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GEOTHERMAL PROGRAM REVIEW VIII

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PROCEEDINGS

"The National Energy Strategy — The Role of Geothermal Technology Development"

April 18-20, 1990
San Francisco, CA

Sponsored by:

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Division
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PREFACE

Each year the Geothermal Division of the U.S. Department of Energy conducts an in-depth review of its entire geothermal R&D program. The conference serves several purposes: a status report on current R&D activities, an assessment of progress and problems, a review of management issues, and a technology transfer opportunity between DOE and the U.S. geothermal industry.

This year's conference, Program Review VIII, was held in San Francisco on April 18 - 20, 1990. The theme of this review was "The National Energy Strategy -- The Role of Geothermal Technology Development." The Administration is developing the National Energy Strategy to define the Nation's approach for a reliable, economic and environmentally safe energy supply. The ultimate contribution of geothermal energy to the NES hinges upon expanding the U.S. geothermal reserves. Only by improving the economic and technological viability of geothermal energy can the exploitable geothermal reserves increase sufficiently to fulfill the potential role of geothermal energy in the Nation's energy supply.

Program Review VIII was composed of seven sessions including an opening session with presentations by Mr. Stephen Lipman, President, UNOCAL Geothermal Division, and Mr. Michael Heys, President, California Energy Company. The five technical sessions included presentations by the relevant field researchers covering DOE-sponsored R&D in hydrothermal, hot dry rock, geopressured, and magma energy.

As with previous Program Reviews, a key facet of PR VIII was an "Industry Critique" session organized and chaired by the National Geothermal Association (NGA). This year, five NGA representatives were asked to comment on specific areas of DOE's geothermal R&D: Drilling and Completion, Exploration, Power Conversion, Reservoirs, and Fluid Handling. Their comments provided valuable insight into near-term industry concerns and needs and reinforced the basic thrust of the DOE program.

The success of PR VIII primarily resulted from the individual contributions of the researchers, industry, academia, and federal, state, and local representatives who participated in the conference. The forum was highly productive with substantial exchange of information and ideas at all levels. These inputs will provide a basis for future planning and direction of the geothermal R&D program.

I want to express my thanks to Mr. David Anderson, Executive Director of NGA, for coordinating and serving as moderator of the "Industry Critique" session. I also want to express my appreciation to Meridian Corporation, whose assistance and support in planning and implementing Program Review VIII helped to ensure its success.

Ted Mock

John E. Mock, Director
Geothermal Division
Conservation and Renewable Energy

OVERVIEW

Chairman: John E. Mock
Director, Geothermal Division
U.S. Department of Energy

THE NATIONAL ENERGY STRATEGY
THE ROLE OF GEOTHERMAL TECHNOLOGY DEVELOPMENT

Stephen C. Lipman
UNOCAL Geothermal Division

Our topic today - The Role of Geothermal Energy Development in The National Energy Strategy - is one that you would think we could all agree upon in this room.

We are here today because we believe that there is an important role for geothermal energy in our future. We all know of its successes and its potential. Even at The Geysers, though it is experiencing a loss of productivity because the reservoir pressure is going down, it is still the largest geothermal project in the world and is a major source of electricity for Northern California. We believe that field will continue to meet that demand for many years to come. I will address that field in more detail in a moment.

First, let us address why others do not share our faith in this resource development. I believe it boils down to a few simple facts of life:

1. Not many movers and shakers on the national scene know what commercial development has taken place. We are considered to be in the class of technologies that most people think of as pure research - undeveloped and unavailable for today's needs. Our story of past accomplishments is not getting across to those in control of our national direction.
2. The choices that will be made in meeting our future energy needs will have more environmental forethought than before, but when it gets down to moving ahead with new developments I believe it will be based on short term economics, pure market forces. In that kind of competition, many believe that geothermal energy will lose out because it is too expensive. I am not one of those. I believe we are, and will continue to be, a cost-effective source of electricity.
3. The economic hardships of the past decade of low energy prices and the acquisition mania with its junk bonds have caused many major developers to leave our industry. So, can we maintain a significant role without Philipps, Sun Oil, Gulf, Oxy, Shell, Natomas, Southern Pacific, Grace, MCR, and now Chevron and possibly Freeport McMoRan? The burden to advance our industry is not on DOE, or the California Energy Commission or the national labs and participating universities. It is on those developers who are left - UNOCAL, Magma Power, Oxbow, Ormat, California Energy Company, Pacific Enterprises, Mission Energy, Anadarko, Calpine, and Centennial Energy. I hope more of these companies do step forward and join those of us that are trying to keep geothermal in a prominent role.

