysis techniques were completed using 1095 carbon steel (a poor material) and 310 stainless steel (a relatively good material). The tests were conducted at 100 MPa and lasted up to 22 days. Extensive reactions (mainly oxidation and sulfidation) were noted for magma/1095 steel, but magma/310 stainless showed much more restricted reaction. The 1095 steel reacted with rhyolite to form a thin oxide layer at the contact surrounded by thicker successive rinds of fayalite and magnetite outward toward the magma. Reaction of 310 stainless with rhyolite produced a thin chrome-iron oxide layer surrounded by a thicker fayalite rind. Degradation of the metals is controlled by grain boundary diffusion of oxygen and the formation of sulfides on grain boundaries.

Recently, batch runs that include all 19 metals were completed in the magma high temperature/high pressure facility at conditions of 850°C and 100 MPa. Microprobe studies are in progress, but preliminary indications are that several of the commercially available materials appear promising for long-term heat exchanger use.

Plans for FY86 include completion of the magma/metal compatibility experiments. This will involve interpretation and modeling of the FY85 experiments, possible inclusion of a few new materials, and long term testing (10,000 hours) of the most promising metals. During FY86, the nature of the quenched rind that will form adjacent to the heat exchanger will be investigated. It is not clear whether this material will crystallize rapidly to a mineral assemblage or simply quench to a silicate glass. The differences between these two possibilities are significant with regard to released volatiles and metal compatibility. A major new effort in FY86 will be to set up experimental facilities and begin evaluations of chemical mass transport in open heat exchanger systems. Open heat exchangers utilize fluid flow in direct contact with quenched magma, and the nature of this interaction must be understood to properly design the fluid handling and energy extraction systems. Finally, the explosive hazards associated with drilling into a rhyolitic magma chamber will be addressed by investigating degassing, bubble growth, and vesiculation in volatile-rich rhyolites.

Drilling

Progress in drilling has centered around identification of major problem areas associated with drilling a deep hole into magma. Preliminary well completion programs were developed by Well Production Testing, Inc. (WPT) for magma wells in a typical Long Valley caldera location. Designs for both "open" and "closed" energy extraction systems were developed assuming magma would be encountered at a depth of 5.3 km. These designs call for 0.18 m (7 in.) diameter boreholes in the magma zone with 0.34 m (13 3/8 in) diameter casing throughout most of the region above magma. The computer code GEOTEMP was used at Sandia to estimate drilling fluid temperature profiles for the deep wells. Code input was based on the WPT hole design, an estimated Long Valley temperature profile obtained from measured heat flow and wellbore temperatures, and an assumed fluid flow rate of 350 gpm. Calculations show that bottom hole temperatures can be maintained near 100°C when a nominal insulation thickness (1 cm) is added to the drill pipe. Without insulation, bottom hole temperatures approach 650°C. Both of these drilling options will be evaluated to determine the most cost effective approach.

Several other problem areas were identified that required solution before a deep magma well can be drilled. These include a need to develop both a high temperature weighting material for the drilling fluid and a high temperature casing support material. Additionally, casing thermal stress problems must be addressed for possible transient behavior of the drilling and energy extraction operations. A need for further development work is imposed by the tremendous scientific interest in magma bodies. It is almost essential to obtain core in the magma zone. To accomplish this, a wireline retrievable coring system that allows circulation during wirelining operations is needed.

Plans for FY86 include increased emphasis in the drilling task to address the identified problem areas. Experiments will be initiated to evaluate high temperature weighting materials and casing support materials. Detailed thermal stress analyses of expected casing configurations will also begin. Finally, a preliminary design for a wireline coring system will be developed.

Energy Extraction

Progress in energy extraction was made in several areas during FY85 including: (1) evaluation of the energy extraction and conversion processes with preliminary heat exchanger design, (2) investigation of the nature of thermal stress fracturing in quenched magma surrounding heat exchangers, and (3) studies of magma chamber convection effects that may influence heat extraction rates. Simplified mathematical models were developed to describe the extraction of thermal energy from a crustal magma body. A realistic configuration of concentric pipes (based on the WPT well design) that form a counterflow system extending from the surface into the magma body was analyzed in detail. Parametric studies were used to investigate the influence of the major variables on overall rate of energy extraction. Two distinct magma heat transfer coefficients were chosen to represent both a completely closed system and an open system where direct fluid/magma contact occurs.

Analyses of heat exchanger flow paths demonstrated that significantly higher energy-extraction rates are obtained when flow is downward in the annulus rather than downward in the core. Upward flow of hot fluid in the annulus results in large energy loss to the formation. By assuming an ideal Carnot cycle for conversion of thermal to electric energy, it was found that there is a flow rate that maximizes electric power production. This emphasizes the importance of tailoring the flow rate to heat-transfer processes in the magma zone.

Evaluation of insulation effects led to the conclusion that insulation is required around the core to insulate the hot fluid from the colder annular flow. An insulation thickness of 1.27 cm is sufficient for closed heat exchangers while only 0.64 cm is needed for open heat exchangers. The results show that heat loss to the formation above a magma body is not a problem. In fact, a net heat gain is to be expected, when the core is properly insulated, due to the relatively high formation temperatures. Pressure-loss calculations indicated that pipe friction is not a limiting factor for the heat exchanger geometry and flow rates analyzed. Due to the large differences in hydrostatic pressure between the inner column of hot fluid and the annular column of cold fluid, the counterflow system may operate as a thermosiphon and flow naturally without pumping.

The calculations show that electric power production of about 25 MW can be achieved with the open heat exchanger system in a single magma well. However, this rate of energy extraction should be considered as a preliminary estimate at this point. Further modeling and experimental work are needed to investigate the nature of thermal stress fracturing of solidified magma and the detailed characteristics of fluid flow and heat transfer in this fractured material.

The open heat exchanger concept relies on thermal fracturing of quenched magma surrounding a borehole drilled into the chamber and circulation of a fluid through this hot, fractured region. The nature of the fractured material is key to designing fluid flow systems and estimating heat transfer. Thermal stress analyses were completed which led to both a qualitative description of the fracturing process and specific features of the fractured region. On formation of an initial shell of solidified magma around the borehole, fracturing will occur no matter how thin the shell is. Thereafter, a thin shell of magma may solidify without fracturing but, as its thickness increases, additional fracturing will occur eventually. The fractured region will extend radially to near the outer surface of the solidified magma and will continue to grow as the solidified region grows.

Analyses predict closely-spaced horizontal fractures which provide almost all the new fracture surface area, one radial fracture, and no cylindrical fractures. The spacing between horizontal fractures depends on a material property, the plain strain critical stress intensity factor, which can be determined from fracture mechanics experiments. Using a value for glass of 7.5×10^5 $Nm^{-3/2}$ gives a predicted horizontal crack spacing of about 1 cm.

A series of fracturing experiments were initiated to provide qualitative fracturing behavior, to provide thermal stress fracturing data for validation of theanalytical model and, eventually, to reproduce the conditions of cooling with phase change that will occur in the magma. Initially, cylindrical billets of a well-characterized glass were poured, annealed, and axially cored. Each billet was uniformly heated in a tube furnace and then centrally cooled with air. Patterns of vertical and horizontal fractures that grew with increased cooling time were observed. Current fracture experiments are using glass plates that are uniformly heated and then edge cooled. Very repeatable fracture patterns that vary with initial temperature have been obtained. These tests will be used for refinement of the mathematical fracture model.

Magma chamber convection induced by wall cooling or material injection can have an important effect on energy extraction rates. In a separate analytical study, estimates of the magnitude of the velocity field were made for a convecting magma chamber controlled by three different driving boundary conditions: (1) cooling from above and heating from below, (2) cooling from above only, and (3) cooling from the side. Results show that conditions (1) and (2) above produce comparable maximum velocities on the order of 1 cm/s while condition (3) yields velocities at least an order of magnitude lower. It was also found that these velocities are not particularly sensitive to the rate of heat loss from the body which is usually not well determined.

To further understand thermal convection processes in a magma chamber and the interaction of these processes with the energy extraction device, a laboratory-scale thermal convection experiment was designed. Overall heat transfer, as well as the temperature and flow fields, will be studied. Simulant high viscosity fluids (glucose syrup and silicone oil) will be used. The glucose solution will result in a viscosity variation of up to three orders of magnitude in the experiment, whereas the silicone oil will represent a highly viscous flow with relatively little viscosity variation. A preliminary experiment using glucose syrup was completed to evaluate techniques for flow visualization and measurement.

Plans for FY86 include development of a more complete model to describe the energy extraction process. Complexities such as phase change of the working fluid will be incorporated. The experimental and analytical work on thermal stress fracturing will continue with the goal of providing a quantitative description of the fractured medium expected for open heat exchangers. New experimental and analytical studies will begin to investigate fluid flow patterns and heat transfer rates in fractured media representative of open heat exchangers. The magma convection experiments using simulant fluids and described above will be carried out.

<u>System Studies</u>

Two major studies were completed during FY85. The first, a preliminary design of a magma power plant by Well Production Testing, Inc. (WPT). This study included well and casing design, energy extraction analysis, and surface plant design. A few major results from this investigation are: (1) a 6 km well drilled and completed into magma at Long Valley caldera was estimated to cost \$16 M, (2) plant capital costs were estimated to be \$1.45 M per MW of installed electrical capacity, and (3) energy extraction rates of 20 MW_e were predicted for the base case open heat exchanger system.

The second study was a combined Sandia/WPT evaluation of the economics of magma power generation. This preliminary analysis was conducted for two purposes. First, the study should determine if the anticipated costs of magma power are in a realistically competitive range with other alternative energy resources; and secondly, the analysis should identify the areas where technology improvements could have the greatest influence on the cost of magma power. Well costs were assumed to vary with depth by using the WPT estimates for magma wells at a few depths, and then extending those estimates based on cost/depth data for high technology oil, gas, and geothermal wells. Well maintenance costs; plant capital, operating, and maintenance costs; and realistic plant lifetime and operating factor were included in the analysis. Energy extraction rate and well cost (depth) were used as variable parameters. The immaturity of the magma energy extraction system requires this general parametric analysis of system economics.

Economic calculations determined the price that would need to be charged for electricity in order to balance the costs of power generation and provide a real rate of return of 10% (before taxes but above inflation). Using best current estimates of the parameter values, based on the WPT magma power plant design and modeling of energy extraction, magma based electricty prices would be in the neighborhood of 80 to 110 mils per kilowatt hour. These prices are higher than current prices of 50 to 70 mils for fossil fuels and 60 to 85 mils for hydrothermal resources, but below current prices for new nuclear plants. Based on the uncertainties associated with well costs and energy extraction rates, the conclusion at this point is that magma appears to be in the same "economic ballpark" with other energy resources. In addition, the analysis identified well cost, well productivity and well lifetime as the parameters most critical to the economics of magma energy extraction.

Next year plans are to begin a comprehensive system study of the energy extraction/conversion process. The Mechanical Engineering Department at the University of Utah, with extensive experience in thermal systems analysis, will review current energy extraction options and make recommendations. Since the current economic model includes parametric variation of the important (and uncertain) variables, further refinement of the model is not necessary during FY86.

Permeability Enhancement

The objective of the Permeability Enhancement program is to develop the technology and methodology for increasing the production rates or injection rates of geothermal wells. Since drilling cost is a substantial fraction of the overall cost of a geothermal well, it may be more economical to attempt some stimulation action instead of abandoning the well and redrilling. In addition, increased production rates brought about by stimulating producing wells may more than offset the cost associated with permeability enhancement. Major progress during FY85 took place in two areas: (1) evaluation of a fracturing technique developed to create multiple fractures in natural gas wells and (2) development of a finite element porous flow computer model to determine the effects of fracture stimulation on geothermal well productivity.

High energy gas fracturing (HEGF) is a propellant based technology initially developed for enhancing production in natural gas wells. The basic concept involved is that propellants can be chosen to produce burn rates which result in multiple, radial fractures emanating from the wellbore. For very fast propellants or high order explosives, a crushed zone is produced about the wellbore which can result in decreased communication with the surrounding formation. For very slow pressurizations, only hydraulic type fracture occurs. For intermediate burn rates (in the range of 0.1 to 1 MS risetimes), four or eight major fractures emanate from the wellbore. While hydraulic fractures are usually parallel to existing fractures and do not connect additional fractures to the wellbore. The HEGF multiple fractures can serve as conduits into the well from existing formation fractures. For this reason, HEGF is particularly applicable to stimulating naturally fractured reservoirs, Because permeability in geothermal reservoirs is typically fracture dominated rather than matrix dominated, HEGF appears to be a logical candidate technology for stimulation of these reservoirs.

A total of four experiments were conducted in the G-tunnel complex at the Nevada Test Site (NTS) in order to evaluate the potential role of HEGF for hot water geothermal application. Boreholes of 0.1 m diameter were drilled in the tunnel into ash fall tuff. The experiment assembly (propellant canister, pressure transducer, packer and cable tube) was emplaced and the hole backfilled with water. After propellant burn, mineback was conducted to examine the fracture patterns. During the first experiment series, we found that the standard technique previously used to ignite small diameter canisters would not work in water filled boreholes. In addition, pressure risetime was about an order of magnitude shorter than observed in gas-filled boreholes and a factor of S shorter than predicted. These results prompted a series of propellant burn experiments at Sandia's explosive test facility to develop ignitors and propellant burn characteristics in water-filled holes. These experiments produced a small RIP ignitor that properly initiated propellant burn and test data with a different, slower propellant that produced the correct risetimes.

The remaining experiments at NTS produced the three types of fracturing behavior in water-filled boreholes. A single, hydraulic-type fracture was observed in one test. In the remaining two tests both crushing and multiple fracturing were observed in the same borehole. The experiments showed that multiple fractures could be created in water-filled wells, but the fracturing behavior was considerably more complex than previously observed in gas-filled wells. As an example, end effects were much more pronounced for water-filled boreholes with extensive hydraulic fractures extending up to 10 m beyond the test zone. Further, peak pressures observed in water-filled holes were lower by a factor of two or three than would be expected for gas-filled holes.

While it appears that HEGF is a promising technique for producing multiple fractures in hot water geothermal reservoirs, more research is required to optimize the technique and maximize fracture length. The methodology developed for HEGF in gas-filled boreholes should be directly applicable in dry steam geothermal reservoirs. However, additional hardware development is required to produce a proper high temperature propellant and method of isolating the stimulation zone.

A two-dimensional, finite element porous flow model was constructed to analyze the effects of artificial fracture geometry on geothermal well production. Two types of artificial fracture systems were considered, planar and multiple. Fractures in both cases were modeled as discrete cracks having a higher permeability than the surrounding matrix. The planar fractures considered were assumed to extend 100 m in both directions from the wellbore in a vertical plane. The multiple fracture system was assumed to consist of vertical fractures in four planes (eight total fractures) spaced at 45° intervals around the wellbore and extending 7.6 m into the formation. Fracture width in both cases was assumed to be 0.64 cm. These planar and multiple fracture models represent simple approximations to the fracture systems that might be expected from hydraulic fracturing and HEGF treatments, respectively, under ideal conditions. By exercising these models under the same conditions as the pre-treatment case for each formation type, the effectiveness of both treatments in improving well productivity was determined for a variety of reservoir conditions.

The following general conclusions can be derived from the modeling results:
(1) In low-permeability matrix formations, hydraulic or planar fractures are superior to multiple fracture systems in improving well productivity. (2) In high-permeability matrix formations, multiple fracture systems can improve well productivity to a greater extent than planar fracture systems. (3) Closely-spaced natural fractures improve the benefits of multiple fracturing if the natural fractures run perpendicular to the current minimum principal in-situ stress. If in-situ stress conditions have changed since formation of the natural fractures so that the natural and planar fractures are not parallel, then the angle between these fracture systems will determine the relative ranking of the planar and multiple fracture treatments. (4) Near-wellbore permeability damage due to drilling fines invasion or mineral precipitation can be overcome with either planar or multiple fracture treatments; however, multiple fractures are superior over a large range of fracture conductivity. (5) Very large increases in well productivity are possible if the artificial fractures intersect large, highly conductive natural fracture systems. Because of typical in-situ stress conditions, multiple fractures may be far more successful than planar fractures in stimulating well production in reservoirs containing such natural fracture systems.

During FY86, plans are to develop the hardware that would enable use of the HEGF technique in dry steam geothermal reservoirs. This will include high temperature propellant development and design of a system for stimulation zone isolation in a hot, steam-filled wellbore. Additional refinements to the well productivity model are also planned. More realistic models of the geometry and permeability of fractures produced by HEGF are needed. The effects of natural production on well productivity will also be considered. Finally, site specific reservoir parameters will be included in the stimulation analysis.

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SESSION IV

Chairperson: Susan M. Prestwich, Idaho Operations Office
U.S. Department of Energy

OVERVIEW ON

CASCADES DRILLING STATUS

Presented by

S. M. Prestwich

The Cascade volcanic region has long been suspected of containing considerable geothermal potential, as evidenced by recent volcanism and other thermal expressions. There are few known surface manifestations of geothermal energy in spite of the obvious occurrence of heat sources. One possible explanation is that the downward percolation of the extensive regional cold ground-water system forms a so-called "rain curtain" that suppresses surface evidence of underlying hydrothermal systems. This hypothesis can be tested only by drilling below the rain curtain. Resource characterization has been conducted by the U.S. Geological Survey (USGS) and by the states involved--Washington, Oregon, and California and now more recently by industry. However, there have been few wells drilled in the Cascades region to a sufficient depth to properly evaluate the temperature and hydrological conditions beneath the cold water zone. There is general agreement within the geothermal scientific community that there is a great need for characterization and identification of the deeper hydrothermal regime in order to further define the geothermal potential of the Cascades volcanic environment.

DOE initiated the Cascades Deep Thermal Gradient Drilling Program through solicitations issued in FY-85. The objective of the program is to cost-share with industry the drilling of thermal gradient holes to gather data to characterize the deep hydrothermal resource of the Cascades volcanic region and to transfer this data to the public in order to stimulate further development of hydrothermal resources.

DOE budgeted approximately $1 million of FY-85 funds to issue a solicitation which would allow DOE to cost-share at 50% the drilling of up to eight thermal gradient holes.

DOE-Idaho issued the first solicitation with proposals due in December 1984. No acceptable proposals were received. A second solicitation was issued in mid-March, 1985, with proposals due the end of April. To qualify for consideration under the solicitation, the proposals were required to meet the following qualification criteria:

A. The proposed site must be located within the Cascades volcanic region of the United States as delineated by Figure 1 (Page 2).

B. The proposal must include a cost-share plan in which DOE's share shall not exceed 50 percent.

C. The proposed hole must be a minimum of 3,000 feet deep.

D. The proposer must agree to complete the hole and allow DOE access to the hole for data acquisition.

Four proposals were selected for negotiation.

The following work will be performed by each Participant under the negotiated cooperative agreement:

The Participant will drill a deep thermal gradient hole at a location within the Cascades region defined by Figure 1 (Page 2). The hole to be drilled will be a minimum of 3,000 feet in depth. The Participant will perform data collection including well logs, rock samples, and, if appropriate, fluid samples. The Participant will be responsible for any required permits, leases, environmental evaluations, or approvals required by governmental agencies for performance of the project. The Participant will complete and maintain the hole and allow DOE access to the hole to collect data. During the DOE access period, the Participant may perform additional data collection and tests at its own expense on a non-interference basis. The Participant will be responsible for plugging and abandoning the hole. The Participant will be required to submit to DOE several project plans and status reports during performance. The Participant will provide the data collected under the project to DOE. Data and information gathered under this project will be made public by DOE.

Of the four proposals selected, three firms are involved. GEO Operator Corporation, Menlo Park, California, a subsidary of Geothermal Resources International, Inc. (GRI) had two sites selected--one located on the north flank of the Newberry Caldera and a second located on the south flank of the Newberry Caldera. Thermal Power, Santa Rosa, California, a subsidary of Diamond Shamrock, proposed a hole which was selected, located in the Clackamas Geothermal Block of the Mt. Hood National Forest in Marion County, Oregon. The fourth hole selected is located at the Blue Lake Crater in the Santiam Pass area of the Oregon Cascades.

The Newberry holes were selected because of the information that may be provided to better understand the nature and extent of both the hydrologic and geologic implications of the Newberry geothermal system. The Newberry-North 3,000 foot hole is planned to be drilled during the summer of 1986.

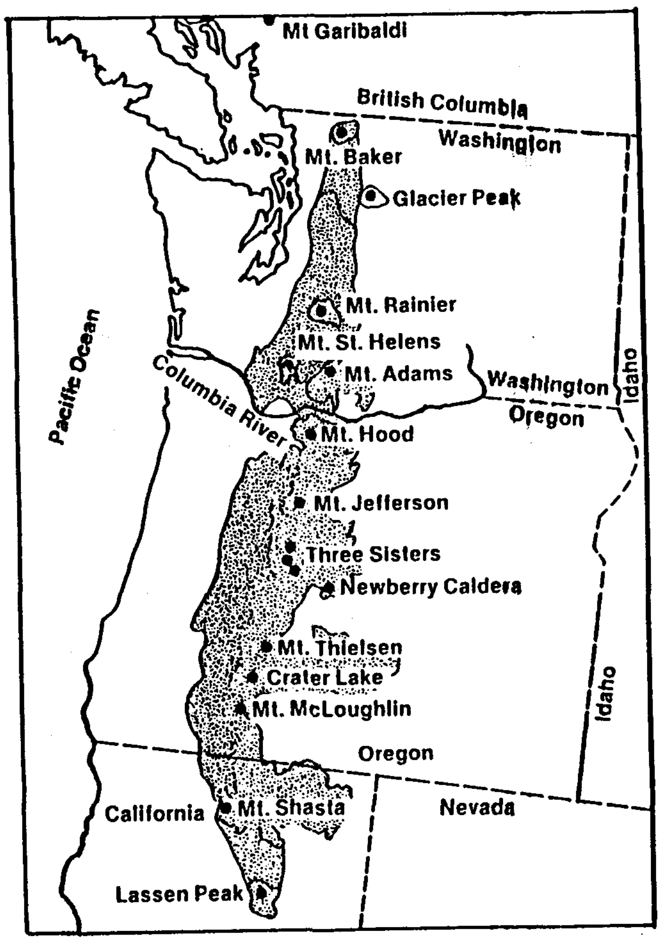

Figure 1. Defined Proposal Area (stippled area)

GEO has begun drilling of the 4,000 foot hole south of Newberry Crater. Surface casing has been set at 470 feet and coring has begun.

Thermal Power's proposed 5,000 foot Clackamas hole was selected for the information it may provide in better understanding the Western Cascades High Cascades transition area. It is hoped that this hole will penetrate the hydrothermal system which may be linked to Brutenbush Hot Springs. The hole is planned to be drilled in the summer of 1986.

The Blue Lake Crater hole at Santeam Pass has been proposed to a depth of 4,000 feet. The proposer, Blue Lake Geothermal Company, anticipates to start drilling the spring of 1986. This hole, located in the High Cascades graben, was selected because it may provide deep fluid samples for chemical data in the High Cascades where thermal springs are generally lacking. The hole will also provide heat flow measurements needed to define the heat flow below the cold ground-water system.

Research is an integral part of the overall program with the intent to further define the geothermal potential and characterize this active volcanic region. One aspect is the data to be gathered from the thermal gradient holes. Data such as well logs, rock samples, and fluid samples gathered from the holes will be analyzed and interpreted in the form of case studies to be transferred to the public. Heat flow measurements from the holes are planned.

Additional research involving lithological studies, geological, geophysical, and geochemical research and analysis, along with aquifer characterization will round-out the research program.

The overall program is planned to drill deep thermal gradient holes and gather data, conduct supporting research with data integration and interpretation, and transfer this information to the public to encourage further exploration and development of the Cascades hydrothermal resources. This will be accomplished by supporting an integrated research effort of independent researchers, USGS, and state geologic groups.

The FY-86 Geothermal Program budget proposes an additional $1 million to support research and additional thermal gradient drilling.

DEVELOPMENT AND APPLICATION OF TRACERS: EXAMPLES OF FIELD AND EXPERIMENTAL STUDIES

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INTRODUCTION

Geothermal fluid must be injected after it has been used to power a turbine. The full effect of injecting cool, supersaturated fluid into the geothermal field cannot be modeled by just measuring the variables of temperature and pressure, which is the normal procedure for reservoir modeling. The additional data required to model injection requires that specific packets of fluid be traced underground, and the temperature, pressure, timing, and saturation indices (RT log $\frac{Q}{K}$) be monitored.

Tracers can be used to monitor the movement of groundwaters and geothermal fluids and they can be used as a reference to quantify changes in fluid chemistry as a result of injection. Despite their potential importance to the geothermal operator, very few tracers are presently available and of those that are, little is known about their stability or behavior at the elevated temperatures that typify resources capable of electric power generation. During the past two years the University of Utah Research Institute has been involved in tracer research and testing, largely through the DOE Injection Research Program. The purpose of this paper is to summarize the results of these laboratory and field investigations.

Our approach involves:

1. Determining the stability of tracers in current use by laboratory measurements.
2. Developing and testing new tracer species.
3. Performing field tests to determine tracer stabilities under actual reservoir conditions.

Our research staff consists of the following personnel: Phillip M. Wright, Project Manager, the geochemical and chemical staff at UURI, Jong-Hong Ahn (post-doctoral student in hydrometallurgy), Milton Wadsworth (Professor of Metallurgy and Dean of Mines, University of Utah), and Harold Bentley (Adjunct Professor, University of Arizona, Director of Hydrogeochem, Inc.).

TRACER DEVELOPMENT

The ideal tracer should be detectable in small quantities, inexpensive, environmentally safe, and be absent from natural geothermal fluids and groundwaters. The tracers currently in use in high-temperature environments fall into three major categories: a) isotopes; b) salts of iodide, bromide or chloride; and c) organic dyes. Each of these classes of tracers has significant limitations. Isotope tracers, although inert, are difficult to handle, expensive to analyze, potentially environmentally hazardous, and once used, contaminate the reservoir for long periods of time. The salts, while relatively stable and inexpensive, nonetheless may be adsorbed by the reservoir rocks. In addition, because of the abundance of chloride in most geothermal waters, large quantities of chloride tracers are necessary. Relatively little is known about the organic dyes. Fluorescein and rhodamine are the most commonly used. However, fluorescein is light sensitive and these dyes, like the salts, may be adsorbed. Their stability at geothermal temperatures is variable. For instance, in a recent 2-well injection test at Svartsengi, Iceland, only 4% of the dye rhodamine WT and 30% of the I^- was recovered after 5 months (Gudmundsson, et al., 1984). Since the tracers were injected together, these relationships suggest that the dye probably decomposed underground. The data indicates zero order decay of the dye. In addition to these limitations, the relatively small number of tracers available restricts the number of wells that can be individually monitored in a producing field at any one time. Thus, in geothermal fields where many injection wells are in use, it is not yet possible to independently trace the movement of fluids injected into each of them.

The fluorinated and sulfonated hydrocarbons are a relatively new class of tracers that do not appear to suffer from many of these disadvantages. These compounds have been used as tracers in groundwater studies in low temperature environments but have not yet been field tested at high temperatures. Some of them are, however, expected to be stable at high temperatures.