Our story of accomplishments must be told on a national and regional level, and by more than a few spokesmen. I get concerned that we often hurt ourselves when we do speak out by focusing on things that we want from the government. Where, in reality, we are not in a bad situation at all.

Let's take a look at some of the common issues that other industries are confronted with.

- Are there enough lands available for industry to develop? I believe industry has a good land position in the western United States. Probably the major land issue facing our industry is in Hawaii. I believe that is solvable with appropriate measures of education, negotiation and compromise.

- Do we have adequate and appropriate technology available for commercial developments to proceed? I think we can all agree that industry has confronted a wide variety of resource problems and has moved ahead with successful solutions. I do not want to convey that these were the best or the optimum solutions.

  We need to keep up research and development on improving our exploration and production techniques and tools. Success in this effort can only result in additional geothermal development and keep our industry strong economically. But my main point is we are not limited by a lack of technical expertise or equipment.

- Are there institutional barriers to development? Certainly, not like there were in the early 1970s. The only one that comes to mind for today's developments is the 80 MW FERC limitation for a geothermal PURPA power plant. As we compete for market opportunities, our industry must not be restricted to this arbitrary limit, while our competition from fossil-fueled cogeneration has no limit whatsoever. I am sure that this playing field will eventually be righted, but we, as an industry, are going to have to get the message across in Washington.

- What R&D efforts are most needed by industry? In a broad context, any and all that reduce our costs and extend the beneficial recovery of the resource. Tools and techniques that reduce our drilling costs, keep the injectivity of wells from degrading with time, and also an area that is not studied by most funded research is in more efficient use of the resource in the energy conversion process. Industry spends large sums of money to find and produce these fluids; it is discouraging to see it used inefficiently.

I believe that the performance of our industry's commercial developments should be studied, evaluated and brought to public awareness. This would highlight our success, provide a technical basis for future developments, and concentrate on finding better solutions for future commercial developments. The Geysers, along with other developments, should be given detailed technical analysis by scientific teams from academia and industry. Studies should not be limited to past performance, but should also include ways to improve future recovery and performance. The benefits from these examinations flow to all sectors of our industry:

- To the national labs and universities in advancing the knowledge of geothermal development,
- To the industrial developers in extending their resource developments,
- To industry and the public at large by opening up the potential of other geothermal developments and maintaining a viable alternative to conventional fuels.

This is a strategic plan for government and industry to embark on. It may not make the front page on our national energy strategy summary, but I believe we will reap many more benefits in advancing geothermal energy development.

Thank you for inviting me to speak today, and I wish you every success in this week's conference.

GEOTHERMAL ENERGY DEVELOPMENT IN THE PACIFIC NORTHWEST

Michael Heys
California Energy Company

Last summer, we established an office in Portland, Oregon, under the banner of CE Exploration, to manage our activities in the Pacific Northwest. To date, we've spent about $15 million exploring and establishing a land position in the region. We now hold the rights to some 340,000 acres in Oregon and Washington -- some of the most promising geothermal prospects in the country. Among them are:

- Mt. Mazama in the Winema National Forest;
- the Newberry Volcano in Oregon's Deschutes National Forest;
- the Bend Highlands, also in Oregon;
- Mt. Baker, in Washington;
- Mt. Adams, in Washington;
- Mt. Shasta, in the far north of California; and
- Glass Mountain, adjacent to UNOCAL's success there;

We anticipate several options in Northern Nevada and Utah, through our Chevron proposal. During the next several years, we expect to invest another $30 million in the region.

Overall, our corporate goals are to have a six-fold increase in power sales agreements, to a total of 1,500 megawatts, and a total of 600 megawatts on-line, by 1994, and we see the Pacific Northwest as a likely source for a good part of it.

But geothermal development is big business, and it involves high finance -- and high risk. To bring the Coso project into being, we had to raise more than $650 million in capital. You can see we are not talking minor-league economics. We had to convince the international investment community not only that we could make the project work but also that geothermal steam is a technologically and economically viable energy resource. We had to persuade them that geothermal energy was a sound investment. Persuade them we did; and Coso is the result.

Now, we must persuade them that it can be done again.

The Northwest Power Planning Council anticipates 3,500 megawatts from geothermal -- How can it do that?

There are no proven reserves in the Northwest. What is needed is:

- investment, to
- identify the prospect in order to
- inventory the resource.

Many of you already know something about the California Energy Company, and most, if not all of you, I'm sure, know at least as much as -- maybe more than -- I do about the kinds of technologies it takes to convert geothermal steam into electricity. You no doubt recognize, too, that it can be a big and often difficult leap from technological know-how to economic viability. But it can be done. It must be done. And it will be done, in the Pacific Northwest.

If ever there was a perfect match between the people of a particular geographic region and an energy source, it is the match between the Pacific Northwest and geothermal steam. The philosophical bent of the people of the region seems to place a premium on a technology that offers to meet their needs for energy without a commensurate detrimental impact on the environment. Moreover, the geology of the region, especially its volcanic origins, virtually assures the presence of heated rock layers close enough to the surface to be accessible by drilling, and our own early exploration efforts show this to be so. Finally, the region is in immediate need of new sources of electricity in order to accommodate economic growth. The Northwest's surplus of 2,000 megawatts has disappeared. The excess power they thought they had into the next century is gone.

The Bonneville Power Administration, once the envy of the nation for this surplus power, not long ago announced that it is short some 80 megawatts this year. For the short term, BPA will just go out and buy surplus power on the open market. But they know, as you and I know, that can't last forever; the open market is not an unlimited resource.

Where will the power come from? The only thing that is certain is that it won't come from the hydroelectric resources the region has relied on since the 1930s and 1940s. It's decision time for the people of the Pacific Northwest. It's time to turn to new resources. Procrastination is a luxury the region can ill afford.

We believe power from geothermal resources is the answer, and we believe our Coso project can serve as a model for development of such new resources. The complex has been generating electricity commercially since June of 1987 and reached its currently planned capacity of 240 megawatts just before the beginning of the year. Nine power plants placed in service in less than 30 months: Quite a record. Now that we have it on-line, we are able to turn our attentions to other promising prospects, among which the Pacific Northwest rates very highly in our estimation.

Without investment, there would be no advancement of geothermal energy. As for technological advancement, I can tell you with the absolute certainty that is borne of experience at Coso that geothermal steam is one of society's safest, cleanest, most economical energy alternatives. Others think so, too. Mr. Charles Condy is in Washington today to receive an Earth Day award from President Bush.

In fact, geothermal is probably the only alternative source available in the Pacific Northwest that combines favorable economics with readily available, ample domestic supply, and that is environmentally benign besides.

So what's to stop us? In a word, information. To put it more precisely, it is the lack of information that often stymies us. To overcome it, we will need your help. For all the successes we've had at Coso, the project of ours that has received the most public attention aside from the financial press is our project in the Winema National Forest, near the boundary of Crater Lake National Park.

This project, which would unobtrusively tap geothermal resources several miles away from Crater Lake, has been under fire by a small but vocal portion of the very people we would expect to be the most vocal proponents of geothermal power. We think their quibbling is borne of fear, the postscript to a lack of information, a lack of awareness of the interrelationship of the various parts of society.

The region needs electricity. Traditional electricity generators emit noxious gases into the atmosphere. Cause and effect. To reduce the effect, alter the cause. But keep the lights on while you do it.

What's needed is a massive education job. The environmental factor is going to play an increasingly significant role in the power-plant decision-making process.

Getting the Coso Project to where it is today required us to thread an intricate course of environmental and regulatory rules. I am convinced that one of the reasons we have had such success in threading this regulatory maze is that we embraced the philosophy early on that cooperation was the best means to a permit. But it also no doubt reflects a growing attitude, not just among the regulators, but among the public at large, that we must find fuels other than the fossil fuels that we are presently using, that are presently doing immeasurable and perhaps irrevocable harm to our environment. Society is in desperate need of an energy source other than the fossil fuels -- coal, oil, natural gas.