The fluorinated hydrocarbons are produced by substituting fluorine for hydrogen in organic molecules. Thus, a large number of different fluorinated hydrocarbons, which vary regularly in their chemical and physical properties (i.e. a homologous series), can be produced. Because the properties of the individual compounds are similar, the geothermal fluids can be analyzed for all of the components in the series simultaneously by chromatography. These compounds have the additional advantage of being detectable in extremely small quantities. Using presently available technology, the fluorinated hydrocarbons can be detected in concentrations in the parts per billion range, and it appears likely that detection limits of several tens to hundreds of parts per trillion is feasible. Although dilution factors between wells will probably vary greatly from place to place, it can be assumed that only minute amounts of tracer will be present during the initial breakthrough of the injected brine. For example, dilution factors of 10^8 have been measured in the Wairakei geothermal field. Current detection limits of the fluorinated hydrocarbons are compatible with dilution factors of this magnitude. Furthermore, fluorinated hydrocarbons are absent from natural waters and they can be designed to partition in either the gas or the liquid phase of a geothermal fluid, allowing the possibility of investigating both components of a two-phase system separately. In addition to the fluorinated hydrocarbons, several sulfonated hydrocarbons will be tested because they perform well as groundwater tracers.

EXPERIMENTAL PROCEDURES

Four experimental reaction vessels were put into operation during 1985 to determine the stabilities of the organic dyes, fluorescein and rhodamine, and selected hydrocarbons. These vessels are housed at the University of Utah's Department of Metallurgy and are dedicated solely to the tracer stability investigations. A fifth vessel capable sustaining temperatures of up to 350°C is currently being fabricated and we expect to be able to install this unit prior to the end of FY 1985. The use of multiple reaction vessels make it possible to perform experiments of relatively long duration (days to weeks) on several different tracers or under different conditions simultaneously.

At the beginning of each experiment, aliquots of the solutions containing the tracer are encapsulated in sealed quartz tubes (Fig. 1). The ampules are filled with approximately 30 ml of solution and sealed in an oxygen-methane flame. At least two ml of the ampule are occupied by a gas phase during each experimental run. The gas phases used for these experiments are pure nitrogen or an atmospheric mixture of oxygen and nitrogen which is approximately 20% oxygen by volume. These gas phases were chosen as end-members to bracket the variable oxidation potentials produced by different surface treatments during injection.

The solutions of the experimental runs that used a nitrogen gas phase were purged with nitrogen gas in the ampule for up to 2 hours. The neck of the ampule (see Fig. 1) was aspirated to prevent oxygen contamination from the oxymethane flame during sealing.

Three ampules can be tested within each reaction vessel. Under normal experimental conditions the reaction vessels are heated to the desired temperature within three hours. During long experimental runs, the reaction vessel can be brought back to ambient temperature to remove individual ampules and then reheated. Cycling the temperatures in this way can be done rapidly, in less than six hours. By keeping the duration of the experimental run at least ten times the duration of the heating and cooling cycles, adverse chemical effects are minimized. Chemical analyses of the solutions are performed both before and after each experiment to evaluate the reactions and conditions during the test.

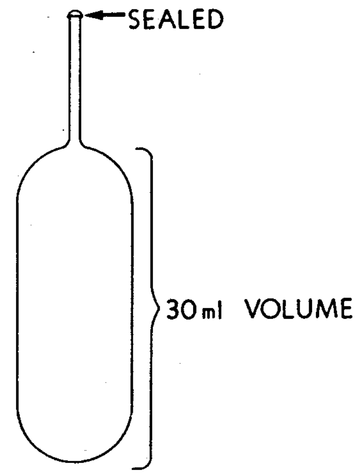

FIGURE 1
Illustration of quartz tube used for hydrothermal experiments.

EXPERIMENTAL RESULTS

The experimental runs were designed to evaluate the effects of four different parameters: temperature, time, solution chemistry, and the partial pressure of oxygen. To date, our investigations have centered on the stability of fluorescein, three fluorinated hydrocarbons, and two sulfonated hydrocarbons. These experiments have been conducted at temperatures ranging from 100° to 200°C.

The hydrocarbons tested were:

α-, α-, α- trifluoro-m-toluic acid;
p - fluorobenzoic acid;
pentafluorobenzoic acid;
p - toluenesulfonic acid; and
benzenesulfonic acid.

The factors investigated with fluorescein can be divided into destabilizing and stabilizing factors. Increasing oxygen pressure and temperature have a destabilizing effect. These effects are shown in Figures 2 and 3. Inspection of these figures shows that the presence of oxygen in the gas phase is the major destabilizing effect. The initial concentration of 5 ppm was reduced to less than .05 in 20 hours with oxygen (Fig. 2), while the nitrogen runs show little degradation even at 90 hours (Fig. 3). The effect of temperature is so small between 150° and 200°C that it is within the experimental error.

The stabilizing factors found to date are boron and boron + pH. The effects of boron are illustrated in Figure 4 where a solution with an initial concentration of 5 ppm fluorescein was run for 118 hours at 150°C. The composition of the gas phase during this experiment may have contained some oxygen, as indicated by the low con-

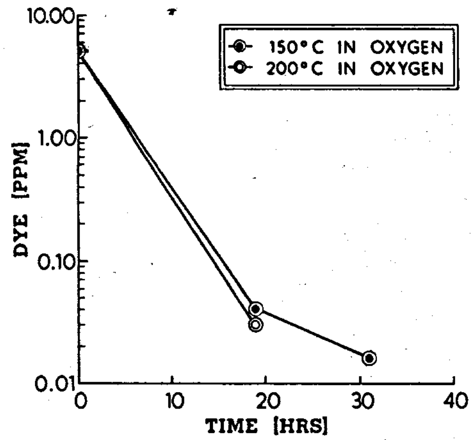

FIGURE 2
The effect of atmospheric oxygen in the gas phase on fluorescein stability at 150°C and 200°C. The initial fluid phase contained 825 ppm NaCl and 5 ppm fluorescein.

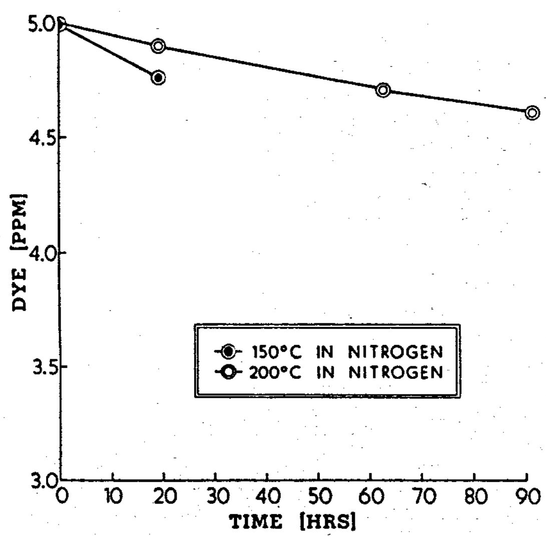

FIGURE 3
The effect of purging the gas phase with nitrogen on fluorescein stability.

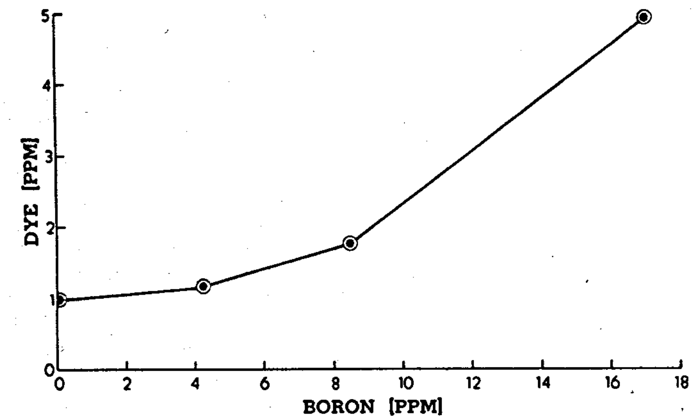

FIGURE 4
The effect of aqueous boron on the stability of fluorescein. The run temperature was 150°C. The initial fluid phase contained boron, 825 ppm NaCl, and 5 ppm fluorescein. The pH was buffered to ~ 6.5.

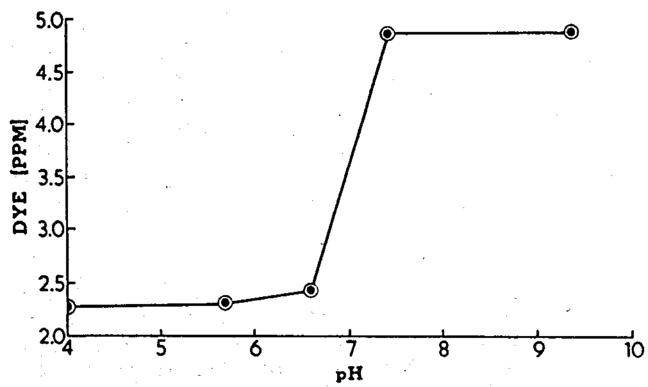

FIGURE 5
The effect of buffering fluorescein solution pH with boric acid and sodium borate. The run temperature was 150°C. The initial solution contained 825 ppm NaCl and 5 ppm fluorescein.

centrations of fluorescein in the 0 to 8 ppm boron runs. However, the trend of increasing stability with increasing boron is clear. The effect of increasing pH on fluorescein stability is shown in Figure 5. During this experiment the pH was buffered with boric acid and sodium borate. Thus the dramatic increase in stability between pH 7 and 8 could be due to pH-dependent changes involving either boron or fluorescein. Since borates change species at a pH of approximately 9, phenol groups at 6 to 7.5, and carboxyl groups at 4 to 6, the pertinent disassociation is probably the phenol group on the fluorescein molecule.

This conclusion is supported by an experimental run at high pH without boric acid/sodium borate buffering. In this run, the solution was geothermal brine (boron = 1.0 ppm, pH = 8.7). The fluroscein was only reduced to 4.8 from an initial value of 5.0 after being heated to 200°C for 92 hours.

Our plans for future higher temperature experiments using fluorescein are to use various geothermal brines as solvents as well as distilled water, rather than parameterizing the effect of each solution component. This approach will be taken because: (1) the separate compositional dependence of fluorescein on each element in a geothermal brine is beyond the scope of this project, and (2) geothermal brine compositions are limited to a relatively narrow range of elemental ratios.

There may be other compositional factors in addition to those tested to date. If this is the case, then the runs using geothermal brine as a solvent will produce significantly different results. In this case the approach will be modified.

The initial stability tests on fluorinated and sulfonated hydrocarbons were very enouraging. Solutions containing all 5 of the hydrocarbons at an initial concentration of 10 ppm each were run for up to 174 hours at temperatures of 125° and 150°C in oxygen and in nitrogen. The only compound to detectably decay was pentafluorobenzoic acid (Fig. 6). The decay of pentafluorobenzoic acid was complete and occurred at all temperatures, times, and in all gas phases. These experiments will be repeated in geothermal brines and at higher temperatures.

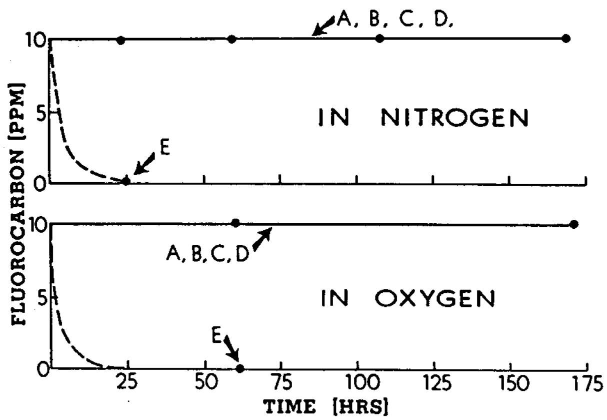

FIGURE 6
The stability of fluorinated hydrocarbons and phenyl-sulfonates at 125° and 150°C in the presence of an oxygen or nitrogen gas phase. Compounds A to E are p-fluorobenzoic acid (A), α-, α-, α-trifluoro-m-toluic acid (B), p-toluenesulfonic acid (C), benzenesulfonic acid (D), and pentafluorobenzoic acid (E).

FIELD APPLICATIONS

Tracers were used by UURI to monitor the scaling behavior of silica and calcium during injection tests at the East Mesa geothermal field (Adams, 1985). The major and minor cations and anions in the fluids were also monitored during these tests.

Figures 7 and 8 show the concentrations of Ca and SiO_2 in the fluid being withdrawn after injection. The horizontal axis is in units of the volume of injected fluid. The dashed line in these figures, or recovery curves, represents the concentration that would occur in the fluid if no water-rock reaction had occurred. The solid line represents the actual concentration measured in the fluid.

Two wells were tested at East Mesa, Wells 56-30 and 56-19. The tests are referred to below by their test number with the test well in parentheses.

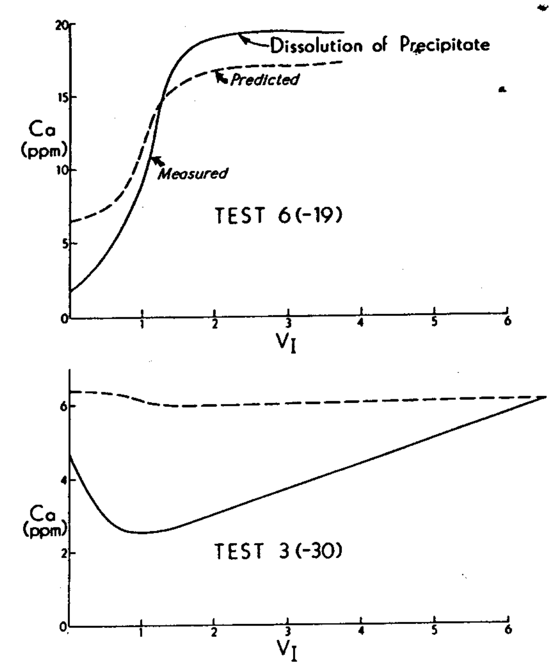

FIGURE 7
Recovery curves contrasting the behavior of Ca in Wells 56-19 and 56-30. Dashed lines are predicted concentrations and the solid lines are measured concentrations. V_I = the volumes of injectate recovered.

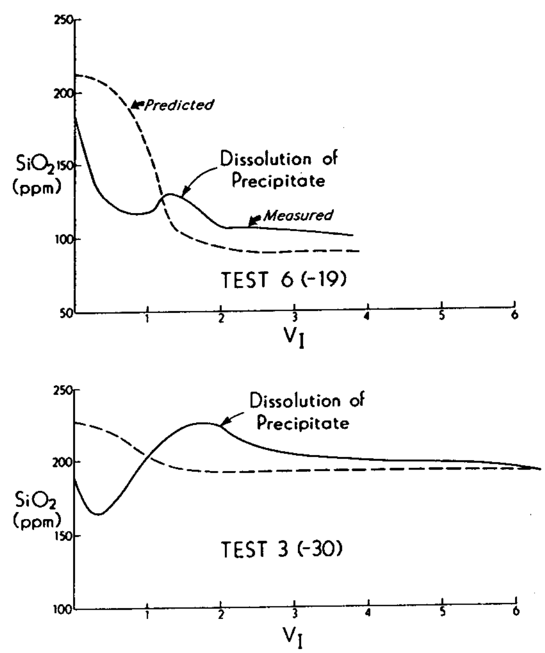

FIGURE 8
Recovery curves contrasting the behavior of SiO_2 in Wells 56-19 and 56-30. See Figure 7 and text for explanation.

Ca and SiO_2 Behavior

During the injection-backflow tests at East Mesa both Ca and SiO_2 were lost during injection. Inspection of the recovery curves in Figures 7 and 8 shows that, in most cases, minerals that precipitated during injection were then dissolved after the unmixed body of injectate had been recovered. The only case where this did not occur was during Test 3(-30) (Fig. 7). During this test aqueous Ca concentrations were reduced to as low as 30% of the injected concentration. In addition, reservoir Ca concentrations did not return to the background values of 6.0 ppm until 6.5 injection volumes had been recovered. The prolonged precipitation of Ca from the reservoir fluid in Well 56-30 may have been due to the attainment of critical nucleation size or may simply be related to the degree of supersaturation in the fluid.

The maximum amount of Ca precipitation in Well 56-30 (Fig. 7) occurred at least 0.6 injection volumes away from the wellbore (Michels, 1983). However, the maximum Ca precipitation during Well 56-19 tests occurred adjacent to the wellbore. Thus it appears that, unlike the behavior of Ca in Well 56-30, the scale inhibitor failed to prevent near-well borehole precipitation in Well 56-19.

Although up to 50% of the injected SiO_2 was lost during injection in both wells, recovery of this species differed between the two wells. Recovery of the silica precipitate in Well 56-30 was rapid and complete, i.e. no silica from the injected fluid was left in the well. Recovery of the silica precipitate in Well 56-19, however, occurred somewhat later than in Well 56-30 and was incomplete. Up to 20% of the injected silica was left in Well 56-19.

It has been suggested by Fournier (1981) that chalcedony should be considered as the equilibrium SiO_2 polymorph for geothermal systems with temperatures below 180°C. Despite this generalization, the predicted quartz geothermometer temperatures for the East Mesa test wells are in close agreement with their measured temperatures of 174°C and 126°C. The recovery curves for Well 56-19, however, display flat minimums where concentrations are in agreement with chalcedony equilibrium; this occurs despite the abundant quartz in the East Mesa reservoir rock.

Na/K

Temperature-induced shifts in the Na/K and Na/Ca ratios of a fluid co-existing with alkali-bearing alumino-silicates have been predicted by theory and empirical data (e.g., Fournier and Truesdell, 1973). As shown in Figure 9, these shifts occurred in the fluid injected into Well 56-19. The Na-K-Ca (-Mg) geothermometer temperatures (Fournier and Truesdell, 1973; Fournier and Potter, 1979) were calculated from chemical analyses of the recovered fluid. Although these predicted temperatures are not valid due to the precipitation of calcite during the tests (Fournier and Truesdell, 1973), the similarity between the predicted and measured temperatures demonstrates that the ion ratio shifts were of the proper magnitude and direction for decreasing fluid temperatures.

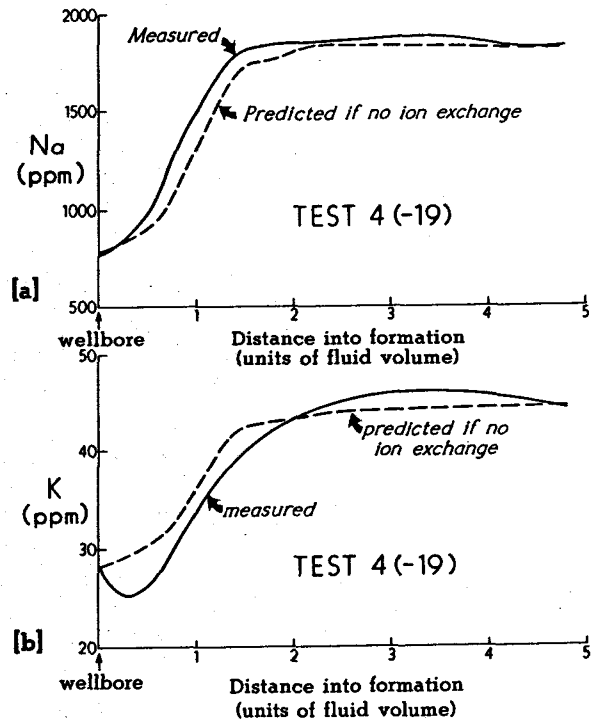

FIGURE 9
Recovery curve contrasting the behavior of Na and K in Well 56-19. See Figure 7 and text for explanation.

SUMMARY

The chemical behavior and movement of injected fluids are a vital concern to geothermal operators. This behavior cannot be determined by equilibrium analysis, as shown by the metastable precipitation that occurred during the East Mesa injection tests. The only method of tracking the fluids and measuring subsurface precipitation, dissolution, and ion exchange is by referencing fluid concentrations to a chemical tracer. The chemical tracers currently in use by the geothermal industry are largely inadequate. They are either unstable, inaccurate, or clumsy to use.

Our current program at UURI is designed to develop and test new tracers. The fluorinated and sulfonated hydrocarbons appear to be superb candidates. To date we have found 4 compounds more stable than the organic dyes currently used by the geothermal industry. In addition, we have identified and quantified the stabilizing and destabilizing effects of the geothermal environment on the organic dye fluorescein.

Much more laboratory testing is required to determine the stabilities and assess the high-temperature properties of the fluorinated and sulfonated hydrocarbons. As the characteristics of these hydrocarbons become better understood, it will then become possible to design and test new species for specific applications. Bench tests however can only approximate the actual conditions occurring in the geothermal reservoir. Once the basic data is obtained, field tests of these tracers will be required to confirm their behavior.

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BOREHOLE GEOPHYSICAL TECHNIQUES FOR DEFINING PERMEABLE ZONES IN GEOTHERMAL SYSTEMS

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ABSTRACT

Borehole electrical geophysical methods have considerable potential for helping to define hot and permeable zones in geothermal systems. Borehole geophysics differs from geophysical well logging and has a much greater area of search around a borehole. Very little developmental work has taken place in borehole electrical methods to date. At UURI, we have been developing computer methods to model various electrical arrays for borehole configurations. We plan to compare the several possible survey methods and then design a field system based on the method that appears from the computer studies to be optimum.

From our studies to date we tentatively conclude that the cross-borehole method produces larger anomalies than does the single-borehole method; cross-borehole anomalies using a pole-pole array are smaller than those for a dipole-dipole array; the cross-borehole mise-à-la-masse method produces larger anomalies than does other cross-borehole methods; and, the anomalies due to a thin structure are generally much smaller than those for a sphere, as is to be expected.

INTRODUCTION

The key problem worldwide in development of hydrothermal resources appears to be more in locating permeable zones than in locating high temperatures. Grindly and Browne (1976) note that of 11 hydrothermal fields investigated in New Zealand, all of which have high temperatures (230°C to 300°C), five are non-productive chiefly because of low permeability. Three of the eleven fields are in production (Wairakei, Kawerau and Broadlands) and in each of these fields permeability limits production more than temperature does. Hot but unproductive holes have been drilled at many of the major geothermal areas in the world, including The Geysers, Roosevelt Hot Springs, Coso, and Meager Creek, to name a few.

Permeability can be primary or secondary. Primary permeability in clastic rocks originates from intergranular porosity and it generally decreases with depth due to compaction and cementation. In volcanic sequences, primary intergranular porosity and permeability exist, but greater permeability exists in open spaces at flow contacts and within the flows themselves. Primary permeability in crystalline igneous rocks is generally very low. Secondary permeability occurs in all rock types in open fault zones, fractures and fracture intersections, along dikes and in breccia zones (Brace, 1968; Moore et al., 1985). Changes in permeability come about through mineral deposition in open spaces or by leaching by the thermal fluids.

Although none of the geophysical methods maps permeability directly, any geological, geochemical, or hydrological understanding of the factors that control the permeability in a geothermal reservoir can be used to help determine geophysical methods potentially useful for detecting the boundaries and more permeable parts of a hydrothermal system. At UURI, we have been developing electrical borehole techniques to detect and map permeable zones in the subsurface, especially fractures.

BACKGROUND--BOREHOLE GEOPHYSICS

It is important to understand the differences between geophysical well logging and borehole geophysics. In geophysical well logging, the instruments are deployed in a single well in a tool or sonde, and the depth of investigation is usually limited to the first few meters from the wellbore. Well-logging techniques have been developed by the petroleum industry over a period of half a century and have been applied with variable success by the geothermal industry. The major adaptations to the geothermal environment are the requirements of high temperature tools and the different interpretation required for hard rock (volcanic, igneous) lithologies. Other differences include a strong emphasis in geothermal exploration on fracture identification and the effects of hydrothermal alteration upon certain log responses. Much research remains to be done in order to understand fully the responses of various well logs in geothermal reservoirs and their typically fractured, altered, commonly igneous and metamorphic host rocks. In spite of the relative lack of knowledge of well-log response in geothermal reservoirs, several logs or log combinations have been used successfully to investigate such properties as lithology, alteration, fracturing, density, porosity, fluid flow and sulfide content, all of which may be critical in deciding how and in what intervals to complete, case, cement or stimulate a well (Glenn and Hulen, 1979; Keys and Sullivan, 1979; Sanyal et al., 1980; Glenn and Ross, 1982; Halfman et al., 1982).

By contrast, borehole geophysics refers to those geophysical techniques where energy sources and sensors are deployed (1) at wide spacing in a single borehole, (2) partly in one borehole and partly on the surface, or (3) partly in one borehole and partly in a second borehole. Thus, we speak of borehole-to-surface, surface-to-borehole and borehole-to-borehole surveys. The depth of investigation is generally much greater in borehole geophysical surveys than it is in geophysical well logging.

Only one of the several borehole geophysical techniques, namely vertical seismic profiling (VSP), has been developed to any extent. The petroleum industry has funded relatively rapid development of VSP over the past several years.

VSP

Vertical seismic profiling (VSP) can be done using both P- and S-wave surface sources (usually mechanical vibrators) arranged circumferentially around a well. Direct and reflected seismic waves are detected by strings of down-hole geophones clamped to the wall of the well or by hydrophones. VSP has been used mainly to trace seismic events observed at the surface to their point of origin in the earth and to obtain better estimates for the acoustic properties of a stratigraphic sequence. Oristaglio (1985) presents a guide to the current uses of VSP.

Borehole Electrical Techniques

Borehole-to-borehole and borehole-to-surface electrical methods appear to have considerable potential for application to geothermal exploration. In a benchmark introductory paper, Daniels (1983) illustrated the utility of hole-to-surface resistivity measurements with a detailed study of an area of volcanic tuff near Yucca Mountain, Nevada. He obtained total-field resistivity data for a grid of points on the surface with current sources in three drill holes, completed a layered-earth reduction of the data, and interpreted the residual resistivity anomalies with a 3D ellipsoidal modeling technique.

The borehole electrical techniques, however, are in general poorly developed. One reason for this is that there are a large number of ways that borehole electrical surveys can be performed and it has been unclear which methods are best. At the same time, computer algorithms to model the several methods have not existed so that it has not been possible to select among methods prior to committing to the expense of building a field system and obtaining test data.

R&D PROGRAM AT UURI

The objective of our program is to develop and demonstrate the use of borehole electrical techniques in geothermal exploration, reservoir delineation and reservoir exploitation. Our approach is:

1. Develop computer techniques to model the possible borehole electrical survey systems;
2. Design and construct a field data acquisition system based on the results of (1);
3. Acquire field data at sites where the nature and extent of permeability are known; and,
4. Develop techniques to interpret field data.

To the present time, we have made considerable progress on item (1) above and we are now at such a point that item (2) could be started.

Our research staff has consisted of the following personnel: Stanley H. Ward, Project Manager; Luis Rijo, Professor of Geophysics, Universidade Federal Do Para, Brazil (on 2-year post-doctoral leave at U of U and UURI); F. W. Yang, Peoples Republic of China (visiting scholar); J. X. Zhao, Peoples Republic of China (visiting scholar); Craig W. Beasley (doctoral candidate U of U, awarded MS degree); Richard C. West (MS candidate at UU). Additional technical support has been provided by Philip E. Wannamaker, Howard P. Ross and Phillip M. Wright of UURI and by Gerald W. Hohmann of U of U. Project costs for Rijo, Yang and Zhao have been minimal because these scientists have been supported by their governments. Thus, a great deal has been accomplished at minimal cost while supporting the education of several students. The remainder of this paper will discuss the significance of our research to date.