Regulators -- the people who set the rules that we producers must follow -- are beginning to look at conventional fuels with an increasingly jaundiced eye. Ted Hallock, who represents the state of Oregon on the regional Northwest Power Planning Council, states flatly, "I oppose coal-fired generators totally because of their carbon dioxide contribution to the atmosphere."

But if we can't use coal -- the dominant fuel worldwide, including the United States -- or oil, a precious, if not noble mineral, which is disappearing faster than many of us are willing to admit, then where are we to get our electricity? Conservation comes first; then come the renewables. Natural geothermal heat stands as a shining contrast to these fuels of the past. And, once you've developed the resource, brought a well to the surface, and piped the steam to the generator, there are no long-term fuel costs subject to inflation or foreign political whim.

With such virtues going for geothermal steam, the wonder is that there is not a widespread public clamor in the environmentally conscious Pacific Northwest for a concerted effort to develop the resources that they have in such abundance.

The public doesn't realize the enormousness of the treasure buried deep in the earth below them. We have met in Portland with representatives of several major environmental groups, to establish a dialogue and build a relationship.

We intend to work closely with them, the Northwest Power Planning Council, the Bonneville Power Administration, and all of the public and private utilities of the region, in order to make certain that geothermal steam will have a very prominent and highly respected place in the energy mix of the Pacific Northwest.

There are, after all, very few options available to society: If we are to continue to experience economic prosperity without jeopardizing our national security, we must diversify our energy production. But it must be a cooperative effort between us in the private sector and you in the public sector. The political, cultural, and social issues will have to be resolved by a public dialogue more suited to the state houses and halls of Congress than to the board rooms of America.

We can offer speakers, and materials, and the science and technology necessary to support the educational effort, but we cannot resolve the issue on our own. The perceptions of the public, their view of corporate motivations, and their level of trust in what we say, make it imperative that the dialogue be directed by third parties -- by you, in government. It is an effort well worth undertaking. The difficulties can be overcome.

Voices are beginning to be heard, however. The Northwest Power Planning Council, which recognizes a need for new power sources, calls geothermal power "possible, practical and desirable for the region's energy future" in a recent report. The Council recognizes the technical achievements of the geothermal industry; the extent of the resource throughout the Northwest; and the social and environmental merits of this clean, renewable energy. The report notes that "safe, reliable operating histories in diverse settings testify to geothermal's 'good fit' with utility operations and 'good neighbor' reputation."

Another way to look at it is to compare construction costs: $1,800 per installed kilowatt for our most recently completed unit at Coso, compared to $1,200 per kilowatt for a combined cycle natural gas plant of comparable size. But at Coso, the cost of developing the steam resource to run a turbine is recovered within a year's time. To keep a 230-megawatt gas-fired plant running for 30 years, it would take more than $1.5 billion worth of fuel at today's prices, with no adjustment for inflation.

Environmental costs are harder to quantify, but consider that it will cost some $800 million just to decommission the San Onofre Unit One nuclear reactor in Southern California.

As the handwriting on the wall comes more clearly into focus, we can begin to discern some unmistakable messages, including the words "RENEWABLE ENERGY" in all capital letters.

Among the alternatives, one stands out: Geothermal. It's there, for the taking, literally at our feet.

Our Coso Project is one of the cleanest power stations in America today, producing vitally needed electricity with virtually no negative impact on the pristine desert air. The California Energy Commission staff has concluded in a report to the commission that Coso "should result in long-term statewide air quality benefits, conserve critical fossil fuel resources and reduce California's dependence on imported oil."

The report also calls California Energy's new geothermal technologies "an important advance in the continued development of this generating resource." We're proud of that assessment in California, that recognition of our commitment to a cleaner, but still prosperous world.

We would like to repeat our successful performance again, and again, and again. We hope to start in the Pacific Northwest.

Thank you.

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THE ROLE OF THE CALIFORNIA ENERGY COMMISSION IN GEOTHERMAL RESEARCH AND DEVELOPMENT

Michael Smith
California Energy Commission

The California Energy Commission (Commission) plays several roles with respect to the development of geothermal energy in California.

(1) The Commission reviews applications and, if appropriate, issues permits for thermal electric power plants with capacities greater than 50 MW.

(2) The Commission prepares biennial forecasts of electricity supply and demand in California for 5-, 12-, and 20-year planning horizons. These forecasts, which appear in the *Electricity Report*, are essential to the Commission's determination of need (for capacity and energy) in its power plant siting process. These forecasts also will play a key role in future proceedings of the Public Utilities Commission (PUC) regarding new long-term standard offer contracts.

(3) The Commission administers programs to promote the development of advanced fossil fuel and nonfossil fuel energy technologies, including geothermal energy.

Since 1981, the Commission has supported the efforts of local governments relating to geothermal energy development. Through its Geothermal Grant and Loan Program, the Commission provides financial (grants and loans) and technical assistance to cities, counties, special districts, Indian governments, and municipal utilities for a wide variety of purposes. Each year, between $2-$3 million is made available for this program. These funds can be used (a) for local planning and policy development relating to geothermal energy; (b) to identify and mitigate the impacts of existing geothermal development; and (c) for resource exploration and development.

Until recently, the latter has focused primarily on the development of low-temperature resources for direct-use projects. The Commission is funding numerous direct-use projects throughout the state, including district heating systems in the cities of San Bernardino, Susanville, Calistoga, Mammoth Lakes, and Bridgeport.

The Commission also is committed to playing a greater role with industry, beginning with a cooperative effort with the entities operating at The Geysers. Last September, the Commission held an informational hearing to examine (1) the causes of the decline of geothermal steam resources at The Geysers KGRA; (2) the resulting effect on electrical energy supply; and (3) options to mitigate the expected decline.

Following the hearing, the Commission established a Technical Advisory Committee (TAC) to assess the implications of the steam decline on the Commission's forecasts and to coordinate efforts to focus industry and government attention on the research opportunities and management options necessary to maximize the resource potential.

The TAC is headed up by Commission staff and is comprised of representatives from the steam development and power plant operating entities in The Geysers as well as the Division of Oil and Gas and the State Lands Commission.

The TAC has three purposes: (1) to provide the Commission with projections of capacity and energy given the present rate of steam decline; (2) to examine options relating to efficient management of The Geysers resource, including research and development, testing, and analyses relating to the reservoir and power plants operations; and (3) to recommend to the Commission cost-effective alternatives for efficient management of the steam reserves.

The TAC already has provided revised projections of electrical energy and capacity from The Geysers for the 1990 *Electricity Report* and is beginning work on the second objective. This includes concurrent assessments of the state-of-the-art reservoir simulation capabilities and power plant design and operation.

Also, the Commission is providing funding support through the Geothermal Grant and Loan Program to cost share with industry and the Department of Energy (DOE) in near-term projects that can lead to resolution of the conditions plaguing The Geysers.

While recognizing the importance of near-term research and development, the Commission also is concerned about the future of the geothermal industry. There must be a balance between the near-term needs of the industry and long-term growth. As the exploration and development of known hydrothermal resources matures, new opportunities must evolve.

To this end, the Commission is working with DOE on several long-term research and development programs.

(1) The Commission is providing $225,000 for the Hot Dry Rock project being conducted by the Los Alamos National Laboratory near Clearlake, California. This joint city/state/federal project is entering its

second phase. The first phase was concluded last year and is providing very promising results.

(2) The Commission recently awarded $1.5 million to Mono County to continue the Magma Energy Project being conducted by the Sandia National Laboratory near Mammoth Lakes, California.

The Commission is very excited regarding the future potential of these geothermal resources. But, we also recognize that state and federal funding will not be sufficient to make these resources commercially viable, particularly given DOE's shift in funding emphasis to near-term projects. Industry must become financial participants with the government if current long-term research and development programs are going to survive.

And lastly, the Commission also administers the Energy Technologies Advancement Program (ETAP). Through this program, the CEC co-funds advanced energy projects that will increase the energy efficiency or cost effectiveness of energy technologies, or help to develop new, cost-effective alternative sources of energy. Projects must include hardware development. Nearly any type of advanced energy technology is eligible for ETAP funding, including those based on energy production, energy conservation (including advancements in recycling technology), and load management. Each year, between $4-$6 million is made available for this program. Industry is encouraged to investigate the possibilities of funding through the ETAP and Geothermal Grant and Loan Program to conduct critical research and development.

THE NATIONAL ENERGY STRATEGY -- THE ROLE OF GEOTHERMAL TECHNOLOGY DEVELOPMENT

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

WHAT IS THE NATIONAL ENERGY STRATEGY?