COMPUTER MODELING OF BOREHOLE ELECTRICAL METHODS

Computer techniques for modeling borehole electrical geophysics have largely been lacking, especially for three-dimensional (3D) cases. Figure 1 indicates conventional usage of the terms 1D, 2D and 3D in geophysical interpretation. In the 1D case, also called the "layered earth" case, the physical property of interest (resistivity for this study), varies only in the vertical direction. In the 2D case, physical property variations in the vertical and one horizontal dimension are allowed, and the anomalous body illustrated has the same shape in and out of the paper for infinite distance. In the 3D case, physical property variations are specified in all three space dimensions. Obviously, the real earth is only occasionally 1D in nature in geothermal areas. The usual case is for physical properties to vary in all three dimensions in the earth, the 3D case. However, the mathematical formulations for electrical anomalies of bodies increase greatly in complexity from the 1D case to the 3D case. This accounts for the fact that in order to begin our task of applying borehole electrical techniques to delineation of permeability, we were required to develop original mathematical formulations of the problem.

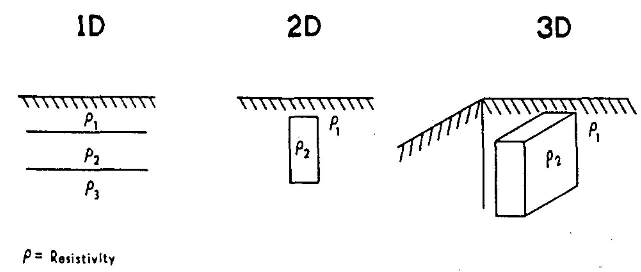


FIGURE 1
Illustration of the meaning of the terms 1D, 2D and 3D in geophysical modeling.

Thick-Body Studies

Prior to 1982, only three published papers considered computer modeling of downhole electrodes for three-dimensional bodies. Daniels (1977) studied six buried electrode configurations and plotted normalized apparent resistivity or apparent polarizability against such configuration parameters as 1) source and receiver depth, 2) depth/bipole length, 3) receiver distance from body, 4) depth of body, and 5) distance of source and receiver from body center. Snyder and Merkel (1973), computed the IP and apparent resistivity responses resulting from a buried current pole in the presence of a buried sphere. Their plots are center-line profiles for normalized apparent resistivity and normalized IP response. Dobecki (1980) computed the effects of spheroidal bodies as measured in nearby single boreholes using the pole-pole electrode array. These three studies are obviously very limited in terms of the problems of defining permeability in geothermal systems.

In 1982, Newkirk (1982) from our group published a study of downhole electrical resistivity with 3D bodies. Using a numerical modeling technique described by Hohmann (1975), theoretical anomalies due to a three-dimensional body composed of simple prisms were computed. The results were presented in terms of 1) the potential, 2) the apparent resistivity calculated from the total horizontal electric field and 3) the apparent resistivity calculated from the potential. Two electrode configurations were considered for each model. Each configuration consisted of a pair of electrodes, where one of the electrodes was remote and the second electrode was located either in the body, for mise-à-la-masse or applied potential, or outside the body, simulating a near miss. Newkirk's computer program was used by Mackelprang (1985) of our group to compute a catalog of models due to bodies that might be of interest in detection of thick fracture zones.

Figures 2a and 2b show the conventions used by Newkirk (1982) and Mackelprang (1985) in calculations of the effects of 3D bodies. The bodies are buried in a homogeneous earth and two of many options for a downhole point electrode are illustrated. Figure 3a and 3b illustrate anomalies on a surface resistivity survey produced by a narrow conductive body buried at a depth of 7 units with the electrode in the body (Fig. 3a) and off the end of the body (Fig. 3b). The peanut shaped anomaly shown in Figure 3a is particularly characteristic on surface resistivity surveys with the borehole electrode in the body.

One basic shortcoming of Newkirk's (1982) algorithm is that it does not apply when the anomalous body becomes thin, i.e. to the case of delineation of fractures or thin fracture zones. To address this important problem, the thin-body studies described in the next section have been undertaken.

Thin-Body Studies

These studies are aimed at targets simulating fracture zones which are thin relative to their other two dimensions. For the most part, we have standardized the aspect ratios of the target dimensions at 10:10:1. While the effect of varying the contrast in resistivity has been examined,

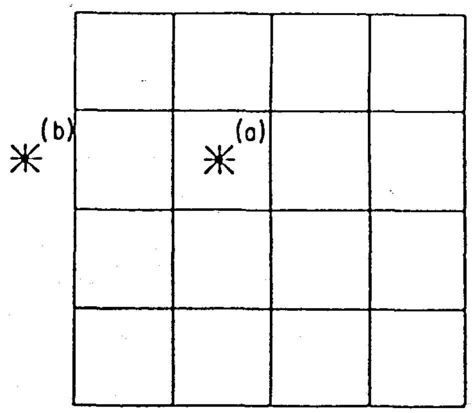


FIGURE 2a
Plan view of standard model.

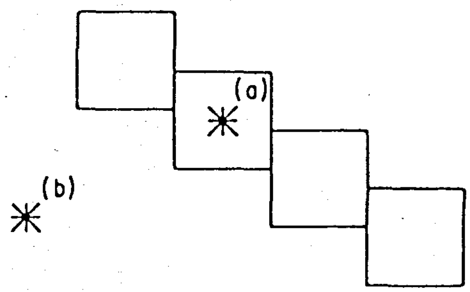


FIGURE 2b
Cross-section view of standard model.

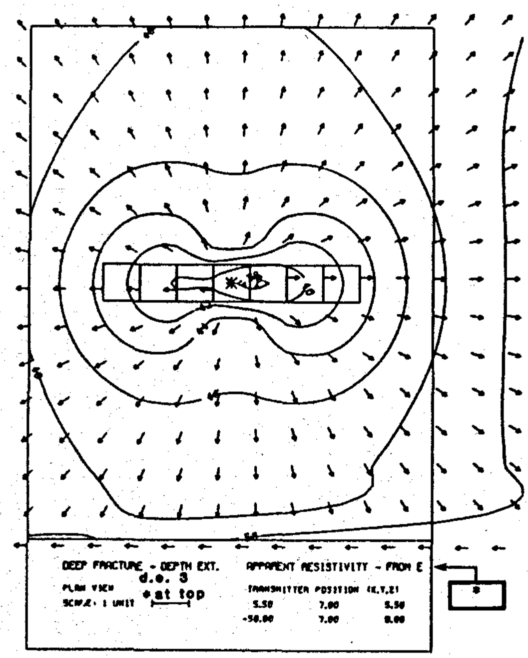


FIGURE 3a
Surface resistivity anomaly due to deep fracture with downhole electrode in body.

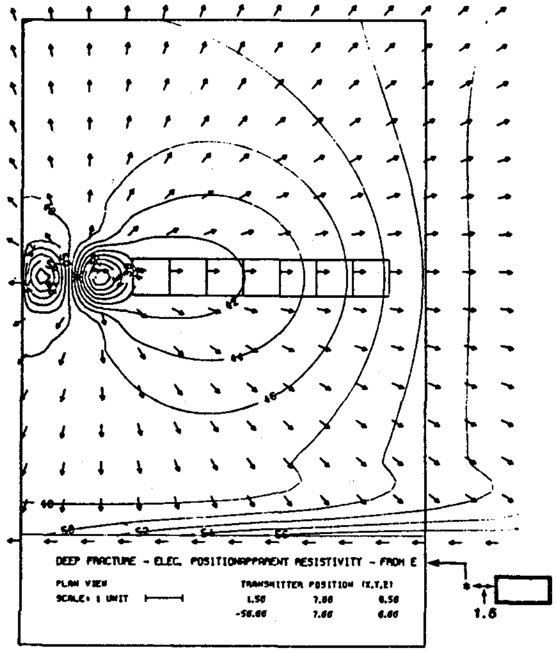


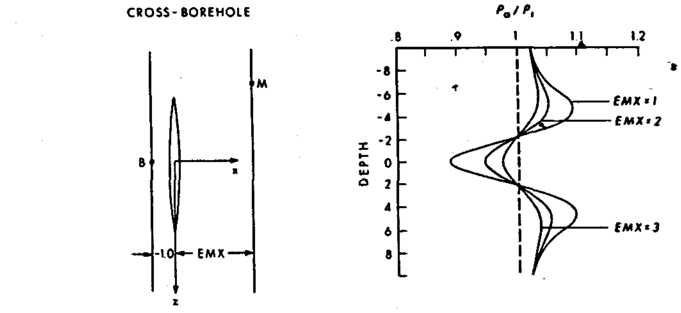
FIGURE 3b
Surface resistivity anomaly due to deep fracture with downhole electrode at side of body.

most of the results are for the case of a fracture zone ten times more conductive than the host rocks.

Four numerical techniques have been utilized in the studies; three have been applied with the D.C. resistivity method. The techniques applied to the resistivity problem are (1) a 3D surface integral equation (Yang and Ward, 1985a,b), (2) a 3D volume integral equation (Beasley and Ward, 1986), and (3) a 2D finite element method (Zhao et al., 1985). A solution for the time domain EM method has also been obtained which uses a 3D volume integral equation formulation (West and Ward, 1985). Elaboration on these four approaches is given below.

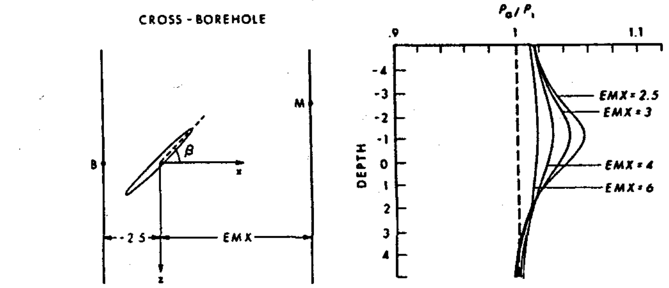
Yang and Ward (1985a,b) present theoretical results relating to the detection of thin oblate spheroids and ellipsoids of arbitrary attitude. The effects of the surface of the earth are neglected and the body is assumed to be enclosed within an infinite homogeneous mass. The surface of the body is divided into a series of subsurfaces, and a numerical solution of the Fredholm integral equation is applied. Once a solution for the surface charge distribution is determined, the potential can be specified anywhere by means of Coulomb's law. The theoretical model results indicate that cross-borehole resistivity measurements are a more effective technique than single-borehole measurements for delineating resistivity anomalies in the vicinity of a borehole.

Figure 4a shows cross-borehole resistivity responses of a vertical conductive fracture zone between two boreholes. The electrode configuration is the pole-pole array with electrode B fixed and electrode M moving in the second borehole. Several curves are plotted depending on the distance between the fracture and the second borehole. The larger anomalies occur when the second



Electrode Configuration	Body Size	Angles	Resistivity Contrast
Fixed Source Moving Electrode SBX=-1.0 SBY=SBZ=0 EMY=0	a=6(z) b=2(y) c=0.2(x)	α=0° β=90° γ=0°	$\frac{\rho_2}{\rho_1}$ = 0.10

FIGURE 4a
Downhole cross-borehole resistivity anomalies for vertical fracture showing effect of varying distance from fracture to second borehole.

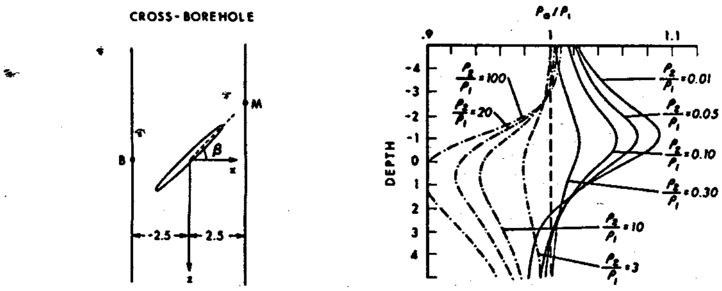


Electrode Configuration	Body Size	Angles	Resistivity Contrast
Fixed Source Moving Electrode SBX=-2.5 SBY=SBZ=0 EMY=0	a=2 b=2 c=0.2	α=0° β=45° γ=0°	$\frac{\rho_2}{\rho_1}$ = 0.10

FIGURE 4b
Downhole cross-borehole resistivity anomalies for dipping fracture showing effect of varying distance from fracture to second borehole.

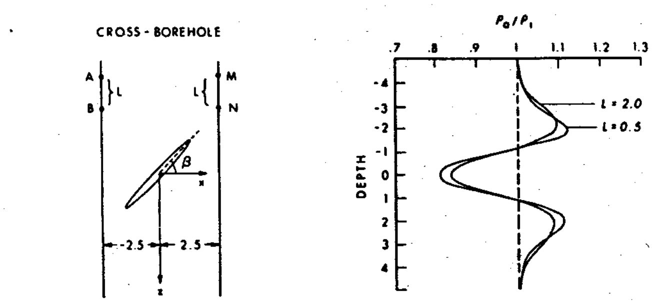
borehole is nearer to the fracture zone. Figure 4b shows anomalies for the same situation as Figure 4a except that now the fracture dips toward the first borehole. Figure 4c shows the effect of varying the resistivity contrast between a dipping fracture and the host medium. As expected, the large contrast cases produce the largest anomalies. Figure 4d shows the change in anomaly shape for the dipping fracture when four electrodes are placed downhole instead of two (compare with Fig. 4b, EMX = 2.5). By study of a large suite of such graphs as these, the comparative capabilities of the various possible cross-borehole arrays can be determined.

The volume integral equation approach of Beasley and Ward (1986) incorporates a half-space formulation, i.e. the earth's surface is not neglected. As with the surface integral equation technique of Yang and Ward (1985a,b), the volume integral equation method requires that only inhomogeneities be discretized. Any number of inhomogeneities of differing sizes and physical properties can be accounted for by this algorithm. Inhomogeneities are discretized into rectangular cells whose size may vary in each of



Electrode Configuration	Body Size	Angles	Resistivity Contrast
Fixed Source Moving Electrode SBX=-2.5 SBY=SBZ=0 EMX=2.5 EMY=0	a=2 b=2 c=0.2	α=0° β=45° γ=0°	—— $\frac{\rho_2}{\rho_1} < 1$ —·— $\frac{\rho_2}{\rho_1} > 1$

FIGURE 4c
Downhole cross-borehole resistivity anomalies for dipping fracture showing the effect of varying resistivity contrast between fracture and host medium.



Electrode Configuration	Body Size	Angles	Resistivity Contrast
Moving Bipole Source Moving Bipole Receiver SAY=SBY=0 EMY=ENY=0	a=2 b=2 c=0.2	α=0° β=45° γ=0°	$\frac{\rho_2}{\rho_1} = 0.10$

FIGURE 4d
Downhole cross-borehole resistivity anomalies for dipping fracture showing the effect of dipole length for downhole electrodes.

the three directions. The fact that targets must be comprised of rectangular or cubic cells means that dipping bodies must be simulated by cells arranged in a staircase fashion. Section and plan views of computed apparent resistivities are the end product of this algorithm. The algorithm is flexible in that it permits a buried electrode to be placed either inside (mise-à-la-masse) or outside (near-miss) the body. The dip of the body and the location of the energizing electrode within it were both varied. The maximum depth at which a body could be located and still produce a detectable anomaly on surface surveys was found to be dependent, as expected, upon the position of the buried electrode and upon the contrast in resistivity between the body and the host. It was found that locating the buried electrode just outside the body did not significantly alter the results from those when the electrode is embedded in the inhomogeneity.

Figures 5a, 5b and 5c show representative results from Beasley and Ward (1986). Each figure is a vertical section through the earth with contours of the resistivity anomaly. A borehole can be placed anywhere on this figure and the resistivity curve that would be observed in such a

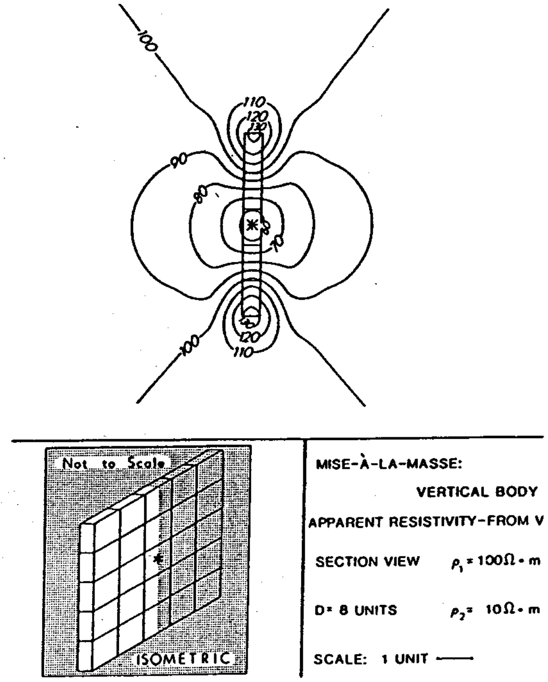


FIGURE 5a
Subsurface resistivity contours for a vertical permeable zone with an imbedded downhole current source.

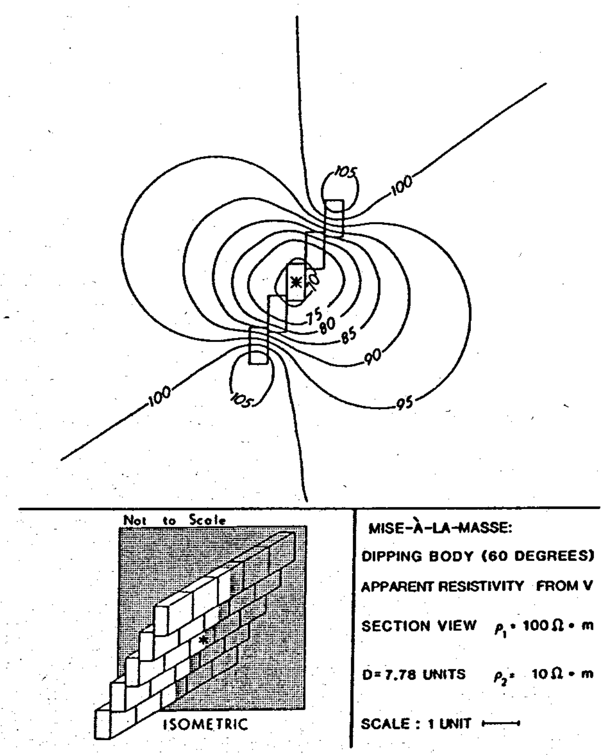


FIGURE 5b
Subsurface resistivity contours for a dipping permeable zone with an imbedded downhole current source.

borehole with a single downhole potential electrode would be given by the intersection of the borehole with the contours. The downhole current electrode source is shown by the star.

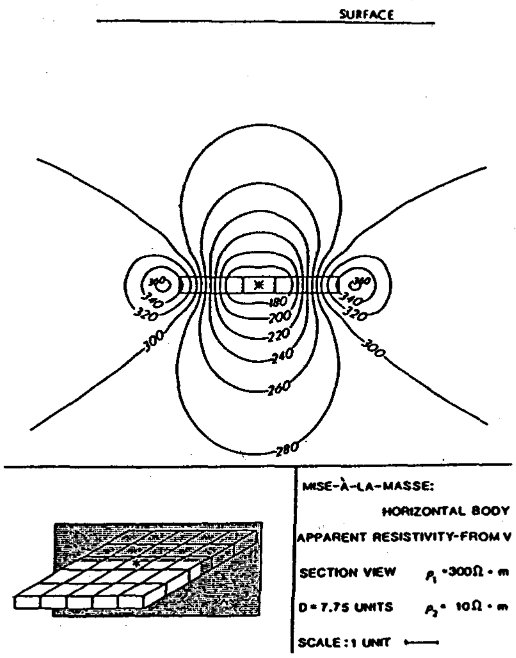


FIGURE 5c
Subsurface resistivity contours for a horizontal permeable zone with an imbedded downhole current source.

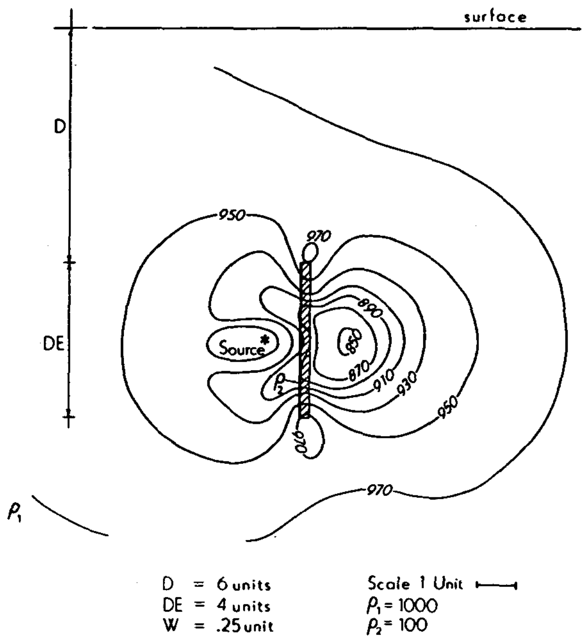


FIGURE 6a
Subsurface resistivity contours for a vertical permeable zone with current source to the side.

Our most versatile algorithm for the borehole resistivity method is the 2-D finite element algorithm used by Zhao et al. (1985). The versatility of this algorithm arises from the fact that the entire subsurface is discretized. Since triangular elements are used for discretization, dipping bodies are readily handled. The algorithm also accomodates a layered-earth host environment. This algorithm was used to evaluate signal-to-noise ratio for various types of noise.

Figures 6a and 6b show typical results from

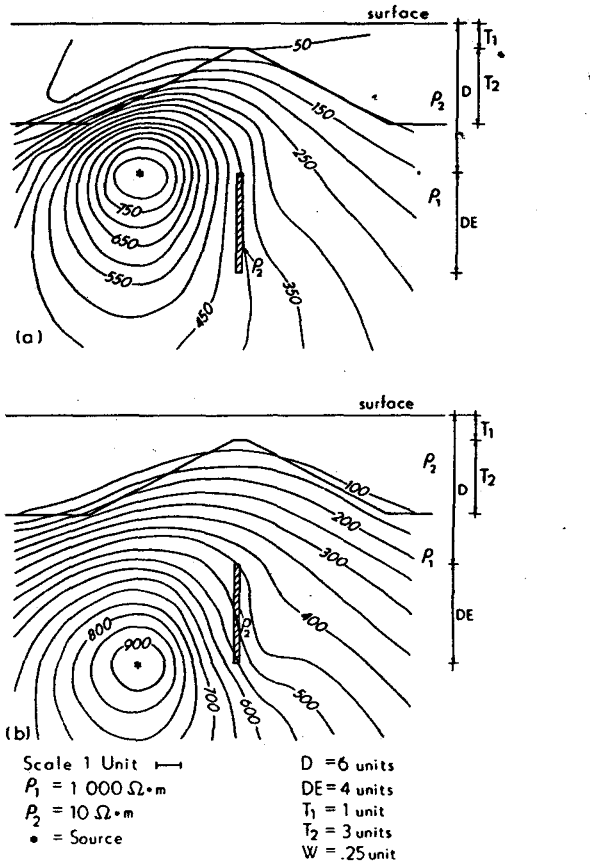


FIGURE 6b
Subsurface resistivity contours for a vertical permeable zone beneath geologic structure with varying positions of the downhole current electrode.

Zhao et al. (1985). Figure 6a shows subsurface resistivity contours in section for a vertical fracture with a current source outside the body. This plot is similar to those given by Beasley and Ward (1986) in Figures 5a, 5b and 5c. Figure 6b illustrates how subsurface topography due to geologic structure affects results. Note that the anomaly due to the fracture is obscured to a great extent by the resistivity pattern created by the contact. This is due in part also to the relatively large distance of the fracture from the downhole current source, shown by the star. A current source in a borehole closer to the fracture would cause a much clearer anomaly.

All computations by Yang and Ward (1985a,b) and Zhao et al. (1985) were performed on an HP9826 desk top computer with 1.6 Mbytes of memory. The algorithm used by Zhao et al. (1985) is currently being extended to 3-D. It is probable that the HP9826 will accomodate the 3-D version. If so, these modeling programs could easily be used in the field with no need to return to a large computing facility.

From the above studies we tentatively conclude the following: the cross-borehole method produces larger anomalies than does a single-borehole method; the cross-borehole anomalies using a pole-pole array are smaller than those for a cross-borehole dipole-dipole array; the cross-borehole mise-à-la-masse method produces larger anomalies than for the other cross-borehole methods; and, the anomalies due to a thin sheet were generally much smaller than those for a sphere, as is to be expected.

Using a 3-D integral equation algorithm developed by San Filipo and Hohmann (1985), West and Ward (1985) performed a model study to evaluate the time-domain electromagnetic (TDEM) response of a horizontal conductive body (fracture zone) imbedded in a half-space. Simplifying assumptions in the algorithm allow modeling only of bodies with two vertical symmetry planes with sources directly above or below. The source transmitter is a large square loop located on the surface of the earth. Receivers are located in boreholes at various locations in the vicinity of the body. Responses are computed at 60 time steps at intervals of 0.4 ms for a total data window of 24 ms. EM field decay curves and plots of decay versus depth are obtained for all three components of the primary, secondary, and total responses. The results are expressed in terms of percent difference plots, and are still under study at this time.

Surface-to-borehole EM in which a large transmitter is coaxial with the well and a downhole detector is run in the well may provide useful information on the location of conductive fractures intersecting the wellbore. Whether this technique will work in cased wells and whether a "crack" anomaly can be distinguished from a stratigraphic conductor are topics under study.

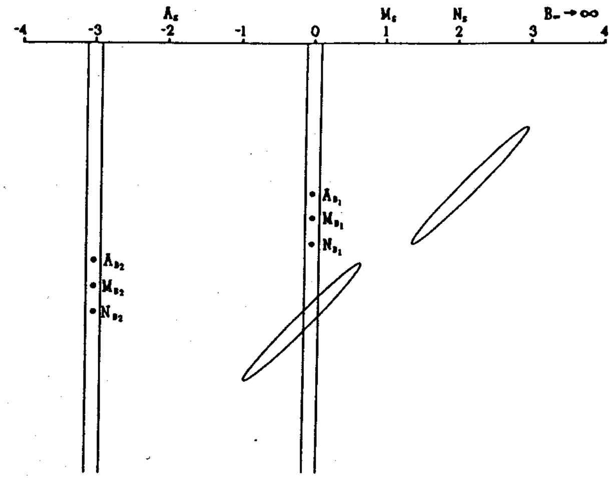
The above discussion outlines our research to date. Other current research involves a model study using the VLF (very low-frequency) method as well as developing a borehole inversion scheme using the finite-element technique. Inversion of the 3D integral equation is also being investigated. An inversion scheme which can incorporate multi-array data is an ultimate goal. Interpretation of complex borehole field data from geothermal sites may then become a reality.

DISCUSSION

The problem of selecting an appropriate borehole electrical system is quite complex. Variables include where to place the electrodes, i.e. how many on the surface and how many down each borehole, and whether to use direct-current galvanic resistivity, which each of the above figures illustrate, or some alternating current, electromagnetic scheme. It is clear that the computer based study of these questions is cost effective in helping select and design an optimum field system.

Our current opinion is that the more data one can collect the better one should be able to characterize the subsurface. We have therefore been making a preliminary investigaton of the design of a system for obtaining both borehole-to-borehole and borehole-to-surface data simultaneously. Such a scheme is conceptually illustrated in Figure 7. We believe we are nearing the stage when a field system can be designed with the very real hope of yielding much more subsurface information than can be realized by presently available systems.

MULTI-ARRAY BOREHOLE RESISTIVITY SURVEY



●LONG LATERAL ARRAY — $A_B B_- M_B N_B$ ∗CONVENTIONAL LOGGING TRUCK

●SURFACE-TO-BOREHOLE — $A_S B_- M_B N_B$ ∗POTENTIAL AND CURRENT ELECTRODES ON SURFACE AND DOWNHOLE

●BOREHOLE-TO-SURFACE — $A_B B_- M_S N_S$

●MISE-A-LA-MASSE — A_B in fracture zone $M_B N_B$ or $M_S N_S$ ∗RAPID SEQUENCING THROUGH ELECTRODES

FIGURE 7
Conceptual illustration of a multi-array borehole resistivity system.