Early in his administration, President Bush directed Secretary Watkins of the Department of Energy to develop a National Energy Strategy (NES). The President said, "We cannot wait for the next energy crisis to force us to respond. Our task -- our bipartisan task -- is to build the national consensus necessary to support this strategy and to make it a living and dynamic document, responsive to new knowledge and new ideas, and to global, environmental, and international changes." Thus, NES is to be a dynamic strategy to provide the U.S. with adequate supplies of clean, competitively priced energy into the next century.

THE INTERIM NES REPORT

In order to develop the information base needed to determine specific short-term, mid-range, and long-term recommendations, a series of 15 public hearings was held in various parts of the country to hear testimony from both the public and private sectors. In addition, written submissions were solicited to seek input from state and local governments, consumer organizations, business, industry, and recognized representatives of diverse points of view.

Early this month, an interim NES report was issued which presents a compilation of hearing and submitted testimony containing more than 4,000 citations to individual documents or presentations, all of which are available for public review. The Interim Report stresses, however, that it is *not* the first draft of the Strategy, but an important step in building a national consensus.

The report section on Renewable Energy presents several broad findings. First, the renewable energy resources that replenish themselves naturally include:

- hydroelectric power
- solar energy
- fuels derived from biomass, including wood and related product wastes
- wind energy
- geothermal energy
- ocean energy

It was determined that these renewable energy sources are currently providing about 9 percent of the nation's domestic energy supply and about 12 percent of all domestic electric power. The installed power capacities of each of these resources excluding hydroelectric power are shown in Exhibit 1.

The report also found that many forms of renewable energy are cost-effective and commercially well established. Conversely, it was noted that others are not yet fully developed and estimates of their potential for growth vary widely. However, witnesses exhibited broad support for renewables, often citing the following reasons:

- The potential of renewables is large, and they are capable of providing a significant and reliable energy supply.
- Renewables can help reduce certain risks and vulnerabilities of our increasing reliance on imported oil.
- Production of renewable energy, with some exceptions, is generally believed to be less harmful to the environment than energy production from other sources.

The renewables section further sets forth "Publicly Identified Obstacles" to renewable development (Exhibit 2) and "Publicly Identified Options" for action to remove or overcome the obstacles (Exhibit 3). To a very large extent, these statements of "obstacles" and "options" reflect the effectiveness of the testimony provided by several geothermal witnesses at the hearings. We are indeed fortunate to have been represented by such strong and broadly knowledgeable geothermal advocates. I want to give a special thanks to Mr. Lipman of Unocal, Mr. Condy of California Energy, Mr. Bronicki of Ormat, and to Governor Waihee of Hawaii and the other state officials who made such a forceful geothermal statement.

The views of these gentlemen are further represented in a discussion in the report entitled "Indirect Costs and Benefits of Renewables." This section notes that many witnesses advocated, as did our witnesses, that "external" costs and benefits be considered in addition to market costs and economic benefits in determining the competitiveness of energy technologies. The "externalities" most often suggested for inclusion in investment decision-making include:

- security of energy supply
- effects of energy production on the environment.

Several options were identified in support of these views. For example:

"A complete fuel-cycle cost analysis could be performed for the energy system as a whole, evaluating the economic, social, and environmental costs of competing technologies to help the private sector better assess the most cost-effective allocation of resources to meet energy needs."

It is impossible to say at this point whether the NES will recommend inclusion of externalities in energy costs, or just how far a separate move in this direction will materialize at the state and local level. What we can say with assurance, however, is that if this shift in policy comes about, geothermal energy will be a winner. It *is* a secure energy supply, and increased use of this resource will greatly enhance the new concept of pollution *prevention.*

It is also impossible for me to address all the 100-plus letters sent to DOE to support NES recommendations favorable to geothermal energy. It goes without saying that I have not had time to read them all, but even without knowing their specific content, I am sure that they were effectively supportive of our mutual goals. Thank you all for participating.

I especially want to say a special thanks to Paul Lienau of the Geo-Heat Center and the others who wrote in support of geothermal direct use applications. Their input is reflected in a section of the Interim Report entitled "Direct Thermal and Lighting Applications." I am sure we all favor energy options that will enhance geothermal direct uses through cost reductions, increased resource knowledge, and other technical advances.