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PAPER UNAVAILABLE

INEL INJECTION RESEARCH: PHYSICAL MODEL STUDIES

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ABSTRACT

The primary objective of the INEL Injection Research Program is to develop a better understanding of injected fluid migration in fractured geothermal reservoirs. The INEL program combines laboratory experimentation, computer simulation and field testing in the study of fluid migration. A sound theoretical understanding of the fundamental processes that control mass, heat and solute transport through fractured rocks is necessary to understand how injected fluids will interact with geothermal reservoirs. A transport algorithm for fractures was developed and a simple single fracture code written. The algorithm was verified against analytical solutions and validated against laboratory data. The FRACSL reservoir code currently uses this approach to tracer transport. The flow and transport components of FRACSL have been validated using a two-dimensional laboratory fracture network. A good match between the laboratory data and the FRACSL simulations was obtained using no empirical parameters.

The laboratory and simulations studies conducted to date have dealt with discrete fractures in impermeable matrix materials. A laboratory model has been developed to allow studies of dual-permeability fracture systems during FY-86.

INTRODUCTION

The primary objective of the INEL Injection Research Program is to develop a better understanding of fluid migration in fractured geothermal systems during injection. This understanding will be used to improve field testing and data interpretation procedures and will provide a basis for optimizing geothermal injection and wellfield management strategies.

The INEL Injection Program combines laboratory experimentation, computer simulation and field tracer testing in the study of injected fluid migration. By relating observable phenomena (pressure response, fluid enthalpy, fluid chemistry, tracer breakthrough) to reservoir characteristics, methods of interpreting data are refined and predictive techniques are developed. Parametric studies are performed using numerical simulation codes to determine the sensitivity of measurable parameters to changes in reservoir conditions. Codes are not only verified against analytical solutions, but are validated using data collected from laboratory models under controlled conditions. The laboratory validation step provides assurance that the codes deal with the important transport processes properly, allowing the separation of uncertainty in code parameters from uncertainty in reservoir configuration.

Field data provide the ultimate test of the utility of newly developed data interpretation procedures. Field testing also provides an opportunity for interaction between research and industry personnel, allowing researchers to get a better feel for industry concerns while industry is exposed to the latest testing and analytical methods.

There are four components to the INEL Injection Research Program. These are:

1) Fundamental Transport Processes
2) Data Interpretation Tools
3) Field Data Acquisition
4) Demonstration and Technology Transfer

The FY-85 research efforts concentrated primarily on the first two components.

THE FRACSL CODE

The objective of the data interpretation research is to develop tools that can be used to interpret pressure, temperature or tracer data obtained from testing geothermal reservoirs. Data interpretation tools are based on either analytical solutions to an idealized reservoir configuration (type-curve matching) or on distributed parameter simulation techniques. Because of the complexity of fractured, dual-permeability geothermal reservoirs, the INEL program emphasized the latter approach. By adding the capability to match tracer response curves to the ability to match pressure and temperature data, additional information on reservoir conditions can be obtained.

Because of the complexity of fractured geothermal reservoirs, it is not considered possible to simulate the entire reservoir deterministically. There are too many fractures to incorporate all explicitly into the simulation and there is too little information on the individual fractures. Therefore, statistical descriptions of the fracture system are first generated, and an equivalent continuum used to describe these fractures. Only the major fractures are explicitly simulated in the model. The continuum portion of the reservoir, however, can have considerable flow, and therefore this type of system cannot necessarily be simulated using a dual-porosity approach. A code is needed that can deal with flow through both the explicitly simulated fractures, and the complex fracture network that makes up the bulk of the reservoir. This is the goal of the INEL program.

Accomplishments in this area include development of the FRACSL code as a tool to aid in the investigation of flow and transport in porous media, discrete fractures and dual-permeability systems. The code has been coupled with a three-dimensional fracture flow code to provide expanded capabilities. The finer fracture structure and the rock itself are modeled as rectangular matrix cells of unit thickness. The larger fractures are represented as discrete elements superimposed on the edges and diagonals of the matrix cells. A single head distribution drives otherwise independent flows in the matrix and in the fractures. Static or transient flow conditions may be simulated. Solute transport is simulated by moving imaginary marker particles in the velocity field established by the flow model. Advective, dispersive and diffusive effects are included.

The FRACSL code has been validated against analytical solutions for flow and transport in porous media. Correlation of tracer testing conducted at the East Mesa geothermal field demonstrated the utility of the code. Results from the analysis of data collected at East Mesa quantified the dispersion characteristics of the aquifer, natural flow rate through the reservoir, and the ratio of maximum to minimum hydraulic conductivities. Analytical solutions for transport in fractures have been derived for special flow conditions and used to analyze data from field testing at the Raft River geothermal field.

PHYSICAL MODEL VALIDATION

Physical models provide a means for studying the dispersion phenomenon in fractures under controlled conditions, where observation can help increase the understanding of the transport processes. They also provide a means of validating computer codes that simulate flow and transport in fracture networks and allow evaluation of field test procedures under known reservoir conditions. While the conditions represented by the physical models are not necessarily realistic, demonstrating that a simulation code can successfully match lab data provides assurance that the code can be applied to actual reservoir data.

The validation of FRACSL against laboratory models has been a useful and revealing exercise. Because the laboratory models could be explicitly defined, no empirical parameters could be used in the validation study. Thus, it was possible to determine whether sufficient understanding of the processes that control flow and solute transport through fracture systems is incorporated into FRACSL to allow predictive applications. The simulations of the laboratory model with FRACSL have demonstrated that the code is very useful and versatile.

The physical models tested include single fractures, single fracture junctions and discrete fracture networks. All models have been built of plexiglas, which allows visual observation of tracer movement. Piezometers are installed in fractures to measure pressure distributions. Platinum electrodes are embedded in upper and lower fracture walls to measure fluid resistivity. This permits very precise measurement of tracer concentration changes within the fractures without disturbing the flow field.

Much of the physical modeling effort this year was oriented towards validating the particle tracking algorithm used in FRACSL, and developing a better understanding of transport processes in fractures. The former activity has shown that particle tracking has many advantages over numerical methods for simulating solute transport. The latter activity has provided important insight into how to design future testing of fracture systems.

Experiments in single fractures and single fracture junctions demonstrated that both infinite parallel plates and rectangular channels can be simulated. The ability to handle rectangular channels is necessary for simulating laboratory models, which are rectangular channels with finite aspect ratios. Computer simulations were quite successful in matching the laboratory results with no manipulation of parameters.

The particle tracking algorithm was also used to simulate infinite parallel plates under conditions where analytical solutions to the transport equation could be derived. The first case is for zero diffusion in the fracture, and transport based on a parabolic velocity profile (Figures 1 and 2). The second case is for diffusion homogenizing the tracer solution across the fracture (Figures 3 and 4). The particle tracking algorithm matched this broad range of flow conditions well.

Laboratory tests using the discrete fracture network model have demonstrated the significance of density effects. When a fluid of equal density to the reservoir fluid is injected, transport of the injected tracer through the fracture network is parallel to the hydraulic flow pattern (Figure 5). Only minor (less than 0.1%) differences in fluid density can result in substantially different tracer transport patterns (Figure 6). Figure 7 shows a comparison of the FRACSL-simulated concentration and measured tracer concentrations at a single point in the fracture network.

While transport of solutes through fractures is important, most fracture systems occur in formations where the rock has some permeability and porosity. This matrix porosity will greatly affect the transport of solutes and heat transfer in a geothermal reservoir. The general approach to solving dual porosity systems is to ignore flow in the matrix blocks, and to treat heat and mass transfer between blocks and matrix as a one-dimensional diffusion process. This approach is based on the assumption that pressure gradients across matrix blocks in a dual-porosity fracture network are trivial compared to pressure gradients between blocks and fractures.

This assumption may be true for continuous fracture systems in low permeability matrix materials, but not for systems with dead end fractures or in rocks with high matrix permeability. Diffusion is not the only process for transferring material from fractures to matrix and vice versa; advection can play an important role.

Preliminary simulations of the dual permeability model have been made with FRACSL. Figure 8 shows the predicted pressure distribution within the model under steady-state conditions. The slope in the pressure gradient is not uniform from inlet to outlet, but shows some very steep discontinuities. The very steep pressure gradient between points C and D drives solutes into the matrix between two dead end fractures. Figure 9 is a map view of the fracture network, somewhat distorted, and shows position of the tracer solution, injected as a five minute slug, after 60 minutes of moving through the fracture network. Tracer has moved into the matrix in a number of locations. After longer times, tracer will connect to other fractures, and move out of the matrix into new fractures, and then back into the connected fracture system. This model design provides a number of very rigorous tests to assess the capabilities of the dual-permeability simulation code.

FY-86 RESEARCH ACTIVITIES

The proposed FY-86 INEL Injection Program will continue development of techniques to evaluate and predict the impact of injection on geothermal reservoirs. Primary emphasis will be placed on dual-permeability physical model tests, final validation of the FRACSL code and cooperative injection tests with industry.

Fundamental Processes - Laboratory experiments will be conducted with dual permeability fracture networks to obtain a better understanding of physical, geochemical and heat transport processes in these systems. Additional investigations using the fracture junction model will evaluate tracer mixing across streamlines. In a cooperative effort with UURI, water/rock interactions will be studied. Kinetic reaction equations will be integrated so that tracer decay, mineral precipitation and ion exchange reactions can be simulated.

Data Interpretation Tools - Heat transfer capabilities will be validated for the dual permeability FRACSL code. The ability to deal with turbulence in fractures near wellbores will be added and the final 2-D form of the code will be documented and published. In a supporting task, current efforts in the hydrogeology community to relate fracture networks and continuous hydrologic parameters will be evaluated. A methodology to relate statistical descriptions of fracture networks to hydologic parameters will be developed.

Field Data Acquisition - A key task in the FY-86 program effort is cooperative injection tests with industry to evaluate the usefulness of innovative testing and data analysis methods in geothermal fields. In a continuation of a current effort, a site or sites will be selected for joint field tests in cooperation with industry partners. Emphasis is placed on sites currently undergoing commercial development so that long-term monitoring and confirmation of predictions can be accomplished.

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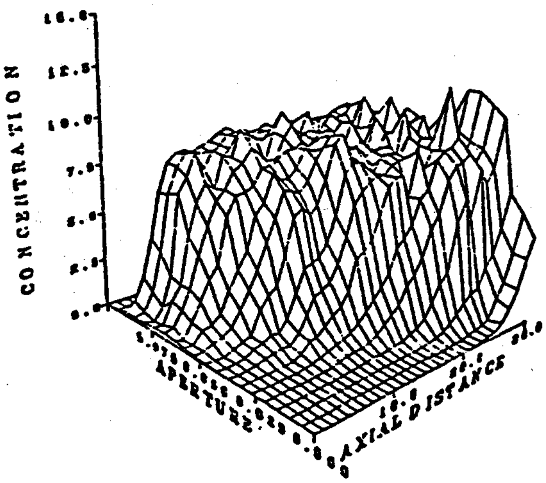

Figure 1. Map of tracer concentration in a fracture where dispersion is controlled by the parabolic velocity profile (Pe = 0.0).

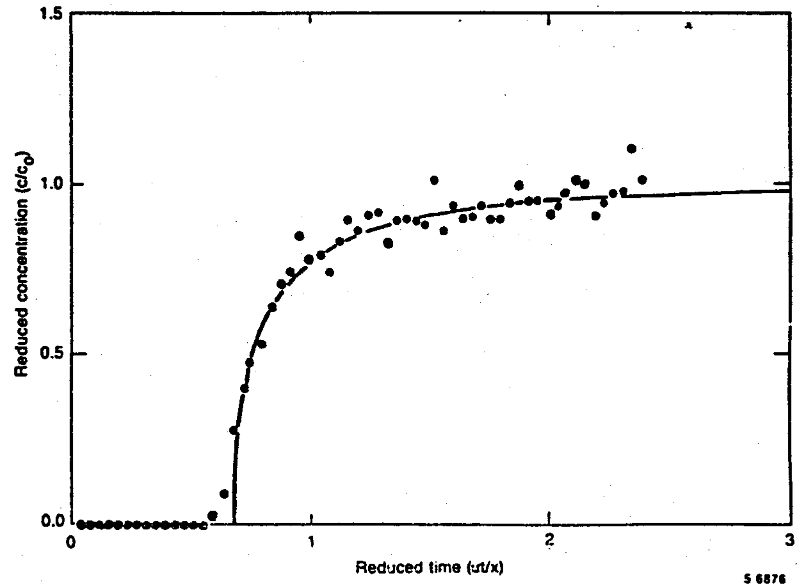

Figure 2. Comparison of analytical (line) to numerical (points) solutions for tracer breakthrough where dispersion is controlled by the parabolic velocity profile (Pe = 0.0).

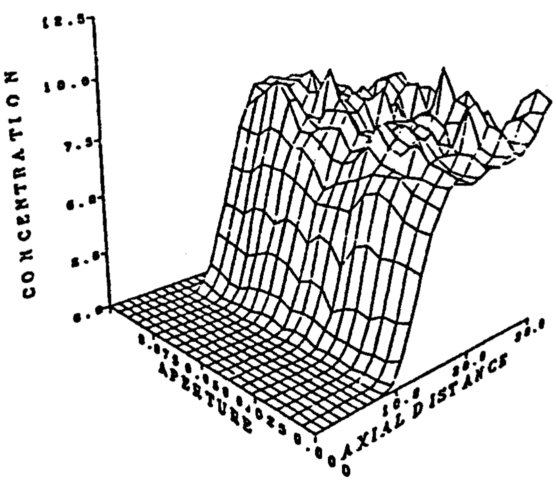

Figure 3. Map of tracer concentration in a fracture where transverse molecular diffusion dominates development of a parabolic velocity profile (Pe = 500).

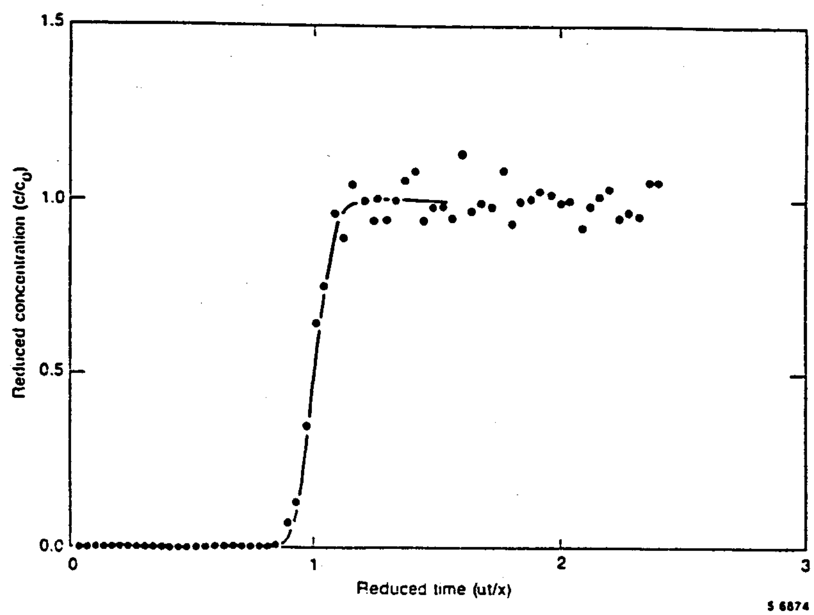

Figure 4. Comparison of analytical (line) and numerical (points) solutions for tracer breakthrough where transverse molecular diffusion dominates development of a parabolic velocity profile (Pe = 500).

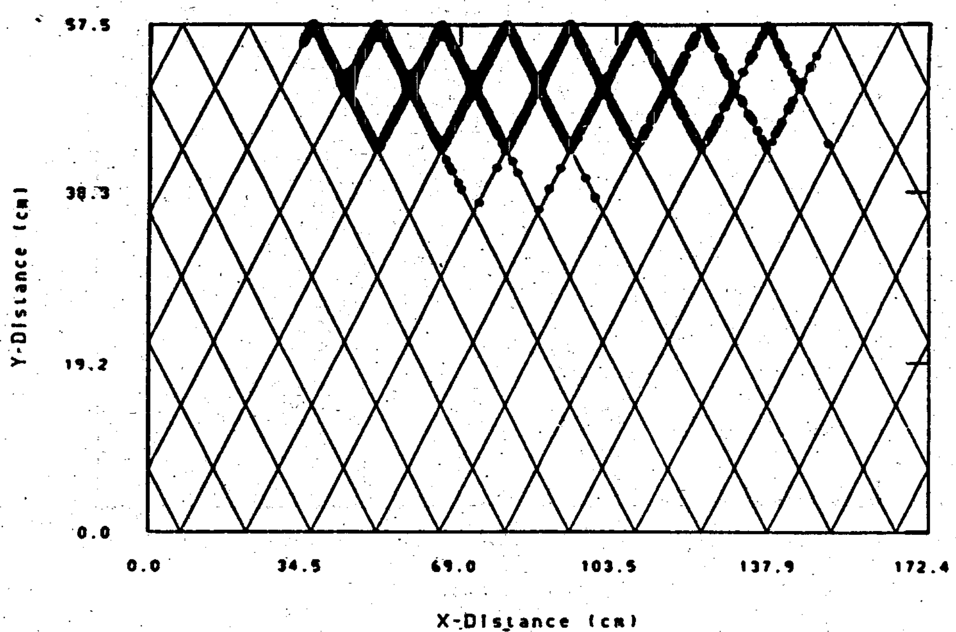

Figure 5. Simulated distribution of tracer in the physical model at the end of the 94 minute injection period. Transfer of tracer through junctions is based on stream tubes.

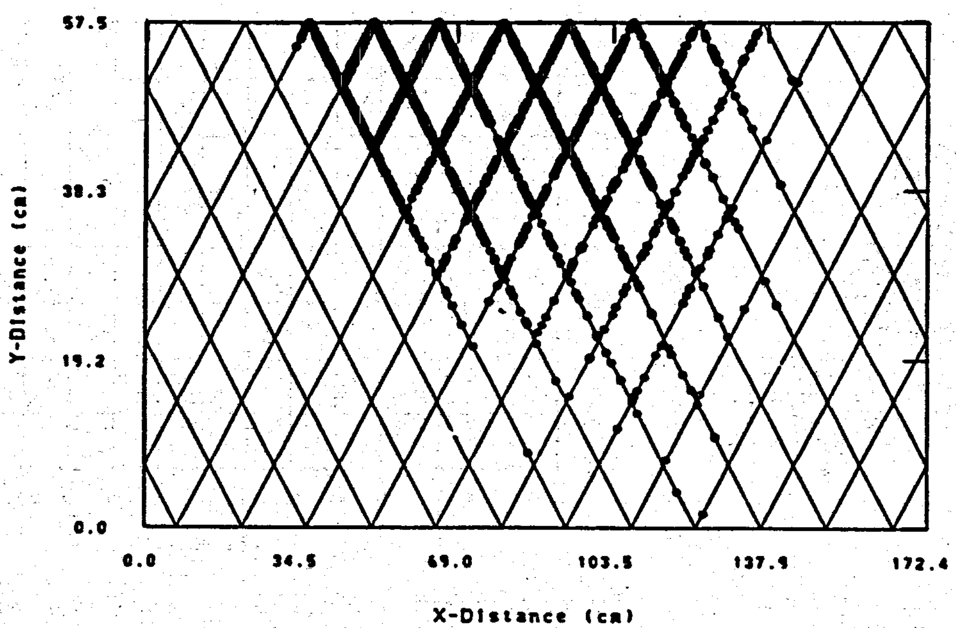

Figure 6. Simulated distribution of tracer in the physical model at the end of the 94 minute injection period. Transfer of tracer through junctions is based on diffusive mixing with a density-induced effective diffusion coefficient of 4.5×10^{-2} cm^2/min.

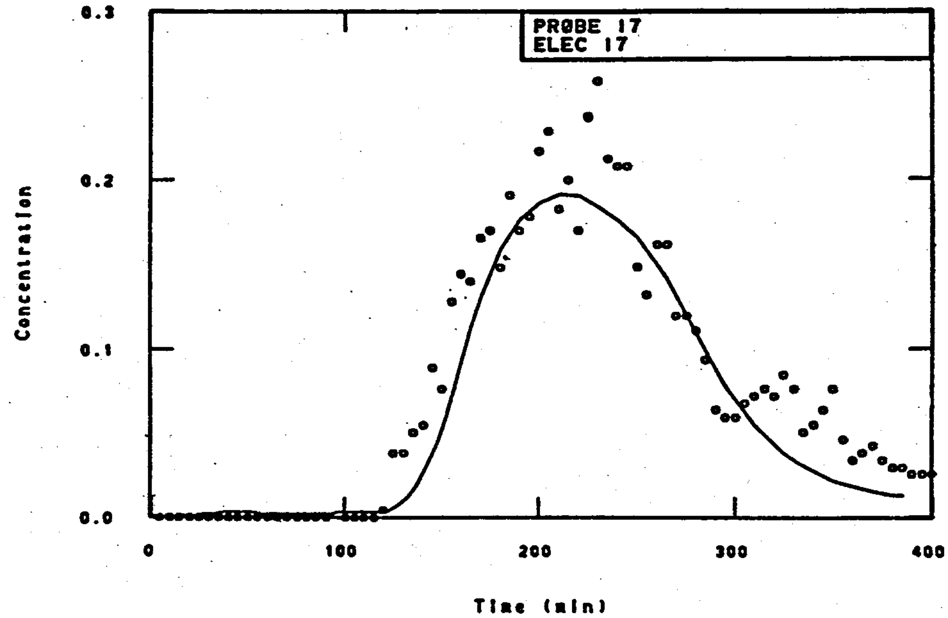

Figure 7. Comparison between FRACSL simulated concentration (points) and laboratory model data (line) for electrode 17.

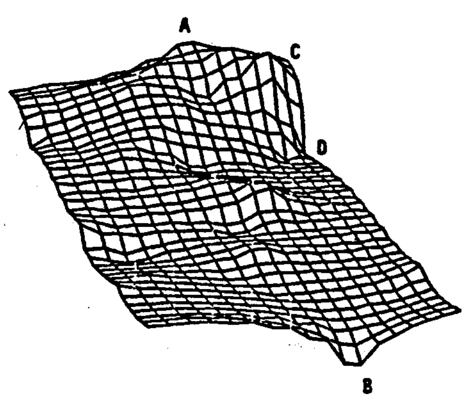

Figure 8. Steady-state pressure distribution in the dual-permeability laboratory model calculated using the FRACSL code.

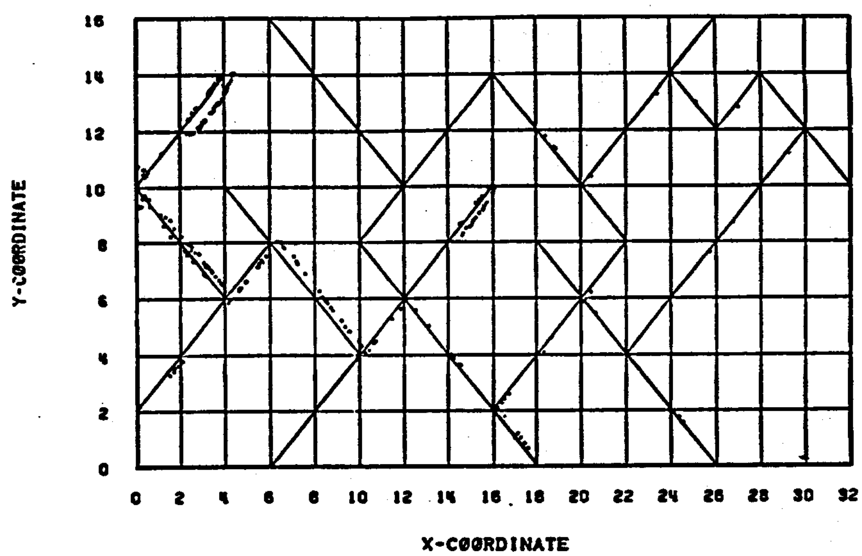

Figure 9. Positions of tracer particles, injected as a five-minute pulse, after 60 minutes of flow in the dual-permeability model. Predictions based on the FRACSL code.

Brine Injection Studies

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ABSTRACT

The program of the Lawrence Berkeley Laboratory in Brine Injection Technology is comprised of field and theoretical activities. Emphasis is given to the study of migration of injection fluids and compositional effects in the reservoir, and optimizing the heat extraction from geothermal systems. A joint injection test program with industry has also been initiated. The results of the FY1985 effort and the proposed plans for FY1986 are described.

INTRODUCTION

The overall purpose of the Lawrence Berkeley Laboratory Brine Injection Project is to develop and demonstrate methods for predicting, monitoring and analyzing the short- and long-term response of geothermal reservoirs to fluid reinjection. The project addresses the main reservoir engineering issues in brine injection (Table 1), which can be summarized by the following three statements: (1) predict, control and monitor the movement of the injection plume, (2) maintain, and if possible increase, the injection capacity of the wells and (3) optimize the production-injection system to enhance the heat extraction from the reservoir and reduce thermal degradation of producing wells.

SUMMARY OF MOST IMPORTANT FY1985 ACTIVITIES

Modeling of sharp fronts. Numerical dispersion is a serious problem in modeling sharp (thermal or compositional) fronts associated with injection plumes. A second-order upwind/central difference method for convection-diffusion type of equations that greatly reduces numerical diffusion errors has been developed (Lai et al., 1985). On Figure 1 a comparison between the sharpness of a modeled front using the conventional upwind-difference numerical scheme (graphs on the left) is compared, for different injected volumes, with that obtained with the new approach (graphs on the right). A much sharper front, that closely matches analytical results, is given by Lai et al.'s method.

Table 1. Main Issues In Brine Injection

- Prediction and monitoring of migration of injection fluids
- Maintaining well injectivities
- Analysis of heat extraction and compositiional effects in geothermal reservoirs during injection
- Development and improvement of mathematical tools to model processes relevant to the migration of injected fluids in the reservoir

Compositional Effects. We developed the capability of modeling heterogeneous reactions between solid phases and gaseous components under geothermal reservoir conditions which has been applied to study the origin of CO_2 in the Larderello field (Pruess et al., 1985). This effort complements our previous modeling work on H_2O/CO_2 mixtures for different phase compositions (O'Sullivan et al., 1985).

The dissolution and precipitation of silica in nonisothermal systems are being studied, including the corresponding changes in reservoir porosity and permeability (Lai et al., 1985b; Verma and Pruess, 1985). Equilibrium as well as kinetic relationships for silica-water reactions have been developed and incorporated into existing LBL computer codes.

Heat Extraction Studies. This year we completed the modeling of Stanford's heat extraction experiments using the method of "multiple interacting continua" (MINC; Pruess and Narasimhan, 1985). A chapter of a Lam et al. (1985) report, describing the LBL modeling code and involvement in the project, was contributed by K. Pruess.

To more accurately describe fractured geothermal reservoirs the MINC method was extended to include variations in fracture spacing. This will allow a more realistic modeling of the heat transfer between irregularly shaped rock blocks and adjoining fractures.

Analysis of Injection Test in Fractured Reservoirs. Models to analyze injection tests in geothermal systems have to consider nonisothermal effects and the fractured nature of the reservoir; otherwise wrong permeability-thickness products will be obtained. Cox and Bodvarsson (1985) studied pressure transients resulting from nonisothermal injection into horizontal and vertical fractures with variable rock matrix and fracture parameters (Figure 2). They show that the pressure is greatly controlled by the movement of the thermal front through the fractures, because of the temperature-dependent fluid properties. These effects are quite different than those derived for porous systems because of unlike thermal front advance rates. This study also describes differing pressure data analysis procedures that depend on the geometry (vertical versus horizontal) of the fractures and the properties of the injected and reservoir fluids.

Evaluation of Composite Reservoir Systems. A new technique was developed for evaluating well interference test data in radially symmetric composite reservoirs (Benson and Lai, 1985). By analyzing variations in the apparent storage coefficient, both the mobility (k/μ) and the size of the inner region can be calculated. The technique is particularly useful for evaluating heterogeneous systems where the intersection of several faults or hydrothermal alteration has created a zone of high (or low) permeability region in the center of geothermal field. The method has been applied to characterize the Klamath Falls, Oregon, system (Figure 3).

Joint DOE-Industry Injection Tests. In collaboration with Magma Power Company and Dow Chemical USA, LBL began an injection monitoring program at the East Mesa KGRA. LBL is interpreting falloff test data being collected by the operators and is designing future joint injection and falloff tests. LBL is also evaluating wireline log data to determine the stratigraphy and identify fracture zones that might intersect a deeper injection well (Well 84-7).

PROPOSED PLANS FOR FY1986

An outline of LBL's FY1986 Brine Injection Program as proposed to DOE is given below. The final program will be determined based on discussions between DOE and LBL program managers.

Subtask 1: Migration of Injection Fluids

1A. Perform laboratory experiments to study dispersion of phase fronts.

1B. Improve techniques for resolving chemical fronts.

1C. Demonstrate a numerical method for explicitly tracking phase fronts.

1D. Perform generic studies to find optimal injection well depths and locations.

Subtask 2: Heat Extraction Efficiency

2A. Continue development of the MINC-method for reservoirs with arbitrary fracture distributions.

2B. Develop methods for determining fracture porosities

Subtask 3: Compositional and Geomechanical Effects

3A. Implement a more realistic description of brines into numerical codes (non-condensible gases, dissolved solids, chemical reactions).

3B. Perform generic studies of compositional effects in injection (including rock-fluid interactions, mixing of waters of different composition).

3C. Investigate and evaluate the occurrence of thermal stress cracking near injection wellbores.

Subtask 4: Field Case Studies

4A. Apply the MINC-method to a "real" fractured porous media reservoir.

4B. Design, implement and analyze injection tests in porous or fractured media reservoirs (subject to field access).

ACKNOWLEDGEMENTS

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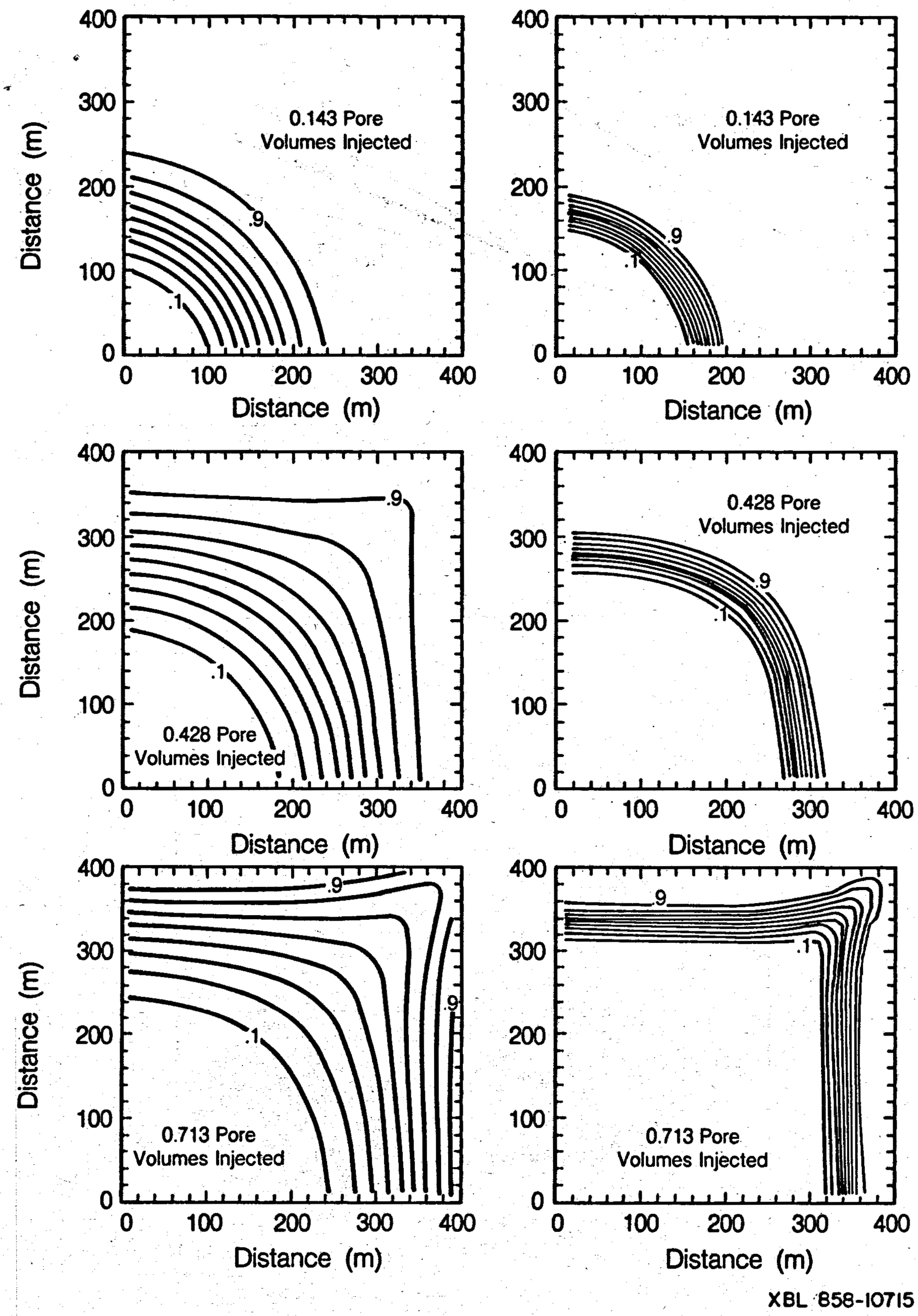

Figure 1. Comparison between results using the conventional first-order upwind difference scheme (left column graphs) and the monotonized upwind/central difference scheme of Lai et al., 1985b (right column graphs). Fluid is injected in the lower left corner and extracted from the upper left corner of the system, lines represent isocons.

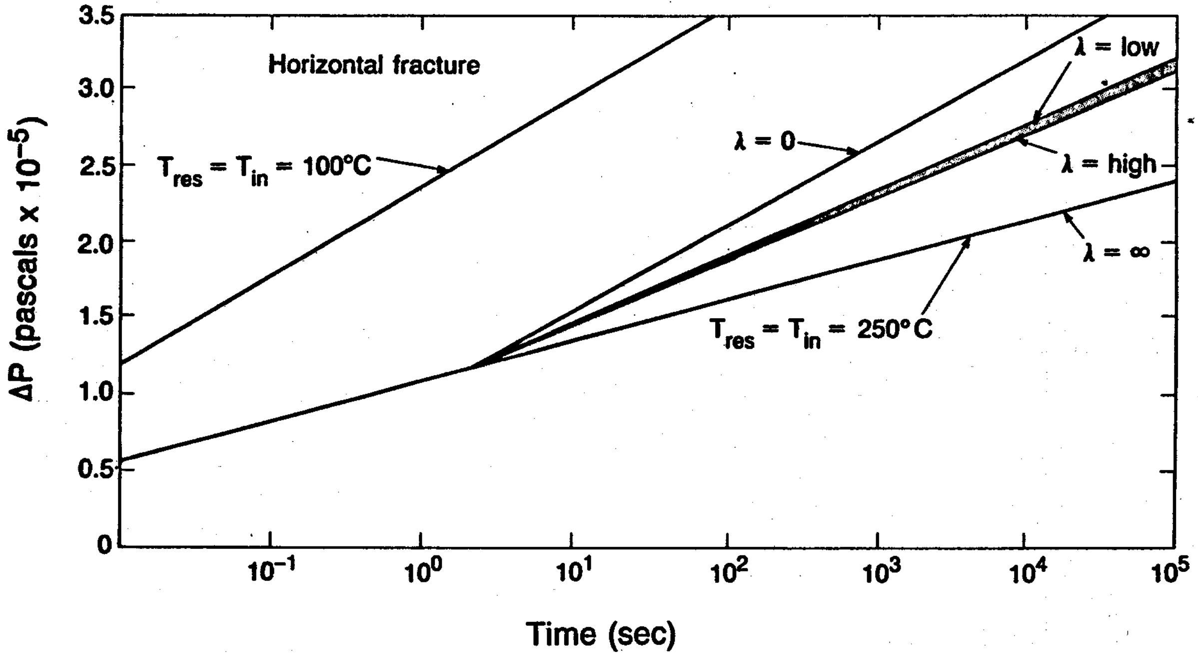

Figure 2. Pressure transients data for nonisothermal injection into a horizontal fracture (Cox and Bodvarsson, 1985).

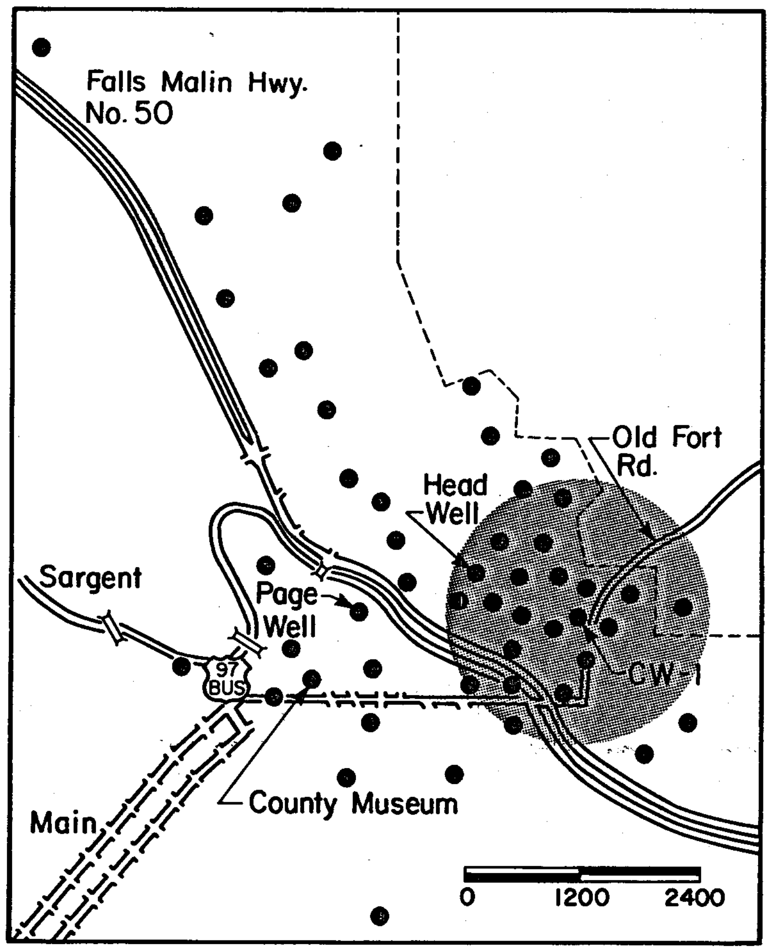

Figure 3. High-permeability region inferred in the Klamath Falls geothermal field based on the composite-reservoir analysis of Benson and Lai (1985).

HEAT CYCLE RESEARCH EXPERIMENTAL PROGRAM, FY-1985

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ABSTRACT

The Heat Cycle Research Program, which is being conducted for the Department of Energy, has as its objective the development of the technology for effecting improved utilization of moderate temperature geothermal resources. Testing at the Heat Cycle Research Facility located at the DOE Geothermal Test Facility, East Mesa, California is presently being conducted to meet this objective. Current testing involves a supercritical vaporization and counterflow in-tube condensing system. The paper presents a brief description of the test facility and a discussion of the test program. Results of the experiments for the supercritical heaters and the countercurrent, vertical, in-tube condenser are given for both pure and mixed-hydrocarbon working fluids. The heater and condenser behavior predicted by the Heat Transfer Research Institute computer codes used for correlation of the data was in excellent agreement with experimental results. Preliminary results of tests in which the turbine expansion "passed through the two-phase region" did not indicate efficiency degradation assignable to these metastable expansion processes.

INTRODUCTION

The overall objective of the Heat Cycle Research Program, which is being conducted for the Department of Energy, is to improve utilization of moderate temperature geothermal resources. Major concerns of this program are directed toward (1) advances in binary cycle technology, (2) development of direct-contact heat exchanger technology for use in applications with resources having high corrosion or scaling potential, and (3) special studies including value analyses for estimating economic advantages of plant improvement concepts and other energy conversion cycles. The total program is summarized in some detail in Reference 1. This paper updates results of the task of experimentally exploring the supercritical binary cycle. The primary purpose of this task is to investigate the heating of pure and mixed-hydrocarbon working fluids at supercritical pressures, and the counterflow, in-tube, integral condensing of those fluids in order to confirm the cycle performance gains predicted for such systems. In addition, turbine efficiency is being determined for both normal and supersaturated expansion processes. Initial test results were described in Reference 2, and presented at the third DOE Geothermal Program Review in October, 1985.

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FACILITY DESCRIPTION

The Heat Cycle Research Facility (HCRF) is an experimental binary-cycle facility used to investigate different concepts and/or components for generating electrical power from a geothermal resource. In the binary power cycle, the energy from the geothermal fluid is transferred to a secondary working fluid, which is in turn expanded through a turbine driving an electrical generator. The facility, which was formerly located at the Raft River geothermal site in Idaho, is now located at the DOE Geothermal Test Facility (GTF) at East Mesa in the Imperial Valley of Southern California. A photograph of this installation was included in Reference 1.

The HCRF in its current configuration is shown schematically in Figure 1. In this configuration the facility is operated as a supercritical cycle; that is, the working fluid vapor leaving the heaters is at a temperature and pressure higher than its critical point. As indicated in Figure 1, there are two supercritical heat exchangers, a preheater and a vapor generator. The energy from the geothermal fluid, which is flowing on the tube side of the units, is used to heat a hydrocarbon working fluid flowing on the shell side. (The geothermal fluid is supplied from GTF Well 6-2, and enters the HCRF at a temperature between about 312 and 322°F.) The high-pressure working fluid vapor leaving the supercritical heaters can either be expanded through a turbine which drives an electrical

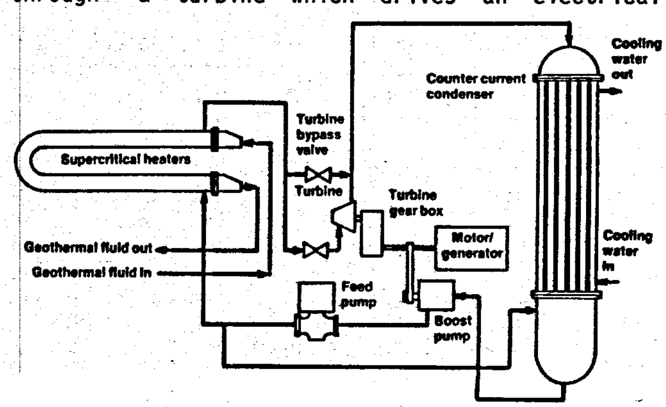


Figure 1: Schematic of Heat Cycle Research Facility

generator (power loop operating mode) or be expanded through a turbine bypass valve (thermal loop operating mode). The low-pressure vapor leaving the turbine or bypass valve is discharged to the condenser where it is desuperheated and condensed. The liquid condensate is then pumped back to the heaters, and the cycle is repeated. In the condenser, which is a counterflow in-tube condensing unit, currently in a vertical orientation, the heat rejected in condensing the working fluid vapor is transferred to cooling water on the shell-side of the unit. The cooling water is supplied from the GTF cooling-water system which includes a conventional wet cross-flow tower.

A major emphasis of the current phase of testing is on the performance of the supercritical heaters and the counterflow condenser with pure and mixed hydrocarbon working fluids. The heaters are arranged in a hairpin configuration with the preheater on the bottom and vapor generator on top (refer to Figure 1). The geothermal fluid and the working fluid have countercurrent flow paths through the heaters with the working fluid flow on the outside of the tubes. The preheater tube length is 28.21 feet (tubesheet face-to-face) with an outside shell diameter of 5.56 inches. It contains 27, 1/2-inch OD, 19 fins/inch, low-fin tubes made of admiralty brass. The vapor generator contains 39 of the same type of tube with a 29.21 ft length (tubesheet face-to-face) and an outside shell diameter of 6.63 inches. Both units were designed for a temperature and pressure of 350°F and 800 psi.

The condenser in its present orientation is a vertical unit also having countercurrent flow paths. The condensation occurs on the inside of 1/2-inch OD, internally finned tubes made of 90/10 cupro-nickel (Noranda forge fin No. 6, with six straight longitudinal fins inside each tube giving an inside to outside area ratio of 1.293). The vessel is 18 inches in diameter and contains 419 of the tubes which have a length of 18.54 ft (tubesheet face-to-face). The design temperature for the unit is 350°F with a tubeside design pressure of 350 psi and shell side design pressure of 175 psi. The cooling water enters the shell side just above the lower tubesheet and leaves the vessel just below the upper tubesheet. The working fluid condensate collects in the lower portion of the vessel (below the lower tubesheet), which acts as a hot well.

The supercritical heaters and the condenser have intermediate shell side temperature measurements, in addition to the inlet and outlet measurements on the shell and tube sides of each unit, to provide a more detailed unit temperature profile for comparing predicted and measured heat exchanger performance. The shell side of the supercritical heaters has five intermediate temperature sensors (two on the preheater, two on the vaporizer, and one between heaters). The shell side (cooling water) of the condenser has nine intermediate temperature sensors in addition to the inlet and outlet measurements.

The turbine-generator assembly was designed and built by Barber-Nichols Engineering, and consists of an axial-flow impulse turbine driving an induction motor/generater through a 6.135:1 speed-reduction gearbox; the working-fluid boost pump is driven from the generator drive shaft. The generator's rated speed is 3600 rpm, and the rated power of the assembly is about 75 KW. For the present nozzle area and turbine inlet state points, the turbine power produced is on the order of 40 KW.

EXPERIMENTAL APPROACH

The emphasis during the current phase of testing has been to investigate the performance of the supercritical heaters and the counter-flow, internally-finned condenser, particularly when mixed-hydrocarbon working fluids are used. First, baseline performance data is established with a single component working fluid. Then mixtures are tested in which the primary component is the fluid used in the baseline tests with increasing amounts of a secondary fluid. Two families of working fluids were tested: the isobutane/hexane family and the propane/isopentane family (the primary constituent given first for each family). The order of testing for each family is single component (primary constituent), 95%/5%, and 90%/10%. For each fluid, i.e., 95% isobutane/5% hexane, data were taken at four different heater pressures, two of which are above the critical pressure, one just below the critical pressure, and the last enough below the critical pressure to assure the heater is acting as a boiler. At each pressure, the flow rates of the working fluid, geothermal fluid, and cooling water were varied so that the heat loads, superheat levels, and temperature differences across the heat exchangers were varied. At each test condition, the composition of the working fluid was verified using a gas chromatograph analysis.

In operating the facility, generally the heater outlet vapor conditions are set along with the flow rate of the cooling water and either the working fluid or the geothermal fluid. The heater pressure is controlled whenever the turbine is not operating. The geothermal fluid flow rate or the working fluid flow rate is varied to provide the desired heater outlet vapor temperature. If a particular condenser inlet vapor condition is desired, the heater outlet temperature is varied until the desired condition is obtained. In general, expansion through the "dome" or two-phase region is not done either with the turbine operating (isentropically) or in the thermal loop mode (isenthalpically) unless necessary to provide specific condenser inlet conditions. However, several special tests were conducted in which the turbine inlet state was selected such that the expansion process passes through the two-phase region in order to investigate the effect of supersaturated expansion processes on turbine efficiency. To date, because of mechanical problems with the turbine assembly, including lube-oil pump failures and gear-box distortion, only a fraction of the planned turbine tests have been completed.

METHOD OF ANALYSIS

Heat Exchangers - The analysis of the heat exchanger data from these experiments had a two-fold purpose. First, data was obtained and verified for the phenomena of supercritical heating in a finned tube heat exchanger and the condensation of hydrocarbon mixtures inside finned tubes. Second, this data was used to determine how well a heater or condenser similar to those tested could be designed using standard techniques. To achieve these purposes, it was decided to use the computer codes developed by the Heat Transfer Research Institute (HTRI) to rate the exchangers, because these codes are commonly used for heat exchanger design, and a direct comparison between experiment and calculation will give a measure of how well the codes serve as design tools for this application.

Great accuracy in the thermodynamic and transport properties is needed because the temperatures of working fluid and geofluid approach each other during heating to within less that 5°F and even closer in the condenser. Standard references such as Starling (Reference 3) for thermodynamic properties of isobutane appeared to show some inaccuracy in data near the critical point. A new computer code developed by J. F. Ely at the U. S. National Bureau of Standards (NBS) (Reference 4) was used which calculates thermodynamic and transport properties for pure fluids and mixtures using an "Extended Corresponding States Theory" (Computer Code EXCST). The results obtained using Ely's properties gave more consistent energy balances than other codes available to us for calculation of properties of mixtures.

For the heaters the HTRI computer code ST-4 MOD 5.4, the shell-and-tube code with no phase change, was used. Previous investigators have indicated that a single-phase heat-transfer correlation is adequate to describe supercritical heating if variable fluid properties are taken into account (Reference 5). Unfortunately, this code uses average properties for a given exchanger and linear temperature profiles. At pressures slightly above the critical pressure, the thermodynamic and transport properties change quite rapidly with temperature. Very non-linear temperature distributions result within each heat exchanger along with large variations in the transport properties. In order to account for these variations, the heater was divided into six separate increments and the vaporizer into nine. The computer code assumes that each of these increments is an individual exchanger and applies end corrections to each increment. These end corrections were removed in a separate calculation. The clean overall heat transfer coefficients and temperature differences were determined, and fouling values consistent with the measured temperatures for each increment (three in each exchanger) were calculated.

The condenser results were analyzed using CST-1 MOD 2.0 (the HTRI condenser code). The thermodynamic properties (from the EXCST code) used in the analysis assumed completely mixed phases during the condensation (integral condensation). Because pressure measurements were not accurate enough to predict the behavior for the close approach temperatures encountered during the testing phase, the working fluid exit temperature was used as a reference. The analyses assumed that the fluid was saturated but completely condensed, and results were correlated in terms of the predicted condensing temperature minus the actual outlet temperature. However, it is recognized that in actuality the bubble-point temperature was somewhat higher (1°F) than the measured outlet (hot well) temperature because of apparent subcooling, due in part to noncondensibles in the hot well in addition to possible uncertainties in the thermodynamic properties.

Turbine - Turbine isentropic efficiencies were determined in two ways. First, the actual enthalpy change of the working fluid from the turbine inlet to discharge was evaluated from inlet and exhaust working-fluid state-point measurements, using the NBS thermodynamic properties. The actual enthalpy change was then divided by the isentropic change in enthalpy of the working fluid expanding from the turbine inlet state to the turbine exhaust pressure. Again, NBS properties were used. The second approach was to start with the wattmeter reading from the generator output (corrected for gearbox losses, generator efficiency and working fluid boost pump power consumption as provided by the manufacturer) to obtain turbine shaft power. The actual working-fluid enthalpy change was then calculated from the turbine shaft power divided by the working fluid flow rate. The isentropic enthalpy change and turbine efficiency were then calculated as for the first approach.

As discussed in some detail in Reference 6, turbine efficiency calculated by the first approach results in considerable scatter because of the high sensitivity of anthalpy to small errors in temperature and pressure measurements and/or thermodynamic properties. this sensitivity is amplified in the present tests,particularly those in which the turbine expansions "pass through the two-phase region," because of the close proximity of the turbine inlet state to the critical point and the large magnitudes of specific heat and uncertainties of properties in that region. Trends shown by the efficiencies based on wattmeter readings are considered to be more reliable. Both approaches for calculating efficiency are being used in the presentation and interpretation of experimental results.

RESULTS

The heater data was analyzed for at least 6 runs for each working fluid and the condenser for at least 10. The working fluids for which data are analyzed at this time are: isobutane, propane, 95/5% propane-isopentane mixture and 90/10% propane-isopentane. For the heaters, tests at the nominal pressure (slightly supercritical for optimum thermodynamic performance) with 100, 75 and 50% of nominal working fluid flow were analyzed along with one run at a higher pressure and one at a lower (subcritical) pressure. The system operated well at slightly subcritical pressures, but there was an indication from energy balances that all of the liquid may not have been vaporized. Although the computer code was not set up to handle boiling heat transfer, specifically, some boiling tests were analyzed. These results are not presented in detail because the primary purpose of the testing was to determine heater performance at supercritical pressure. The condenser tests analyzed at this time include the nominal working fluid flow, with cooling water flows of 125, 100, and 75% of nominal and several tests which varied the superheat entering the condenser from its nominal value.

Heaters - Agreement between the calculated temperature distribution in the heater-vaporizer heat exchangers and measured was quite good. Figure 2 shows this comparison for a working fluid containing 10% (by mass) isopentane and 90% propane. Flow and temperature conditions are close to the design values and the pressure is uniform in each heat exchanger. The agreement of this curve with the experimentally measured temperatures is typical of the supercritical and boiling runs with each working fluid. Measured temperatures are within a few degrees F of the calculated values for all cases.

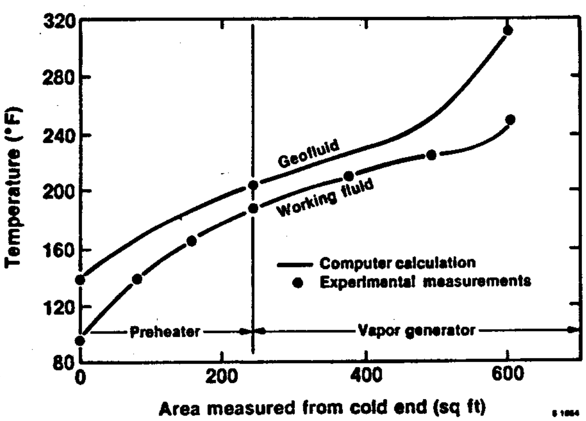


Figure 2: Heating 90-10% Propane-Isopentane

Figure 3 shows the calculated fouling resistances referred to the inside area (geothermal-side), where it is expected that the major portion of the fouling will occur. The results are shown for each heat exchanger separately, and plotted with time of operation of the facility. The time at which each fluid was tested is noted across the top of the curve, progressing from isobutane to propane and then to 95/5% and 90/10% mixtures of propane and isopentane. The boiling tests (slightly subcritical working fluid pressures) and those points with energy balances in error greater than 7% were omitted from the plot. The preheater is shown with squares and the vapor generator with triangles. The solid line is a least-squares fit of a quadratic curve for all of the data except for the boiling tests and those tests whose energy balance was out by more than 7%. An alternate interpretation of the data is shown with the dashed line. This interpretation assumes that the fouling has leveled off and is relatively constant for all of the propane and propane mixture tests. More data is needed to establish which behavior is actually being observed.