THE ROLE OF GEOTHERMAL ENERGY IN EXPANDING OUR ENERGY RESOURCE

In looking ahead to our detailed discussions on geothermal technology development here at the annual program review, it occurred to me that we perhaps overlook the primary goal to which we, along with other energy communities, are all working. That is, to increase the amount of our country's energy that can be economically recovered and used for beneficial purposes.

Clearly, the U.S. does not have a shortage of energy, but technology limitations exist on the amount that we can exploit economically. While those of us in the geothermal field are acutely aware of the technology limitations confronting wider exploitation of geothermal energy specifically, we may not see our research as part of a national effort to increase all of our energy reserves -- "reserve" being defined as that portion of the identified resource which can be economically extracted with existing technology under present economic conditions. Yet, isn't *that* what this meeting is all about?

Geothermal energy accounts for nearly 40 percent of our total resource base of nearly 4 million quads, or about 660,000 billion barrels of oil equivalent. Yet, the geothermal reserve is estimated to drop to only 4 percent of the total reserve of 6,400 quads. In fact, the current reserve includes only two categories of geothermal energy -- hydrothermal convection systems with temperatures of 150°C or above and low-temperature (>40°C) hydrothermal fluids for direct use applications. Our job for the present, as I see it, and our legacy for the future, is to increase the geothermal portion of the nation's energy reserves. I want to see the gap between geothermal and coal and biomass dwindle each year that we devote to geothermal technology advancement.

In broad terms, our research program for FY 1990 is geared toward three basic approaches to achievement of this goal -- 1) to preserve the productivity of The Geysers, the largest geothermal producer yet identified; 2) support the improvements in technology needed to find, evaluate, and develop geothermal resources which are not now in the reserve category; and 3) reduce the cost of exploiting current reserves to increase the competitiveness of the U.S. geothermal industry -- both in this country and abroad.

THE GEYSERS RESEARCH PROJECT

As is well known by now -- both within and without the geothermal community -- serious problems have arisen at The Geysers. These include:

- decline in productivity
- appearance of corrosive chlorides
- increases in noncondensible gases
- adverse effects of pressure decline on turbine efficiency.

While operations at The Geysers are, and always have been, an industry pursuit, the government feels an obligation to help restore the productivity of the field and to alleviate the other problems to the extent that we can. This is because The Geysers complex offers an opportunity to determine the needs for managing mature geothermal fields, our first such opportunity in the U.S., and we see this as equally an important government function as supporting the technology needed to open new fields. In addition, the success of The Geysers, and now its decline, have received so much attention worldwide that restoration of confidence in this field is critical to maintaining confidence in all proven and yet-to-be-proven geothermal fields.

However, government support of Geysers research is critically dependent on two factors. One is industry willingness to provide all existing data pertaining to the characteristics of the field. Funds are not available to start from "Square 1." Second, industry cost-sharing is essential. While GTD has allocated over $1 million for this effort for FY 1990, that amount will not go far in face of today's costs.

Despite the fact that The Geysers may have been the subject of more research than any other geothermal reservoir, several parameters remain poorly understood. These include:

- the initial distribution and amount of liquid water
- reservoir thickness
- matrix permeability
- characteristics of the fracture network.

In order to fill these information gaps, to address the other problems plaguing operations at The Geysers, and to determine whether water injection is the optimum "cure" for The Geysers, GTD has funded 11 research projects for FY 1990. Those selected for immediate funding were judged to be the most critical and most responsive to industry needs. In those projects where only partial funding was available, the pace of research will be slower than proposed. However, all of these projects are available for cost-sharing with industry to increase the pace of research or to augment the projects with additional studies, and suggestions or comments from the geothermal community would be greatly appreciated.

In addition, the proposers of other research projects that were not selected for this first round are being encouraged to solicit industry cost-sharing for partial support. And, it is to be remembered that the Geothermal Drilling Organization and the Geothermal Technology Organization are available to act as funding consortia to support the most important research projects, and both provide 50 percent cost-sharing by DOE.