The fact that the calculated fouling factor is negative at early times in the test series is an indication that the computer code was slightly under-predicting the heat transfer coefficient in the clean configuration. The clean overall heat transfer coefficient for these fluids at nominal conditions is between 100 and 140 Btu/hr ft^2°F. This means that the code is under-predicting the heat transfer by 12 to 18% at the clean condition if the solid curve is correct and 16 to 24% if the dashed curve is correct. This implies a conservatism with respect to design, in that if the code is used for design, the actual area needed will be about 12 to 24% less than the area calculated by the code.

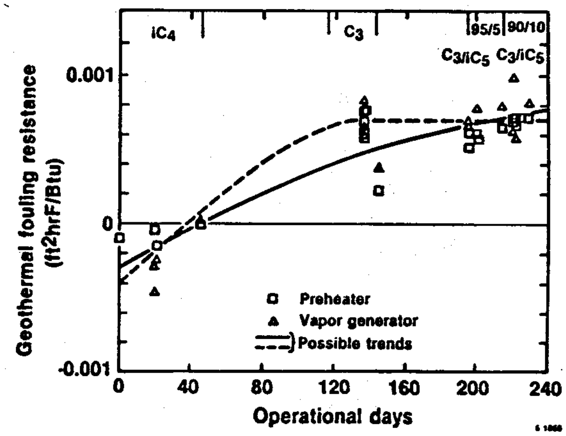
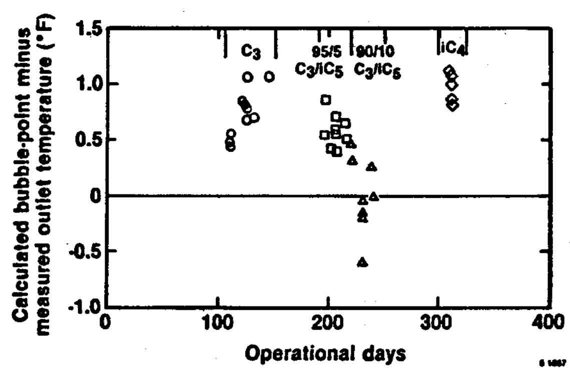


Figure 3: Fouling in Geothermal Heat Exchanger

Condenser - The method of analysis was to determine the condensing temperature (bubble point temperature) necessary to give the actual condenser area using the computer code. Figure 4 shows the difference between the computer-calculated condensing temperature and the measured condenser outlet temperature for propane, the propane-isopentane mixtures and isobutane. The time scale on this figure is the same as for the heater fouling curve. Although the temperature difference is lowest for the 90/10% propane-isopentane tests, there is no real trend evident in this data. The results indicate that the difference ranges between -0.2°F and 1.1°F with one exception. No evidence of fouling is shown or was expected to be apparent in the condenser data. The calculations assumed a clean heat exchanger. If cooling water fouling of 0.001 hr ft^2°F/Btu was



Figue 4: Correlation of Calculated Condensing Temperature

added, the overall heat transfer coefficient would change approximately 2.5%, well within the experimental scatter of the data. These results would indicate that if one designed a similar condenser using the HTRI code CST-1, the NBS thermophysical properties, and the assumption that the fluid left the condenser at the bubble point, the resulting condenser would produce a condensing temperature lower than the design value by 0.45 ± 0.65^oF. This is well within the uncertainty of the experimental measurements, and constitutes a slightly conservative design method.

Figure 5 shows the temperature distribution in the condenser with a 90/10% propane-isopentane mixture at the nominal conditions (the same test as was shown for the heater). The circles indicate experimental measurements of the cooling water temperature. The curves are from the computer-code calculation. The largest difference between the measured and calculated values is approximately 2^oF. The flow regimes predicted by the computer code are shown on the figure. In the desuperheating region the local overall heat transfer coefficient is 39 Btu/hr $ft^{2o}F$. In the shear-controlled region it varies from 90 to 87, while in the gravity-controlled regions, between 87 and 81. The average overall heat transfer coefficient was 81.2 Btu/hr $ft^{2o}F$, and the average mean temperature difference was 9.2^oF.

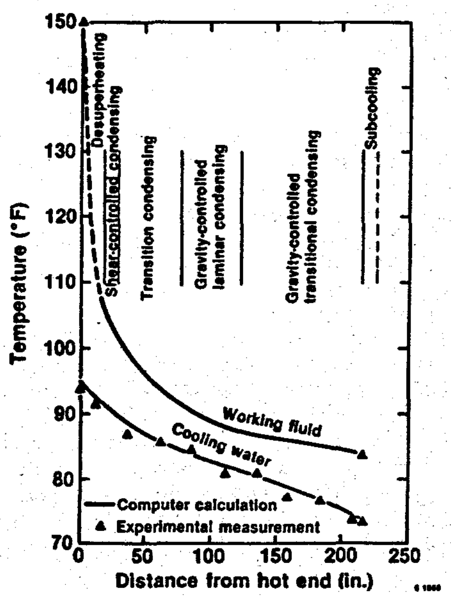


Figure 5: Condensing 90-10% Propane-Isopentane

Figure 6 shows a similar curve for pure propane condensing. Note that the approach or pinch-point is much closer for the pure fluid than for the mixture, 1.5^oF compared to 6^oF, and creates a much lower mean temperature difference in the desuperheating and initial condensing regions for the pure fluid. This gives rise to a much larger desuperheating region for the pure fluid as well as low heat fluxes in the shear-controlled condensing region even though the local heat transfer coefficient is quite high in that region. The local overall heat transfer coefficients are: 28 Btu/hr $ft^{2o}F$ in the desuperheating region, from 188 to 128 Btu/hr $ft^{2o}F$ in the shear-controlled region, from 124 to 103 in the transition region, and from 98 to 93 in the gravity-controlled region. The average overall heat transfer coefficient is 92.8 Btu/hr $ft^{2o}F$, and the average mean temperature difference is 7.4^oF. Note that although the overall heat transfer coefficient is higher for the pure fluid by 14.3%, the lower mean temperature difference more than compensated for it.

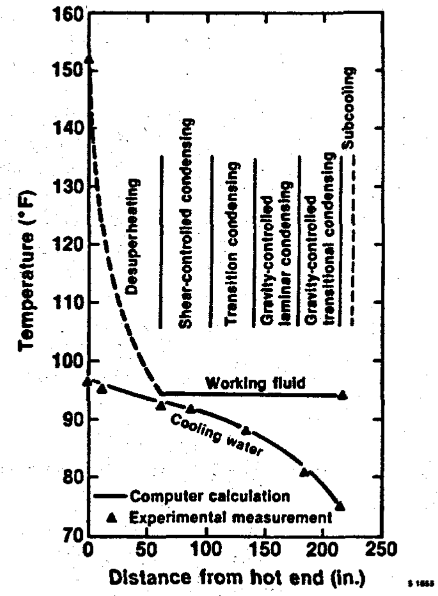


Figure 6: Condensing Pure Propane

Figure 7 shows the effect of heat load on the approach of the condensing (bubble point) temperature to the inlet cooling water temperature. The curves, which are least-squares fits of the experimental data, show the three propane-family working fluids. Note that the more isopentane in the mixture, the closer the approach to the cooling water temperature. This is primarily because the temperature difference between fluids is much closer to a constant value throughout the heat

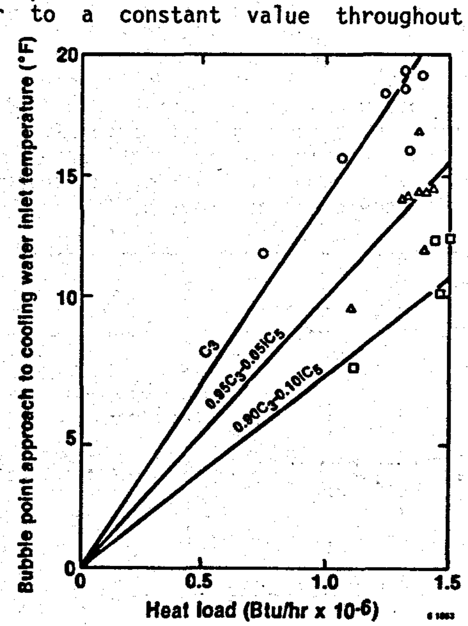


Figure 7: Condenser Approach Temperature

exchanger, and in the mean, larger for the 90/10% mixture.

Turbine - A series of six turbine-expansion tests with isobutane working fluid has been run with all tests having essentially the same turbine inlet and exhaust pressures. Two of the expansions remained in pure-vapor equilibrium states throughout; during the other four expansions the turbine inlet entropy was reduced such that the isentropic nozzle flow (outside of the boundary layer) reached equilibrium moisture conditions ranging from about 7 to 22%. Figure 8 is a schematic temperature - entropy diagram for isobutane showing the six turbine expansion processes. The vertical lines through the six inlet state points (at 560 psia) represent the nozzle expansions to the exit pressure (60 psia). Since the turbine is the impulse type, pressure in the blading is approximately constant; the constant pressure lines connecting the lower end of the vertical line and the lower end of the inclined line (turbine exhaust state) for each inlet condition, represent the irreversible flows through the blading.

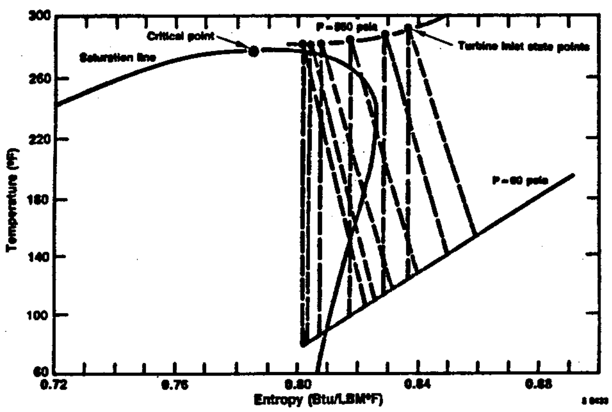


Figure 8: Supersaturated Expansion Conditions, Isobutane

Turbine isentropic efficiency has been plotted as a function of turbine inlet entropy in Figure 9 for these six tests. Values of maximum equilibrium moisture reached during each of the nozzle expansions can be estimated from the vertical lines shown as an auxiliary scale. Efficiencies have been calculated, as described earlier, using the wattmeter reading (solid-faired

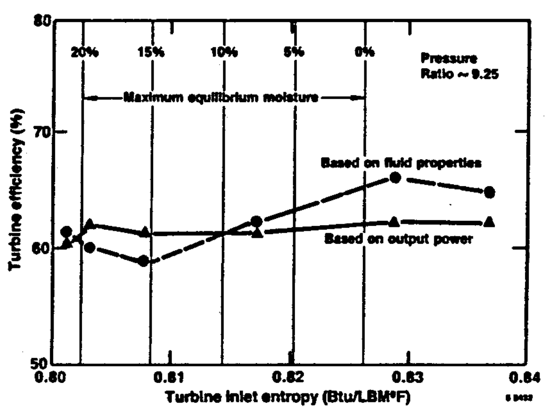


Figure 9: Turbine Performance for Supersaturated Expansions, Isobutane

triangles), and working-fluid state-point measurements (dash-faired circles).. Uncertainties in calculated efficiency, and particularly in trends of calculated efficiency, are being estimated for both calculational approaches (solid and dashed curves) considering both insrumentation accuracy and uncertainty in thermodynamic properties. Preliminary results indicate that values of efficiency predicted from state-point properties could show scatter as large as ± 5.6%; efficiencies based on wattmeter readings should contain about 1/4 of that scatter (± 1.4%).

Unknowns that can affect the relative levels of the two efficiency curves include the precise magnitudes of gear-box losses, pump power consumption, and generator efficiency for the solid-faired curve. For the dash-faired curve, the fraction of turbine-bearing and windage losses that find their way into the exhaust gas enthalpy (as opposed to losses transferred to the lube oil, and from the turbine housing to the atmosphere) are not precisely known. Because of these considerations, interpretation of the results is based on the trends shown by the two efficiency curves rather than their relative magnitudes. Another factor which must be considered in the interpretation of the dashed curve, is that the curve was calculated assuming no moisture in the turbine exhaust. Moisture present would reduce the calculated efficiency below its real value, and could result in a misleading trend on the plot.

In summary, it was found that turbine isentropic efficiencies under these test conditions are very difficult to evaluate from working-fluid state-point properties, and that trends in efficiency derived from the wattmeter readings constitute the most reliable current measure of performance. Accordingly, it was concluded that the present results do not show turbine-efficiency degradation associated with expanding through the two phase region. Future two-dimensional nozzle tests, which are planned with extensive wall pressure instrumentation and with a LASER system to illuminate condensate droplets formed, should provide a valuable supplement to these and other supersaturated-expansion turbine tests which will be conducted during the next several months.

CONCLUSIONS

The following conclusions are made as a result of the work to date with the HCRF supercritical cycle experiments:

1. The use of the HTRI computer code ST-4 with the NBS properties to design a supercritical heater (with an incremental analysis) should give excellent results. These experiments indicate an area approximately 15 to 25% on the conservative side.

2. Fouling on the geothermal side of the heater increased to a thermal resistance level of approximately 0.001 hr ft^2°F/Btu in approximately 240 days of operation. At this time it is not clear whether it has reached

an asymptotic value.

3. The use of the HTRI computer code CST-1 with the NBS thermophysical properties and the assumption of no subcooling gives a design which will produce a condensing temperature within -1.2°F to +0.2°F of the design condensing temperature (bubble point).

4. Even though the average heat transfer coefficient on the condensing side was lower, condensing of mixtures gave a closer approach to the cooling water inlet temperature than did pure fluids. This result was in part due to the higher mean temperature difference during desuperheating and condensing for the mixture.

5. Preliminary supersaturated turbine expansion tests have not shown degradation in turbine efficiency associated with expanding through the two-phase region.

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SCALE CONTROL IN GEOPRESSURED ENERGY PRODUCTION

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ABSTRACT

When natural gas or oil wells produce a large amount of brine/water along with the hydrocarbon, precipitation of calcium carbonate (scale) may be a problem. This is especially true in the Texas-Louisiana Gulf Coast area where production is frequently from deep, hot, high-pressure wells. The general mechanism of scale formation is understood, and various techniques are available to control it, e.g., chemical inhibitors. The scale-forming tendency may be calculated mathematically if the initial and final conditions are adequately known. A saturation index (SI) has been developed to quantify the scaling tendency of any calcium carbonate brine. A semiquantitative understanding of the processes of scale formation at various SI levels has been developed by the authors via both laboratory and field observations. In order to eliminate the uncertainty associated with calculated SI values, a ΔSI scheme was developed.

A series of tests, 20 to 30 days each, were run at the DOE Gladys McCall No. 1 geopressured well near Grand Chenier, Louisiana. Scale formation has been successfully controlled in the surface equipment by threshold scale inhibitors. When the saturation index increased to above about 1.2 to 1.4, scale formed in the production tubing. This severely limited the feasible sustained production rate. Therefore, an inhibitor squeeze was designed and tested in the laboratory and in the field. The inhibitor squeeze treatment has been successful, allowing production to increase by about 100% without scale formation in the tubing or surface equipment.

INTRODUCTION

When natural gas or oil wells produce large volumes of brine/water along with the hydrocarbon, precipitation of calcium carbonate (scale) may be a problem. This is especially true in the Texas-Louisiana Gulf Coast area where production is frequently from deep, hot, high pressure wells. In these reservoirs the water phase is usually saturated with respect to carbonate calcium and dissolved carbon dioxide. When brine is produced, the pressure and temperature are lowered, carbon dioxide comes out of solution, and the shift in conditions causes calcium carbonate to precipitate as scale on the inside surfaces of tubulars and processing equipment. Since the scale degrades production performance, it must be prevented or controlled.

The general mechanism of scale formation is understood, and various techniques are available to control it, e.g., chemical inhibitors (Tomson, 1983). The use of inhibitors in preventing scale formation has been studied extensively, both in the laboratory and in the field. For a review of this data see Tomson et al. (1984) and Matty et al. (1985). The scale-forming tendency may be calculated mathematically if the initial and final conditions are adequately known. A saturation index (SI) has been developed to quantify the scaling tendency of any calcium carbonate brine (Oddo and Tomson, 1982). The value of the SI for a given brine can be calculated easily from the results of a few simple tests which can be run in the field. A series of nomographs have been developed which provide a simple graphical means of calculating the saturation index (Matty et al., 1985).

A simplified brine analysis kit for use by well operators has been developed (Matty et al., 1985). This kit contains tests for alkalinity, calcium, and chloride and is precise enough to allow the detection of the early onset of scale formation. The kit and the nomographs provide a simple and accurate means of measuring brine chemistry, determining the scaling potential, and monitoring brine changes which may indicate scaling.

SATURATED INDEX AND SCALE FORMATION

It is generally assumed that there is some correlation between high SI values and precipitation rate, but there has been only limited success in attempting to establish a quantitative relationship. A semiquantitative understanding of the processes of scale formation at various SI levels has been developed by the authors via both laboratory and field observations (see Tomson et al., 1985). In order to eliminate the uncertainty associated with calculated SI values, a ΔSI scheme was developed. An advantage of this approach is that systematic errors, whether from measurement or theory in the absolute SI values, are likely eliminated in the final ΔSI value. In order to compare scale phenomena from one well to another, ΔSI values should be calculated relative to downhole shut-in conditions at the beginning of production. Under these conditions it can be assumed that the brine is at equilibrium with respect to $CaCO_3$.

Figure 1 represents a semiquantitative interpretation of the processes which take place at various ΔSI values and has been developed from both laboratory and field observations.

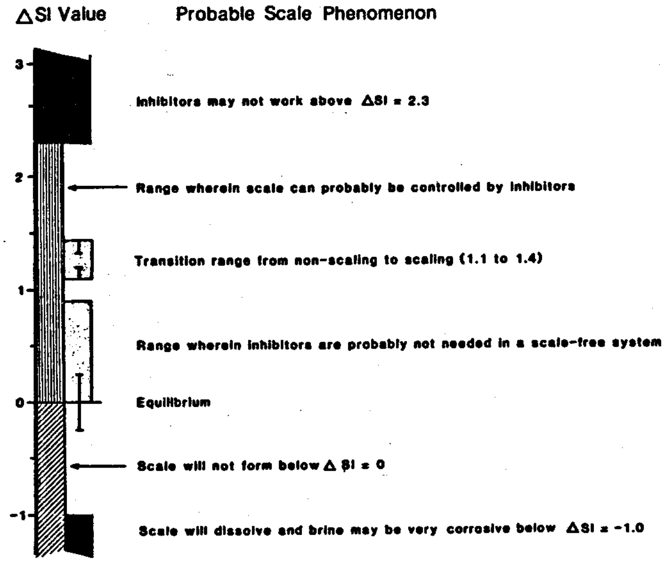

FIGURE 1

Depiction of ΔSI values and corresponding scale-related phenomena for $CaCO_3$ scale-forming brines.

The only point which can be calculated theoretically is the equilibrium point at zero saturation index. Negative ΔSI values typically result from addition of acid to the brine or from a drop in temperature, either of which will lower the brine pH. Typical pHs are from 4.2 to 4.9 and a drop of ΔSI by one unit via acid addition or T drop would result in a drop of pH by about one unit to 3.2 to 3.9. Generally, brines of this pH range are very corrosive. The 0.9 ΔSI value, indicating no scale with certainty, is taken from the shut-in surface values of wells and numerous laboratory experiments using flow-through apparatus similar to that described in Oddo, Sloan and Tomson (1982). Probably the most critical range of ΔSI values is from 1.1 to 1.4 ΔSI, which is the range over which a transition is made from probably non-scaling to probably scaling, in the absence of inhibitors. This delineates the minimum surface pressure at which downhole scale will be avoided, which in turn may limit the production rate. The upper limits at which inhibitors are no longer effective are the most difficult to establish. The range of 2.3 to 2.5 is taken from measurements made on brine at the top of the disposal well, after passing through a separator. Formation of pseudoscale (calcium-inhibitor salt) generally limits the amount of inhibitor used. However, results of mixed-inhibitor tests indicate that a blend of several different inhibitors may provide protection against scaling at higher ΔSI values while avoiding the problem of pseudo-scale formation (see Matty et al., 1985).

Table 1 presents the overall brine chemistry of the Technadril-Fenix & Scisson DOE

Table 1. Brine Chemistry of Gladys McCall No. 1 Well

Parameter	Value
Alkalinity (as HCO_3-)	547 mg/l
Calcium	4,130 mg/l
Chloride	57,900 mg/l
CO_2 gas (volume %)	7.6 %
Hardness (as $CaCO_3$)	12,000 mg/l
Iron	35 mg/l
pH (calculated) surface	4.68
bottom hole	4.13
Pressure surface	5,920 psia
bottom hole	12,910 psia
Silica (as SiO_2)	135 mg/l
Specific Conductance	126,360 μmhos/cm
TDS	96,340 mg/l
Temperature	298°F (148°C)

Gladys McCall No. 1 well near Grand Chenier, Louisiana. A series of tests, 20 to 30 days each, were run at this well in order to establish a better correlation between production rate and scale formation. Results appear in Table 2. Previous results had shown that when the flow rate was 15,000 b/d or less, no scale formed in the 5.25 in. production tubing. Therefore, tests were planned at 15, 20, and 25,000 b/d. The flow rate was maintained at the desired level by adjusting the choke about once per week. When the choke was opened slightly, the surface pressure generally dropped by 50 to 90 psi; however, these pressure changes were not used in the calculations of average daily change in surface pressure (Table 2, Column 5). The average daily decline in reservoir pressure was obtained by measuring the surface pressure within a few minutes of shut-in or the first and last day of each test period. The measured reservoir decline rates were within expected error of the calculated values (Durrett, 1984). The difference between Columns 5 and 6 was assumed to correspond to the increase in frictional resistance due to scale formation in the production tubing. Scale formation was confirmed by caliper logs, then the scale was removed by acid treatment with inhibited 15% HCl. The changes in SI (Table 2, Column 8) were determined using the pressures in Column 4 and the SI nomographs. Other test periods produced results similar to those reported in Table 2. From the ΔSI values in Column 8, it is concluded that, for this well, the range in which scale is likely to form is between ΔSI of 1.10 and 1.30.

Thus, although scale had been successfully controlled in the surface equipment by injection of scale inhibitors, production of gas from the Galdys McCall well was limited by the formation of scale downhole. Methods of downhole treatment were then investigated as a solution to the problem.

INHIBITOR SQUEEZE AT GLADYS MCCALL

Inhibitor squeeze techniques have been used in the past for the control of scale and corrosion in low flow rate oil wells, but modification of existing technology has been necessary for application to high water/brine production geopressured gas wells. The Gladys

Table 2. Summary of Production Data and ΔSI Values During Long Term Tests at Gladys McCall No. 1 Well Performed to Establish a Correlation Between Brine Production Rate and Scale Formation

1	2	3	4	5	6	7	8
Study Period	No. Days in Study Period	Avg. Prod. (B/D)	Range of Surface Pressure (PSIA)	Avg. Meas. Chg. in Surface Pressure (ΔPSI/D)	Avg. Reservior Decline (ΔPSI/D)	Avg. Chg. in Surf. Pressure due to scale Formation (ΔPSI/D)	Range of ΔSI at Surface
June, July 1984	32	20,219	3549-2743	15.3	7.8(7.8)*	7.5	1.30-1.25
July, Aug 1984	34	15,411	4238-4124	4.4	5.8(5.8)	0	1.10-1.12
Aug, Sept 1984	19	24,574	2718-2200	31.9	8.7(9.6)	23.2	1.50-1.30

*The values in paranthesis were calculated using a reservoir simulation model (Durrett, 1984).

McCall well posed an additional challenge due to the absence of calcite in the producing formation. In general, an inhibitor "pill" mixture is injected into the formation, with the expected result of a long-lasting, slow dissolution/desorption of inhibitor in sufficient concentration in the produced fluid to inhibit the precipitation of scale both downhole and in the surface equipment.

Experiments were run in the laboratory using core samples from Gladys McCall, simulating various inhibitor squeeze regimes. It was found that a calcium chloride overflush, which reacted in the formation with the inhibitor to produce calcium-inhibitor salt, was necessary for the squeeze treatment to be effective. This result is illustrated in Figure 2. Laboratory and field tests also showed that the pill could not be mixed with the formation brine, or precipitation would occur before the fluids reached the formation, preventing injection into the formation. The prototype regime optimized in the laboratory was then used to design a pill for field testing.

The pill which was used is outlined in Table 3. The synthetic brines used as spacers were prepared according to stringent specifications. This was necessary to prevent premature precipitation of calcium-inhibitor

Table 3. Inhibitor Pill, Gladys McCall No. 1, June, 1985

Solution	Composition	Volume (Barrels)
NaCl	15%w	300
Pill	6%w Inhibitor in 15%w NaCl	100
NaCl	15%w	100
$CaCl_2$	10 ppg	100
NaCl	15%w	280*

*Only 20 barrels actually pumped into formation

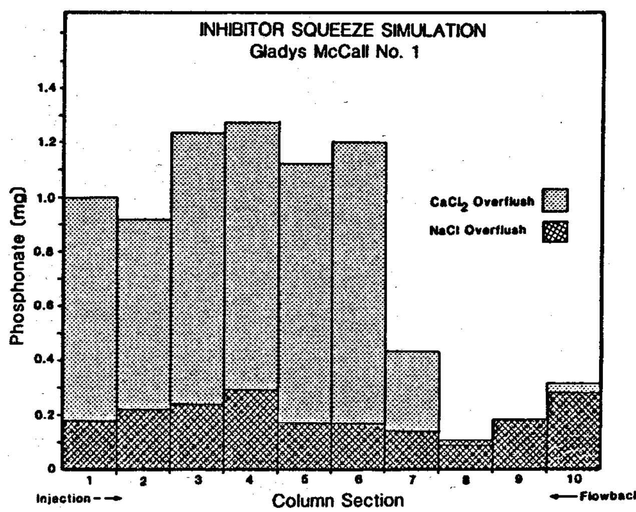

FIGURE 2

Results of laboratory squeeze simulation using core samples from the Galdys McCall No. 1 well. This represents amount of inhibitor remaining in the rock following injection and a short flowback, as a function of depth in the column. The increased effectiveness of the proposed pill with a calcium chloride overflush is significant.

salts and ferric hydroxides which thwarted previous inhibitor squeeze attempts. The pill was successfully injected, although only 20 barrels of the final sodium chloride afterflush reached the formation due to pressure buildup.

The treatment has been considered successful. Following the initial 48-hour flowback period (at a rate of 2,400 b/d) the production rate was increased to 25,000 b/d. This rate was maintained for 25 days with no adverse effects. The flow rate was then increased to 31,000 b/d on July 24, 1985. This production rate has been maintained since then with no apparent scale formation, based on observations of surface coupons and the absence of frictional pressure loss in the production tubing.

Trace element analyses were performed on 75 samples representing the first 4,800 barrels of fluid produced following the squeeze treatment. Representative results are shown in Figure 3. These data will be used in a numerical solution of fluid mixing in the formation, to refine the procedures used for pill injection. Inhibitor data (NH_4 and P values) indicate that about 60% of the inhibitor was returned immediately; this places a limit on the potential life of the squeeze.

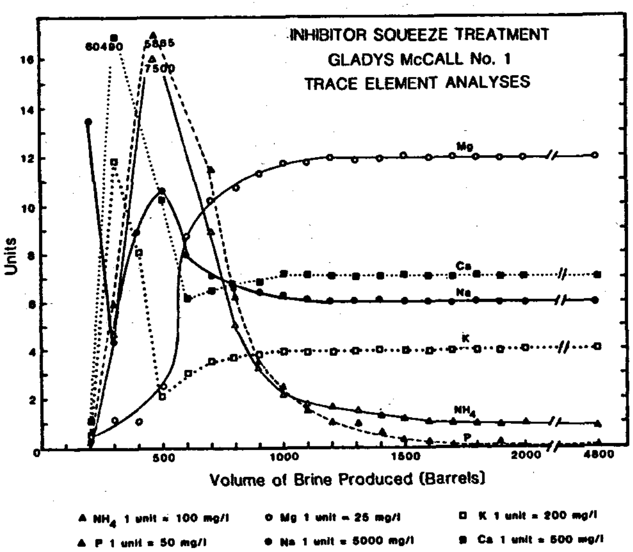

FIGURE 3

Trace element concentrations, inhibitor squeeze treatment, Gladys McCall No. 1 well. NH_4 and P track inhibitor; > 60% returned by 1,000 barrels out. Mg tracks percent of formation brine; dominates by 1,000 barrels out. Ca peak traces $CaCl_2$ overflush. K peak may indicate ion exchanbge for Ca on clays in formation. Na traces NaCl spacers relative to formation brine.

The success of this inhibitor squeeze treatment is important because it is the first time it has been accomplished in a quartz sand formation containing no calcite. It is also significant due to the very high rate of water production.

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OVERVIEW GEOPRESSURE PROGRAM

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ABSTRACT

The Department of Energy has been studying geopressured-geothermal aquifers to evaluate the size of the resource and the possibilities of utilizing the chemical, thermal, and hydraulic energies contained in the brine. The work to date has shown that the potential resource is large (hundreds to thousands of quads of energy) and that it can be produced at sustained rates of over 30,000 barrels per day. Reservoir behavior is not fully understood since the large reservoirs appear to increase in size with increased production.

The next phase of the study will be long term tests that should give a better understanding of reservoir behavior. Future tests will also include a joint experiment with EPRI to combine the thermal energy of the hot brine with the chemical energy of the methane to maximize the amount of electricity which can be produced.

INTRODUCTION

Geopressured aquifers are underground reservoirs of hot, pressurized waters that contain methane in solution. Such geopressured-geothermal reservoirs are known to occur along the Gulf of Mexico Coast, the Pacific west Coast, in Appalachia, and in deep sedimentary basins elsewhere in the United States. The Department of Energy has been studying the technical problems associated with finding, evaluating and using these energy resources since 1975.

The initial target for the Department of Energy's Geopressured-Geothermal Program has been the methane in solution from resource areas in the onshore coastal areas of Texas and Louisiana.

These coastal areas were selected because of the high pressures and temperatures encountered in normal oil and gas drilling which indicated that similarly located aquifers would also have high pressures and temperatures. Thus the methane content of the aquifers should be higher and the wells should be relatively easy to produce due to the excessive pressure.

The geopressured-geothermal development well sites were chosen because of the reservoirs' large sizes and potential ease of energy recovery relative to the contained thermal and hydraulic energy, plus the large data base available from oil and gas exploration in this area. Subsequent efforts will be directed toward the technology needed to utilize the thermal and hydraulic energy in the geopressured resources.

The geopressured program has operated successfully since its inception under the direction of the Nevada Operations Office of the Department of Energy. During this period the resource size has been evaluated and basic research has been conducted on the problems associated with flowing wells and extracting energy from the resource. The remaining work planned for the program will be directed by the Idaho Operations Office of the Department of Energy.

SUMMARY OF PREVIOUS WORK

The Department of Energy has been studying geopressured aquifers to evaluate the technical problems associated with finding, assessing, and utilizing these resources. Specific goals of the program have been to define the physical and chemical properties of the geopressured-geothermal resource, and to establish the technical feasibility of extracting and utilizing the chemical, thermal, and hydraulic energies contained in geopressured brines. The work to date has provided the following results:

- The geopressured-geothermal resource base contains tens of thousands of quads of chemical and thermal energy in place.
- The geopressured-geothermal brine in general is saturated with methane
- The brine can be produced at rates in excess of 30,000 barrels/day.
- It is feasible to separate the dissolved gas from the brine by standard gravity separation.
- Spent brine may readily be injected into shallower saline aquifers at rates comparable to production rates.
- Brine may be readily reinjected into the producing aquifer with only a small increase in pressure.
- Permeability of the reservoir rocks to brine is typically three to five times greater than that expected for gas bearing sandstones.
- Extensive brine reservoirs exist in conjunction with the expected small sized reservoirs normally found on structures in the course of oil and gas drilling.

- Conventional reservoir engineering techniques are not adequate to assess the size of brine reservoirs or to predict the decline in reservoir pressure that occurs from flowing a well. Long term flow data indicate the reservoirs could be from two to ten times larger than initial predictions would indicate.

- No adverse environmental effects have been detected.

FUTURE PROGRAM SUMMARY

A five year program has been planned by the Department of Energy to help resolve the technical issues which remain in conjunction with geopressured-geothermal energy utilization. Priority tasks are as follows:

- Increase our basic understanding of the geopressured-geothermal reservoirs.
  - role of oil and gas in reservoir depletion
  - significance of rock compression and creep in reservoir performance
  - effect of shale dewatering on reservoir production
  - effect of brine leakage across faults

- Improve our ability to predict reservoir size and flow capabilities from geology, well logs, and well test data.

- Verify that geopressured-geothermal wells can be depended on as a long term reliable source of energy for electric power or direct heat applications.
  - rework Pleasant Bayou well and use a portion of the brine production to carry out the EPRI electric power generation test

- Assure that there are no adverse environmental effects from the long term use of geopressured-geothermal energy.

FY-85 ACCOMPLISHMENTS

Program Management

The geopressured-geothermal program was transferred from the Nevada Operations Office of the Department of Energy to the Idaho Operations Office smoothly and efficiently. All programs were continued with no major interruptions. A new operating contractor was selected to carry out the FY-86 program. The transfer of the geopressured-geothermal program is a model example of a DOE field office cooperative effort.

Well Operations

The Gladys McCall well has operated at 94.5 percent on line time during FY-85. On August 10 the ten millionth barrel of fluid was produced and, if production can be maintained at the current rate, the well will have produced over 14 million barrels of brine by the end of 1985.

The Gladys McCall well had been restricted to a flow rate of 15,000 barrels of brine per day to prevent deposition of $CaCO_3$ scale. However, the squeezing of a phosphonate pill into the reservoir allowed brine production to be increased to over 30,000 B/D with no evidence of scale formation. Since the pill application, over 1-1/2 million barrels of brine have been produced.

Bottom hole pressure tests and pressure buildup measurements were again taken in the Gladys McCall well. These measurements, along with production data, indicated a reservoir of over two billion barrels compared to earlier reservoir engineering estimates of 500 million barrels in the #8 sand section. Heavy oil was detected in the brine production during the year and an automatic system was installed to collect the oil. Analysis of the oil shows it to be highly aromatic.

The Pleasant Bayou and Hulin wells were idle during the year. Both wells were monitored for pressure buildup above the mud, and some buildups were noted. Studies were completed on retubing both wells and based on these studies 7 inch tubing has been programmed for the Pleasant Bayou well. The 7 inch tubing is planned for Pleasant Bayou so that the well can be produced at maximum flow rates.

Research Results

Reservoir analyses are being conducted at the University of Texas at Austin, UTA, and at S-Cubed in San Diego. Both groups have developed models of geopressured-geothermal reservoirs and are studying which of the potential drive mechanisms, (i.e., shale dewatering, a gas cap, fault leakage, or rock creep) best explains the unexpectedly slow decline in reservoir pressure that has been measured. Studies at UTA, LLL, USWL, and LBL are in progress to analyze and explain the oil found in all geopressured reservoirs tested to date. Work is also in progress at UTA to develop an automated system for monitoring and interpreting mud salinity. A data bank of well log data has been computerized and made available to the public by UTA, which also has established a major computerized bibliography of geopressured-geothermal technical literature, including abstracts.

At LSU environmental monitoring around geopressured test wells has shown that, to date, the production and disposal of geopressured fluids has not resulted in any adverse environmental effects.

Texas Southern University provided assistance to Rice University in obtaining data to plan the successful scale inhibitor "pill" test at Gladys McCall. The USGS has continued to store geopressured data at their data center in Mississippi.

FY-86 PRIORITIES

The following summarizes priority tasks for FY-86:

1. Maintain all wells in a safe condition, rework the Pleasant Bayou well for high flow rates.

2. Continue environmental monitoring to assure no adverse consequences result from the geopressured well testing.

3. Continue research on the basic understanding of geopressured reservoirs.

4. Initiate installation of the EPRI electric power generator system at the Pleasant Bayou site.

5. Continue long term testing of the Gladys McCall well. If the scaling protection afforded by the phosphonate pill ends, carry out another pill squeeze to insure high production rates without carbonate precipitation.

6. Conduct other pressure drawdown and buildup tests on Gladys McCall. These together with the production data should continue to give us a better fix on the actual volume of brine in contact with the well bore.

7. Initiate Hulin well design analysis. This well was given to the DOE by Superior Oil Co. when they depleted the gas sand at 21,500'. The well was drilled through a 500 foot geopressured-geothermal reservoir which should be at approximately 350 °F, 18,000 psi, and should contain somewhere between 40-50 cubic feet of methane per barrel of brine.

8. Initiate work on advanced concepts for generation of electric power from geopressured resources.

Conclusions

Technology developed in geopressured-geothermal brine production is critical to continued production from existing water drive gas reservoirs as they begin to produce water. Abandonment is largely due to fear of brine disposal costs and environmental red tape. In addition the precipitation of calcium carbonate often becomes a major problem in gas-water co-production. The successful application of the phosphonate pill to inhibit deposition of $CaCO_3$ at Gladys McCall shows that such scaling problems can be handled in sandstone reservoirs even when high brine production rates are encountered.

Water and hydrocarbon production technology is an across-the-board problem for all fluid energy resources. Geopressured-geothermal represents the limiting case for Geothermal and Petroleum extraction technology. Gepressured-geothermal research wells are unique in that they represent experiments where key production parameters can be held constant. This is exemplified by the discovery of aromatic condensate. This effect would be masked in a hydrocarbon productive well. Corrections to electric logs for brine salinity calculations and rock plasticity models would not be as apparent in conventional hydrocarbon wells. If an operational problem can be solved in a geopressured-geothermal well, it can be solved for any well.

Geopressured-geothermal resources are currently not exploited as primary exploration objectives. With $2.00 to $2.50/MCF gas it's hard to show a profit even on deep expensive gas reservoirs. However, if dry holes or depleted wells have penetrated extensive aquifers, their production may be profitable on an incremental investment basis. Wells like the Hulin prospect may be the key to bringing geopressured-geothermal development into common usage. Only when this technology has been developed can sound business decisions be made on whether to bring in the geopressured-geothermal reservoir as an additional source of income.

AN OVERVIEW OF GEOPRESSURED-GEOTHERMAL RESEARCH

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During the past year significant research developments have occurred at The University of Texas through the Center for Energy Studies (CES) and the Bureau of Economic Geology (BEG). Areas of interest include liquid hydrocarbon migration and subsidence studies through the BEG; and well-logging research, geothermal simulation, geothermal information systems, and rock mechanics research at the Center for Energy Studies.

Hydrocarbon migration, resulting in anomalous heavy hydrocarbon content in geothermal brines at Pleasant Bayou, appears to result from movement of hot, extremely saline brines upwelling from the Lower Frio along growth faults. These fluids result in the introduction of liquid hydrocarbons at shallower depths in the Upper Frio, as well as causing a distinct thermal anomaly [1].

Subsidence in coastal Texas appears consistent with recent surface faulting, either due to ground water withdrawal, or possibly due to petroleum reservoir fluid withdrawal. Such production may have regionally depressured sediments in the hydrothermal regime, resulting in reactivation of existing faults over structural highs. However, these results are not conclusive at this time and further attempts to better understand the role of fault reactivation continue [2].

Well-logging research has indicated extreme variation in mud resistivity during drilling. Log header data on Rm and Rmf often are at variance with actual Rm values while drilling by as much as 400%, causing extreme errors in calculations of water saturation and salinity. Methods to improve measurements of mud and filtrate resistivity while drilling continue; these include use of ion-selective electrodes, development of a mass balance equation for mud additives while drilling, and other techniques. It has been determined that the Overton formula for calculating Rmf from Rm is valid for lignosulfonate muds. This material is described in greater detail in a paper by Williams and Dunlap [3].

Two major data bases continue development in the Geothermal-Geopressured Information System (GGIS). The first concerns well logs, with more than twenty million curve feet of logs digitized at present. The data base contains log header information, geological and paleontological data, and drilling data, as well as log programs to analyze these data. The second consists of a bibliography and thesaurus containing some three volumes of abstracts of papers to date in the field of geopressured-geothermal energy. Additional information is found in Appendix I.

Rock mechanics research has concentrated on cores of shales and sandstones from geopressured zones. High-pressure test vessels have been modified to test triaxial creep and both uniaxial and triaxial compaction under restored state conditions of poorly consolidated shales as well as sandstones. An elastic-plastic compaction model has been developed for sandstones, and a model describing creep behavior is nearing completion (Appendix II).

In the area of reservoir simulation, recent work has focused on the Gladys McCall well in Louisiana, since it is the only well that has been on production this past year and is currently flowing at the rate of 31,000 barrels of water per day. This well has now produced more than 8×10^6 bbl of fluid, and the rate of depletion has decreased as the reservoir pressure has dropped. On the basis of conventional reservoir analysis methods (including history matching simulation), the reservoir volume at the end of the initial reservoir limits test was estimated to be 4.2×10^8 bbl, with a total production of 0.3×10^6 bbl. As production continued, revised estimates were increased to 3.0×10^9 bbl in the reservoir with a total production of 5.5×10^6 bbl. Current estimates are in the process of further revision, since the well has already produced more than the revised estimates. It appears that shale recharge is the most likely source of increased reservoir limits, and compressibilities appear to be at least two orders of magnitude higher than those originally postulated (5×10^6/psi). The productivity, gas/water ratio, and temperatures have remained steady throughout production, indicating that the potential for increased gas and heat recovery from these reservoirs may be considerably greater than originally anticipated.

APPENDIX I: DATA BASES
Robert R. Schneider and Kamy Sepehrnoori

Development of a Relational Data Base for Well and Reservoir Data

The efforts of this project have been focused on the development of a comprehensive relational data base that is designed to store data components which uniquely identify well and reservoir data. Additionally, the data model is designed with the flexibility to extend the data base to even larger logical structures such as fields or basins. The data model is designed to be as comprehensive as possible to ensure that the data base may serve both as an archive for historical data and as a source of data for further research such as use with a reservoir simulator.

Existing data bases at the Center for Energy Studies at The University of Texas at Austin have been of a hierarchical nature and have also been very specific in content. As an example, some twenty million curve feet of digitized well log data are available to local researchers. To manage these data, a data base was constructed which contains certain basic well information such as the well name and operator, a summary of the digitized well log information, and pointers to where that information may be found on some permanent storage medium. Other information one would expect to find with digitized well log information--such as drilling information or specific information on where the well was located--was kept in a separate data base that was used only for those types of data components.

There are many reasons for the diversity of data bases, the primary being that it was the most economical method, both in monetary and machine costs, at the time the data bases were constructed to store the data. As demands to access to the data grew, however, it became increasingly obvious that another method of storage would have to be devised so that both local researchers and researchers outside The University of Texas campus could access these data. For these reasons and others work was begun on the development of a comprehensive relational data model that would unify all of the existing data bases, provide data structures for storing all possible information that would be of interest to researchers in fields related to petroleum, and also ensure a high level of access to the data themselves [4].

It is important to make the distinction between a relational data model and the relational nature of the data structures. While the two are interconnected by the relational structures of the data model, as opposed to the relationships of the logical data structures, a full use of the data model is possible only by understanding the relationship of the data model to the logical structures of the data themselves.

In a relational data base, components are stored in what is basically a two-dimensional matrix of data values called a table. In this table individual data values are stored as rows, while data components are defined as columns, or domains, of the table. Related sets of components are stored in similar tables. As an example, values obtained during a run of drilling information may be stored in a single table. To relate each table of information, it is necessary to have a single or multiple keys that relate each component of the data. For each set of similar information, a table is then defined to store the data, and a set of keys is derived that uniquely identify the data components.

By using the definitions of the data model, it is then possible to impose the relationships of the logical data structures and the relationships among those logical data structures and others. Certain obvious groupings of data groups are easily defined, such as tables for drilling information, individual curve information, completions cards, scout tickets, well location, core information, geophysical surveys, paleontological information, production information, and other sets of information that are related to the data components which uniquely define a well.

These sets of information are then related by a set of keys in the data model so that the sum of these sets defines the total information known about an individual well. In the present definition of the data base, reservoirs are similarly defined by adding data sets that uniquely define a reservoir and the relationship between those reservoirs and the well information tables that were previously defined [5]. There are obvious extensions to higher level logical data structures such as fields and basins.

The attributes defined in each table of the data model are defined relative to the type of data stored in the data base. As an example, character values such as well names, operator names, reservoir names, state names, etc., are typed as being character data. Integer values such as API numbers, run numbers, township-range locations, etc., are typed as being integers. Floating point values such as mud resistivity values are typed as being floating. While the data model is only concerned with defining the attributes that are to be stored in the data base, many relational data base management systems allow a large degree of control over such machine-dependent functions as the width of an integer value, allowing it to be either an eight, sixteen, or thirty two bit value. These options may influence both the number and size of individual attributes that may be stored in a table.

The logical structure of the data model is defined such that individual tables are created. These define attributes necessary to describe a single grouping of data components which uniquely define some attribute of either a well or reservoir [6]. Individual tables are created which match logical groups of data attributes. Examples of such groupings are well information, drilling information, curve information, well location, core analysis, paleontology, scout tickets, completion cards, reservoir geologic descriptions, reservoir production history, and other groupings. Each of these tables is related to other tables by a set of keys that are used to define either wells or reservoirs. Keys used to relate well information are such attributes as the API number of the well or the run number for drilling information. Reservoir information is related by a key that is the reservoir identification key. Well information is related to reservoir information by a table that serves as a map between the well information tables and the reservoir information tables [7].

The data base developed by the Center for Energy Studies at The University of Texas at Austin is different from existing data bases in several ways. The primary way in which the data base differs from others on related topics is that it attempts to relate many subtopics of information together which are covered by the other data bases into one large, and complete, data base. As an example, several commercial data bases are available that cover such topics as well production, chemical and petrochemical information for wells, well locations, and other diverse topics. In the data base developed at the university, these topics are simply some of many components that may be found for any given well in the data base. To the best of our knowledge this is the most complete data base yet developed for well information.

Another manner in which the data base developed at The University of Texas differs from existing data bases is that it is relational both in structure and in information content. A commercial relational data base management system is used to store and retrieve the information from the data base. Relational data base management systems offer many advantages for the storing and retrieving of data. It is possible to construct several "views" of the data that meet application needs. In relational data bases, it is also easy to transfer data from one data base management system to another, thereby increasing the portability of the data base.

The data base is also relational in the sense that it defines relations among logical data structures such as wells and reservoirs. Using this approach it is possible to obtain information about a reservoir simply by examining the well information for wells which penetrate that reservoir. The data base is also designed in a way that it is easily expandable to higher level logical structures such as fields and basins.

The most important manner in which the data base differs from existing data bases is its portability. A primary goal in the design of the data base was to ensure the easy distribution of data from the data base. The relational structure of the data base adds to this since it is relatively simple to transfer data from one relational data base management system to another and also since relational data base management systems are commonly found on machines that are connected to networks.

In the event that is is not possible to access the data base through either of these methods, file structures have been designed that make it possible to distribute large, but limited, amounts of information from the data base over such common media as tapes or floppy disks. An example of these file structures would be digitized well log information files that contain well log header information with them.

Development of application programs that use the data base are already underway. An open-hole log analysis program has already been written which takes digitized log data files pointed to by the data base and allows the user to analyze data from those logs in several ways. Other application programs are also planned for development. These will range from simple programs to plot and correlate logs to more complex programs that will simulate reservoir behavior. All application programs will be designed to run on as many computer systems as possible, with the resources of the host computer system being the only limiting factor.

Another task that has been undertaken in regard to the data base is the addition of several tables which describe well blowout features [8]. This work was made possible through the funding of the Texas Petroleum Research Council in conjunction with the Texas Railroad Commission. These tables attempt to fully archive well conditions and history at the time of a well blowout. It is hoped that through the study of past well blowouts it will be possible to predict under what conditions a well may experience a blowout.

Developmental work on the data base is continuing with the goal of refining the descriptions of data components used in the data base. Efforts are also being made to make the data base available to outside users as quickly as possible. Future work will concentrate on adding higher level logical structures to the data base as well as increasing the content of the data base. All of these tasks are subject to funding that would allow work on the tasks and the purchase of equipment as needed.

Geopressured-Geothermal Bibliography

The Geopressured-Geothermal Bibliography provides researchers with data on more than 1,500 information sources concerned with geopressured-geothermal energy resources [9]. These information sources encompass reports, conference papers, journal articles, books, patents, and maps. The subject scope of the bibliography spans the following:

1. Geopressured resource assessment--geographical distribution, estimated reserves.
2. Geology, hydrology, and geochemistry of geopressured systems.
3. Geopressured exploration and exploration technology--geophysical, geological, geochemical, and hydrological methods of detecting and evaluating geopressured resources.
4. Geopressured reservoir engineering and drilling technology--drilling, development, and

production of wells; corrosion; well tests; and measurements.
5. Economic aspects--financial incentives, cost estimates, taxation, and economic feasibility of developing geopressured resources for commercial and/or residential use.
6. Environmental aspects--effects of geopressured development on air, water, and land environments, subsidence, noise, land use, and pollution.
7. Legal, institutional, and sociological aspects--effects of federal, state, and local laws and regulations on geopressured development, land use, and societal considerations.
8. Electrical and nonelectrical use.
9. Other energy sources, especially co-production, methane, and other fossil fuel reserves, associated with geopressured reservoirs.

The information sources included in the Bibliography date from the late 1960s to the present. Future editions will permit greater retrospective literature searching.

Structure of the Bibliography

The introduction explains the organization of the Bibliography and the content of individual entries. The main body of the bibliography comprises the citation extracts, or individual entries. Six indexes in the back of Volume II provide access by author, conference title, descriptor, journal title, report number, and sponsor. These indexes are arranged alphabetically and are cross-referenced by page number.

All available information is compiled to create an individual entry. The fullest citation will contain any pertinent components from: format (e.g., book, journal article, etc.); publisher; date of publication; author (personal and/or corporate); pagination; illustrative features (including bibliographical references); availability (the address to which inquiries or orders may be sent); descriptors (selected from the Thesaurus, discussed below); and abstract. A citation abstract may originate with the author or with the GGIS editor. Other information that appears is explained in the introduction to the Bibliography. A representative citation extract appears in Figure 1.

1224. GGIS-100311/R/ / /M/ / / / / .

Title- Semi-Annual Report on the Project to Design and Experimentally Test an Improved Geothermal Drill Bit
Author(s)- / Barker , L.M. / Green , Sidney / Maurer , William /
Publication date- January 1976
Pagination- 74 Pages
Report/patent- TID--28704
Available- NTIS
(Paper Copy)
(Microfiche)
Local Availability- CES
Sponsor- / U.S. Energy Research and Development Administration
E(10-1)1546 /
Corporate Author- Terra Tek, Inc.
Terra Tek, Inc. , Salt Lake City , Utah , USA
Auxiliary expression(s)-
Illus. / Diagram (7) / Graph (13) / Map (4) / Photo (1) /
Table
Ref.
Descriptor(s)- / Design / Drill bits / Elastomers / Geothermal drilling / High temperatrure / Laboratory testing / Seals / Steels /
Abstract by Author
Work was started on the effort to design and test an improved geothermal drill bit on May 19, 1975. Terra Tek, Inc., is the prime contractor, with Maurer Engineering as a subcontractor and Reed Tool Company providing informal industry participation. The major tasks of the Phase I effort are (1) failure mechanisms of existing bits, (2) new steels and new bearing design, and (3) new seals and lubricants. Considerable progress has been made in understanding the causes of premature drill-bit failure in the geothermal well drilling environment. As a result, there appears to be a high probability that very significant gains in drill-bit life can be achieved by optimizing the drill-bit materials and the design for operation at higher temperatures. Drill-bits of high-temperature steels are being fabricated, as well as a test chamber to simulate the geothermal environment. In addition, several basic properties of the candidate steels and of the conventional drill-bit steels have been gathered from the literature, and provisions have been made for completing the material property picture through a materials testing program at Terra Tek. Considerable background material has been gathered on the drill-bit seal problem and on candidate seal materials. Some seal materials have been selected for further testing, and seal tester is being designed to provide a very good simulation of the environment experienced by seals in geothermal well drill-bits.

Figure 1. SAMPLE CITATION EXTRACT

Geopressured Thesaurus

The Geopressured Thesaurus provides the researcher with a standardized vocabulary to facilitate subject access to the Geopressured-Geothermal Bibliography [10]. A standardized vocabulary unifies the varied "natural language" of a document and allows both general and specific subject indexing. The "descriptors" that compose this controlled vocabulary fit into a framework that is both hierarchical and correlative. Figure 2 presents a sample page from the Thesaurus.

BT refers to a descriptor "broader" than the heading (descriptor listed alphabetically as a main entry); NT refers to a descriptor more "narrow." USE instructs the researcher to use a different descriptor. The original descriptor (labeled here USE) may occur commonly in the literature; however, for reasons of uniformity, the latter descriptor must be chosen. RT, or "related term," guides the thesaurus user to other concepts that are closely related other than hierarchically.

SEE references require special mention, as they serve three purposes:

(1) Certain terms, such as PRESSURE and TEMPERATURE, are considered too broad for useful indexing and searching in a thesaurus of geopressure terms. Both terms, however, encompass many narrower terms. In the Geopressured Thesaurus this problem has been handled by grouping the narrower terms under the broader term with a SEE reference indicating that one or more of the narrower terms should be substituted for the broader term. For example:

PRESSURE
  SEE BOTTOM HOLE PRESSURE
    FLUID PRESSURE
    VAPOR PRESSURE

RT Well testing

Formation thickness
  BT1 Thickness
    BT2 Dimensions
  RT Isopach
  RT Overburden
  RT Stratigraphy

Formation water
  Use Interstitial water

Formations
  See Disposal formations
  See Disposal wells
  See Fractured reservoirs
  See Waste disposal
  See Well design

Fossil fuel power plants
  BT1 Thermal power plants
    BT2 Power plants

Fossil fuels
  BT1 Energy sources
  BT1 Fuels
  NT1 Coal
  NT1 Natural gas
  NT1 Petroleum
  RT Oil shale

Fouling
  RT Antifoulants
  RT Corrosion
  RT Demineralization
  RT Deposition
  RT Plugging
  RT Scaling
  RT Water pollution

Fracture
  See Ffg
  See Fracture properties
  See Rock properties

Fracture flow

Fracture properties
  BT1 Mechanical properties
  RT Cracks
  RT Failures
  RT Fractures
  RT Rock properties

Fractured formations
  Use Fractured reservoirs

Fractured reservoirs
  BT1 Reservoir rocks
    BT2 Rocks

Fractures
  RT Cracks
  RT Deformation
  RT Fissures
  RT Fracture properties

Fracturing
  NT1 Hydraulic fracturing
  Also see Reservoir
    engineering

Fragmental rocks
  Use Clastic rocks

Franciscan
  See California
  See Cretaceous Period
  See Jurassic Period
  See Mesozoic Era

Franciscan Formation
  RT California
  RT Cretaceous Period
  RT Jurassic Period
  RT Mesozoic Era

Francium
  BT1 Alkali metals
    BT2 Metals

Frasch sulfur process
  BT1 Recovery processes
  RT Sulfur

Free ground water
  Use Ground water

Free water
  BT1 Subsurface waters
  RT Artesian water
  RT Capillary water
  RT Ground water
  RT Hygroscopic water
  RT Permeability
  RT Vadose water

Freezing
  See Freezing potential
  See Melting point

Freezing point

Figure 2. SAMPLE FROM THESAURUS

(2) SEE refers the reader away from a verbal fragment generated by the computer when the system encounters a compound term. The fragment itself is not a legitimate descriptor, so the accompanying SEE reference leads to the appropriate compound term(s). For example:

MECHANICAL
  SEE MECHANICAL PROPERTIES

If the resulting compound term is not itself a legitimate descriptor, the verbal fragment will be referred directly to the correct term by means of a SEE reference. For example:

ACID
  SEE ACIDIZATION
ACID TREATMENT
  USE ACIDIZATION
TREATMENT
  SEE ACIDIZATION

(3) A SEE reference under a verbal fragment also will indicate related terms listed under the correct compound term. For example:

EFFLUENTS
  SEE THERMAL EFFLUENTS
  SEE WASTE HEAT
THERMAL
  SEE GEOTHERMAL FLUIDS
  SEE THERMAL EFFLUENTS

The targeted compound phrase, THERMAL EFFLUENTS, is listed as follows:

THERMAL EFFLUENTS
  RT GEOTHERMAL FLUIDS
  RT WASTE HEAT

Use of the Bibliography Access Points

The six appendices to Volume II of the Bibliography, discussed above, allow great flexibility in locating the desired information source(s). Subject access requires combined use of the Geopressured Thesaurus with the Descriptors index. If the researcher already knows the title of a specific item, he or she may proceed directly to the main body of the bibliography, which is arranged alphabetically by citation title. Certain alphabetizing conventions should be noted:

1. A nonalphabetic character has a "lower filing value" than an alphabetic character.
2. Character strings of all capital letters file first.
3. Words beginning with a lower case letter are "ignored" in filing.

Compilation of the Bibliography

Candidate information sources are located by consulting a range of government and commercial data bases. Other sources are provided by staff familiarity with the literature and with current research. Once identified, a candidate item is obtained and screened further for suitability. If selected to appear in the bibliography, the item is read, indexed with the thesaurus-controlled vocabulary and, if necessary, abstracted by GGIS staff. The item then is catalogued and the pertinent citation components isolated. All information is entered into the on-line version of the Bibliography. Errors are controlled by the various authority files for author, title, journal, and conference.

Maintenance of the Bibliography and Thesaurus

Neither the Bibliography nor the Thesaurus remains static; both must be reviewed for errors and structural weaknesses. With the third edition, the Bibliography has grown so large as to require certain revisions. Changes involving the on-line version are discussed in the next section. Most of the other changes relate to assignation of GGIS internal reference numbers and do not affect the user.

The Thesaurus is undergoing revision with an eye to another edition. Numerous new descriptors have been proposed. These must be verified for content, spelling, and appropriateness; they also must be integrated into the controlled vocabulary framework. Editing both the Bibliography and Thesaurus for errors remains an ongoing concern.

Change from Hierarchical to Relational Data Base

The efforts of this project during the year in regard to the bibliographic and thesaurus data bases have been focused on making the data bases more accessible to users outside The University of Texas at Austin. As part of this effort, there is a major revision underway in the structure of the data bases. The revised structure will facilitate making the data bases available to outside users by making the moving of the data bases to other machines, which are attached to existing computer networks, a simpler task.

At present both the bibliographic and thesaurus data bases are defined in a hierarchical model. In this model groups of data components are defined that are common to other groups of data components. The relationship between these groups of data components may be best thought of as a tree. In the tree the group of data components which has the largest number of branches is thought of as the root of the tree. Each of the groups of related data components may be thought of as a branch of the tree. As an example data components related to the proceedings of a conference would be stored in the root group of data components, while individual papers presented at the conference, and presumably in the proceedings of the conference, would be stored as a branch group of data components. The primary reason both data bases were defined in a hierarchical model is that hierarchical models were the most common in use at the time of development.

The revised structure of the data base model for both the bibliography and thesaurus data bases is a relational data base model. In this data base model each group of data components in the data base is a table of data. A table is simply a large two-dimensional matrix in which data values are stored. Each table of information is related to other tables of information by a key, or a set of keys, which define the relationships between tables which group together sets of data. An example of a table might be all the titles of papers in a journal and their associated keys that would relate them to further information on the paper.

Relational data models are currently the most effective form of data base storage. Relational data models are beneficial in many ways. A major advantage of a relational data model is that it is relatively simple to unload data from one relational data base management system and load it into another. Moreover, several commercial data base management systems use relational models. Many of these data base management systems are available on commonly used minicomputers. Some of the relational data base management systems also provide facilities for loading and unloading data to microcomputers from larger data bases on minicomputers or even larger computers. These kinds of features will promote access to the bibliographic and thesaurus data bases either through the distribution of the data bases themselves or by making the data bases available on machines that are more easily accessed.

The current status of this conversion process is that the relational data model for the bibliographic data base has been essentially completed except for minor refinements that will increase the efficiency of storage. Work is now being completed on a comprehensive data entry program that will load data directly from the data sheets generated by the research librarian into the data base itself. Planned work for the next contract year includes the development of several programs for information retrieval from the data base that will be designed to be menu-driven to ensure user friendliness. The thesaurus data base will then be converted to a relational model, and similar programs will be written for use with the thesaurus data base. This process is expected to be relatively simple.

Proposed Expansion of the Bibliography

As stated earlier, the Bibliography includes information sources dating back to the late 1960s. GGIS staff wish to increase the bibliography's usefulness by including earlier materials, while at the same time keeping up with current publications.

The Bibliography primarily presents English-language materials, although citations appear for a few German-, French-, and Russian-language items. These last-mentioned are a prime source of interest, owing to the quantity of relevant citations available. As an example, some 500 citations have already been collected and are awaiting funding for translation and data entry into the bibliography data base. If enough interest is perceived to warrant the effort, GGIS has the capabilities of cataloguing these Russian-language items.

Sponsors and Funding

The GGIS Bibliography and Thesaurus began ten years ago with funding from the United States Department of Energy. They have shared this support with the GGIS well logging and well and reservoir data base programs. The Gas Research Institute provided additional support in 1984-85.

APPENDIX II: ROCK MECHANICS

Eric P. Fahrenthold and Kenneth E. Gray

Compaction and Creep of Geopressured-Geothermal Reservoir Rock

The Center for Earth Sciences and Engineering is engaged in a coordinated experimental and theoretical investigation of compaction and creep behavior of sandstone and shale samples cored from the Hitchcock geopressured-geothermal well. This work addresses fundamental questions on the constitutive behavior of porous media, and is essential to understanding and modeling the performance of geopressured-geothermal reservoirs.

Experimental Work

Experimental study of geopressured-geothermal core has included both compaction and creep tests. Compaction tests measured the effect of overburden and pore pressure loads on the bulk deformation of the reservoir rock, as well as variations in permeability, resistivity, and other material properties. The uniaxial tests simulated uniaxial compaction of the reservoir which occurs as pore fluids are depleted. The triaxial tests employed the standard procedures used to investigate the mechanical strength of rocks. The pore pressure drawdown tests were designed to evaluate the principle of effective stress as applied to porous sandstone.

Creep tests determined the presence and magnitude of time-dependent deformation of the subject rock under constant loading. Jacketed and unjacketed tests were conducted to measure rock matrix and bulk volume creep effects, respectively. Deviatoric creep tests again applied classical methods for investigating variable rock properties.

Sandstone and Shale Compaction

Results of a typical triaxial test on the Hitchcock sandstone are shown in Figures 3 and 4. The figures exhibit nonlinear loading and unloading behavior, hysteresis loops, and residual strain present upon return to the initial stress state. Since conventional rock models predict the loading and unloading curves to be coincident and linear, the departure of geopressured-geothermal core from ideal behavior is dramatic and deserves careful consideration in the development of reservoir models.

Results of a similar triaxial test on the Hitchcock shale are shown in Figures 5 and 6. Because of the difficulties inherent in obtaining and preparing shale samples for such testing, the shale property measurements are particularly important.

Creep Testing

Tests on rock cored from the Pleasant Bayou wells showed that geopressured-geothermal core may compact even under constant mechanical and pore pressure

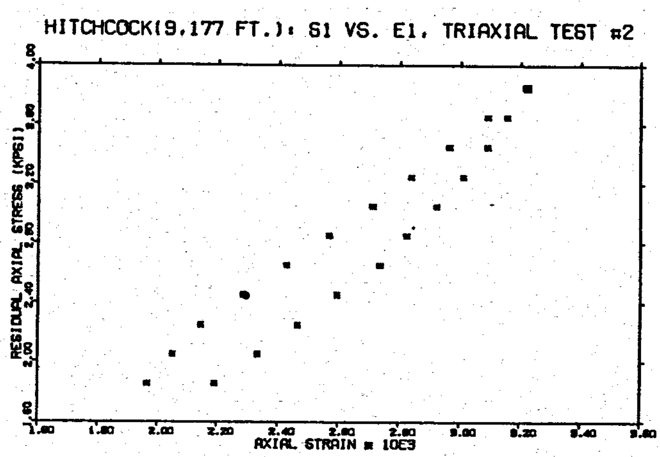

Figure 3. RESIDUAL AXIAL STRESS VERSUS AXIAL STRAIN, SANDSTONE COMPACTION TEST

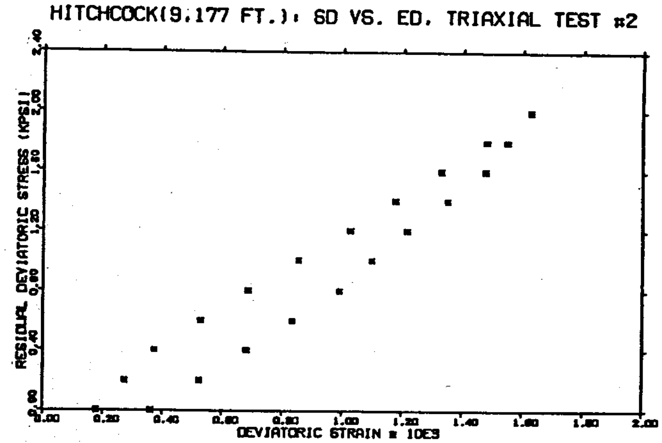

Figure 4. RESIDUAL DEVIATORIC STRESS VERSUS DEVIATORIC STRAIN, SANDSTONE COMPACTION TEST

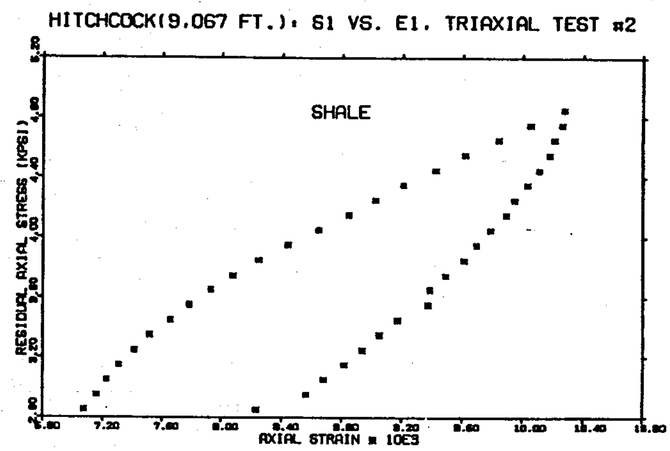

Figure 5. RESIDUAL AXIAL STRESS VERSUS AXIAL STRAIN, SHALE COMPACTION TEST

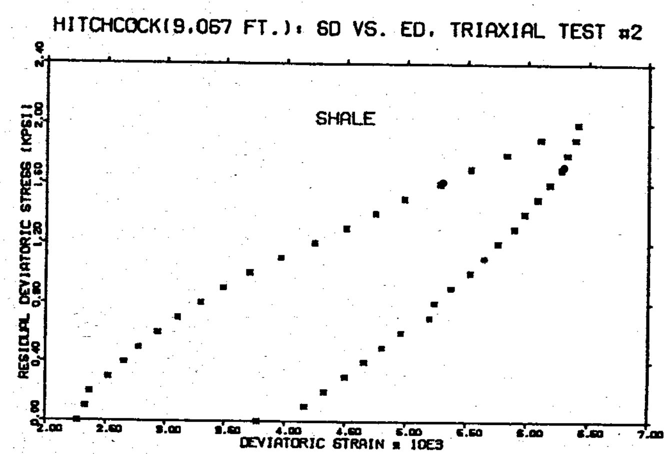

Figure 6. RESIDUAL DEVIATORIC STRESS VERSUS DEVIATORIC STRAIN, SHALE COMPACTION TEST

loading. Such behavior can have a significant effect on the long-term performance of a reservoir. Unjacketed and jacketed tests conducted on the Hitchcock sandstone (Figures 7 and 8) indicate that this rock exhibits a time-dependent behavior and that the predominant effect is a change in porosity as opposed to a solid grain compaction.

Theoretical Work

Development of theoretical models that describe the experimentally observed behavior of sandstone and shale greatly facilitates the application of test results to practical problems such as reservoir simulation and subsidence. Realistic rock models must depart from classical work, much of which is still in use, to account for nonlinear stress/strain relations.

The results of the compaction tests have been utilized in two ways. First, the variation of familiar isotropic and anisotropic moduli with stress state has been calculated to allow the inclusion of nonconstant rock stiffness and compressibility in existing reservoir models. Second, a new compaction model has been formulated that reflects the fundamental loading and unloading behavior of porous rock. This model agrees closely with the experimental data under both uniaxial and triaxial test conditions, as shown in Figures 9, 10, and 11. The next step is the application of this work in the reformulation of reservoir models, and the solution of important boundary value problems dealing with well bore stability and subsidence.

Creep Modeling

Although classical linear rheological models have been used to describe the time-dependent compaction of some rock, such models have had limited success in the study of geopressured-geothermal core. A different modeling structure is called for in the study of the coupled nonlinear deformation of a porous medium. The method of "bond graphs" provides

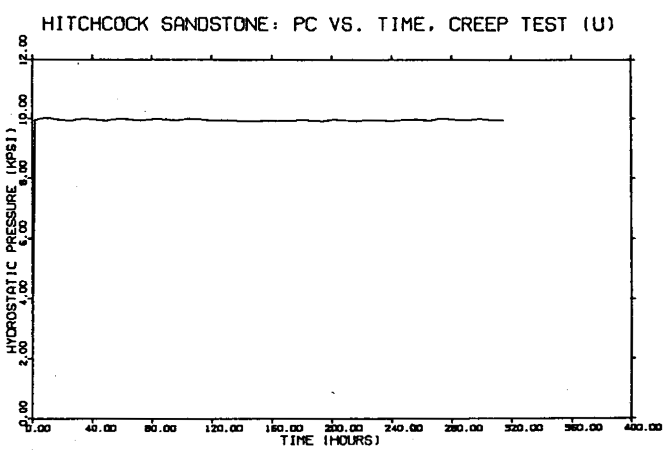

Figure 7. UNJACKETED SANDSTONE CREEP TEST

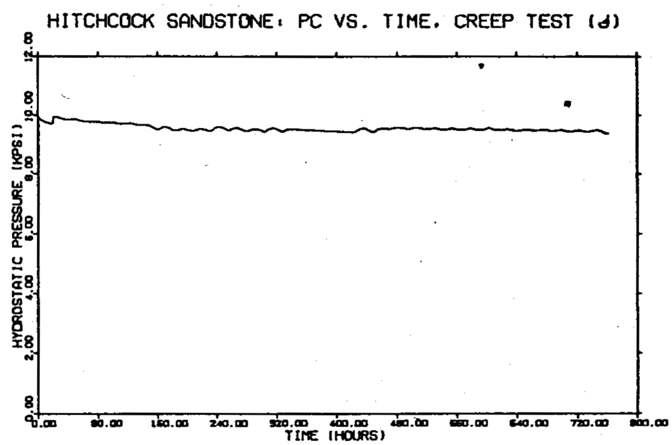

Figure 8. JACKETED SANDSTONE CREEP TEST

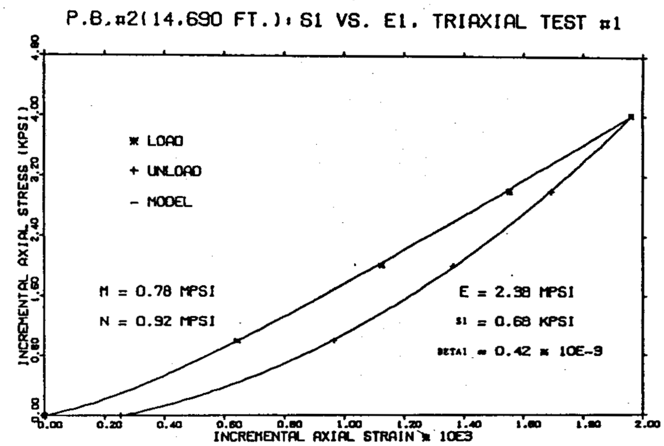

Figure 9. INCREMENTAL AXIAL STRESS VERSUS INCREMENTAL AXIAL STRAIN, TRIAXIAL TEST

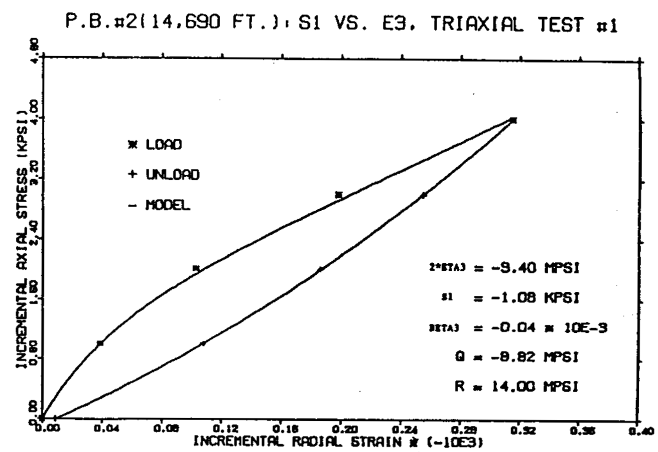

Figure 10. INCREMENTAL AXIAL STRESS VERSUS INCREMENTAL RADIAL STRAIN, TRIAXIAL TEST

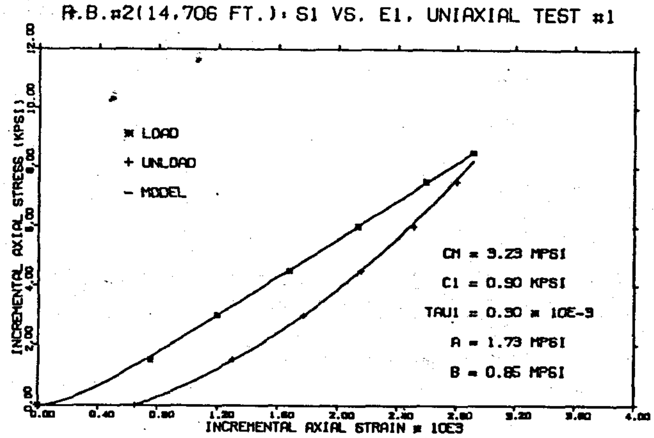

Figure 11. INCREMENTAL AXIAL STRESS VERSUS INCREMENTAL AXIAL STRAIN, UNIAXIAL TEST

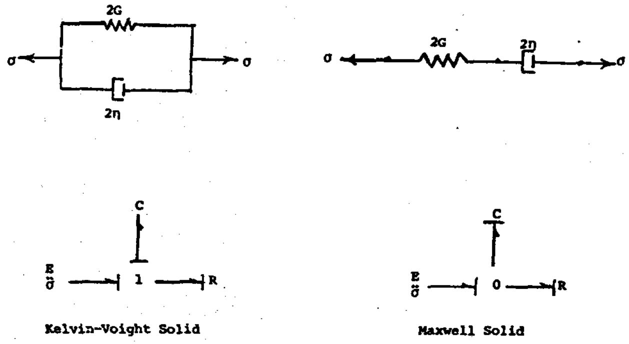

Figure 12. CLASSICAL RHEOLOGICAL MODELS AND THEIR BOND GRAPH EQUIVALENTS

a mechanism for generalizing the classical rheological models and accounting for the observed complex behavior of the solid-fluid mixture. Hence, creep modeling work has focused upon an innovative introduction of the bond graph method to the study of a solid-fluid continuum. Figure 12 shows classical rheological models with their bond graph equivalents. A new bond graph model of uniaxial and triaxial rock tests has been formulated. Work is now in progress to evaluate model parameters using experimental data.

Graduate Student Support

Graduate students in the areas of petroleum, mechanical, and electrical engineering are participating in experimental and theoretical research on the compaction and creep behavior of geopressured-geothermal reservoir sandstone and shale. Students are investigating the variation of wave propagation velocities with temperature and pressure, the constitutive relations that describe rock deformation, and the problems associated with microcomputer-based data acquisition and modeling of compaction and creep tests.

Publications

Dissemination of experimental and modeling work has been pursued, by way of the Sixth US Gulf Coast Geopressured-Geothermal Energy Conference in February 1984 and through other journals. A comprehensive compaction modeling paper has been submitted to the Journal of Energy Resources Technology, ASME, and a creep modeling paper is in preparation.

Testing Equipment

Finally, a major effort has been made to modify existing equipment and acquire additional equipment to improve essential rock-testing capabilities. Displacement transducers were installed on a high-pressure test vessel to improve deformation measurement capabilities for poorly consolidated shale. Improved sample jacketing methods are being introduced for high-temperature creep tests, and additional pressure vessels are being outfitted for creep testing.

A multichannel data acquisition system is on order to improve data-recording capabilities, and several equipment grants for the use of microcomputers in data acquisition and modeling have been funded. These efforts will make possible continued and improved efforts at a coordinated experimental and theoretical study of geopressured-geothermal sandstone and shale.

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FINAL AGENDA

DOE Geothermal Program Review IV
September 11-12, 1985

The Sheraton Washington
Washington, D.C.

FINAL AGENDA

ALL SESSIONS WILL BE HELD IN THE NORTH COTILLION ROOM

Wednesday, September 11, 1985

8:30	REGISTRATION & CONTINENTAL BREAKFAST	

Chairperson: John Mock, Director, Geothermal Technology Division, U.S. Department of Energy

9:30	Introductions - John Mock, Director, Geothermal Technology Division, U.S. Department of Energy	
9:45	Keynote Address - Donna Fitzpatrick, Acting Assistant Secretary for Conservation and Renewable Energy, U.S. Department of Energy	
10:15	Overview of the U.S. Department of Energy Geothermal Program	John Mock, Director, Geothermal Technology Division, U.S. Department of Energy
10:45	Status of U.S. Geothermal Industry	Robert G. Lacy, President Elect, Geothermal Resources Council, San Diego Gas & Electric Company
11:15	Geosciences Research in DOE - 1985	George A. Kolstad, Office of Energy Research, U.S. Department of Energy
11:45	Geothermal Activities in Central America	John Whetten, Los Alamos National Laboratory
12:00	LUNCH (ON YOUR OWN)	

Chairperson: Anthony (Tony) Adduci, San Francisco Operations Office, U.S. Department of Energy

1:30	SAN Overview/Discussion of Heat Cycle Research	Anthony Adduci, San Francisco Operations Office, U.S. Department of Energy
1:50	Heber Binary Project	Robert G. Lacy, San Diego Gas & Electric Company
2:20	Research on Geothermal Chemistry and Advanced Instrumentation	Robert J. Robertus, Pacific Northwest Laboratory
2:30	Salton Sea Scientific Drilling Program: Drilling Program Status	Charles A. Harper, Bechtel Corporation
2:45	Salton Sea Scientific Drilling Project	Al Duba, Lawrence Livermore National Laboratory
3:00	COFFEE BREAK	
3:15	Geothermal Reservoir Technology	Marcelo J. Lippmann, Lawrence Berkeley Laboratory

3:35	Geothermal Reservoir Engineering Research at Stanford	Jon S. Gudmundsson Stanford University
3:45	Pressure Distribution Around a Well Producing at Constant Pressure in a Double-Porosity Reservoir	Abraham Sageev Stanford University
4:05	Advanced Materials for Geothermal Energy Processes	Lawrence E. Kukacka Brookhaven National Laboratory
4:25	Geological and Geochemical Techniques for Fracture Definition in Geothermal Reservoirs	Dennis L. Nielson University of Utah Research Institute
4:40	Geothermal Assessment in the Bonneville Power Administration Service Area	Thomas J. White Bonneville Power Administration
4:55	Technology Transfer on the Heber Geothermal Binary Demonstration Power Plant Project	George S. Budney Energy Technology Engineering Center
5:05	Federal Geothermal Technology Transfer Activities	Daniel J. Entingh Meridian Corporation
5:15	International Agreements DOE/CFE DOE/ENEL	Anthony Adduci San Francisco Operations Office U.S. Department of Energy
5:30	Cocktail Reception	Cotillion Foyer (Cash Bar)

Thursday, September 12, 1985

Chairperson: George Tennyson, Albuquerque Operations Office
U.S. Department of Energy

8:45	Hot Dry Rock Phase II Reservoir Engineering	Hugh Murphy Los Alamos National Laboratory
9:20	Inert and Reacting Tracers for Reservoir Sizing	Jefferson W. Tester Massachusetts Institute of Technology
9:35	Open Hole Packer and Running Procedure for Hot Dry Rock Reservoir Testing	Donald S. Dreesen Los Alamos National Laboratory
9:55	Earth Science Instrumentation Update Review FY1985	Bert R. Dennis Los Alamos National Laboratory
10:15	COFFEE BREAK	
10:30	Sandia Geothermal Technology Program: Interactions with other DOE Research and CSDP	Richard K. Traeger Sandia National Laboratories
11:00	Drilling Technology/GDO	James R. Kelsey Sandia National Laboratories
11:30	The Magma Energy and Geothermal Permeability Enhancement Programs	James C. Dunn Sandia National Laboratories
12:00	LUNCH (ON YOUR OWN)	

Thursday, September 12, 1985 (Continued)

Chairperson: Susan M. Prestwich, Idaho Operations Office
U.S. Department of Energy

1:15	Cascades Thermal Gradient Drilling Status	Susan M. Prestwich Idaho Operations Office U.S. Department of Energy
1:30	Development and Application of Tracers: Examples of Field and Experimental Studies	Joseph N. Moore University of Utah Research Institute
1:45	Borehole Geophysical Techniques for Defining Permeable Zones in Geothermal Systems	Phillip M. Wright University of Utah Research Institute
2:00	Injection Technology Research at Stanford	Jon Gudmundsson Stanford University
2:20	INEL Injection Research: Physical Model Studies	Susan G. Stiger EG&G Idaho, Incorporated
2:35	Brine Injection Studies	Marcelo J. Lippmann Lawrence Berkeley Laboratory
2:50	Heat Cycle Research Experimental Program, FY-1985	O. Jack Demuth Idaho National Engineering Laboratory
3:20	COFFEE BREAK	
3:35	Scale Control in Geopressured Energy Production	Mason B. Tomson Rice University
4:05	Overview Geopressure Program	Hank Coffer Idaho National Engineering Laboratory
4:35	An Overview of Geopressured Geothermal Research	Myron H. Dorfman University of Texas at Austin
5:05	Closing Remarks	John Mock

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GEOTHERMAL PROGRAM REVIEW

Washington Sheraton Hotel
September 11-12, 1985

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