You will be interested in the focus of the projects funded. The geochemical research projects are as follows:

- A thermodynamic investigation of hydrogen chloride in steam by the Oak Ridge National Laboratory.
- Development of new vapor phase tracers by the University of Utah Research Institute that can be used to quantify the mass recovery of injected fluids.
- A study of steam chemistry by the U.S. Geological Survey with the cooperation of operating companies and the International Institute for Geothermal Research.
- Fabrication of a six-liter downhole fluid and gas sampler by Lawrence Berkeley Laboratory based on a smaller version used successfully in the Imperial Valley and in a Continental Scientific Drilling Project well in the Valles Caldera, New Mexico.

The geophysical research projects include:

- Microearthquake studies at The Geysers by LBL in conjunction with the Coldwater Creek Operator Corp. using the 16-station CCOC array presently in place in the northwest portion of the field.
- Continuation of the ongoing Lawrence Livermore National Laboratory seismic attenuation study to locate steam.

The reservoir engineering projects include:

- Investigation of the phenomenon of water adsorption in porous rocks at Stanford University through lab experiments with Geysers core material. In parallel, engineering methods for using adsorption to plan development and forecast results will be explored.
- Examination by Stanford of all the tritium survey data collected by several operating companies in light of physical information on the wells (such as feed point depth) as well as subsequent performance (e.g., temperature and pressure).

The reservoir modeling projects include:

- Development by LBL of a data base for The Geysers, incorporating all available geological, geochemical, and reservoir engineering data, to be subjected to theoretical and applied studies to quantify the impact of increased injection.
- Documentation by LBL of several of the MULKOM fluid property modules so that the simulation capabilities of the code can be made available to the public.

The geological research project funded so far involves fluid inclusion studies by UURI on Geysers core samples where the age relationships among the secondary minerals can be defined. Results of this initial work will provide the necessary background for interpreting similar data to be obtained from cuttings.

We have all agreed that this effort should get off to a fast start and continue at an expeditious pace. I am happy to report that the researchers have now received their funding and their projects should be well underway.

OTHER GTD RESEARCH ACTIVITIES FOR FY 1990

Since you will be hearing in detail about our other research activities for FY 1990 directly from the researchers involved, I will touch only very briefly on them here. However, I think the time is well spent to look at them first as a complete package, and then to digest the component parts. The GTD FY 1990 budget is shown in Exhibit 4.

As discussed above, a large portion of the funds for the reservoir technology project are being expended on work at The Geysers. However, we expect to pursue other activities in the areas of reservoir analysis, injection, and exploration, and plans will soon be finalized.

As shown in Exhibit 5, the hard rock penetration project is focusing on four tasks this year: lost circulation control, rock penetration mechanics, instrumentation, and participation in Geothermal Drilling Organization projects.

Some GDO projects of several years' duration are being completed this year. Service companies are being encouraged through a bid system to take over commercialization of the high-temperature borehole televiewer for inspecting casing downhole, and, after a final field test of the re-designed downhole air turbine for directional drilling, this equipment will be manufactured for sale. The drill pipe protector effort will also be concluded after final testing of additional elastomers at The Geysers. Full-scale rotary head seals, also incorporating high-temperature elastomers, will be fabricated and tested in both geothermal brine and steam environments. New initiatives are under consideration.

The conversion project is continuing with activities in heat cycle research, materials development, and advanced brine chemistry. The major emphasis of the Heat Cycle Research Facility tests will be the investigation of condensation behavior of supersaturated turbine expansion. The materials task is focusing primarily on lightweight, high-alumina cements for well completion with a high resistance to carbon dioxide and carbon steel heat exchanger tubes lined with thermally-conductive polymer concrete. This year's phase of the brine chemistry modeling effort is to extend model parameters for alumina-silicates, sulfates, and hydrogen sulfide. In addition, scaled-up biochemical experiments for detoxifying geothermal wastes will be continued.

The major effort at the geopressured well sites this year is completion of the experimental testing of a hybrid binary unit at Pleasant Bayou. From August 1989 to April 1990, the turbine operated over 1300 hours, and the gas engines operated over 2400 hours. Both met specified design performance.

Activities at the Fenton Hill hot dry rock site continue to be oriented toward preparation for the long-term flow test of the Phase II reservoir. The procurement and installation of requisite equipment will be completed by September 1. Research is continuing at the 2,500 foot phase of the magma exploratory well, and scientific experiments are being conducted with other well sponsors.

A FAST TRACK FOR RENEWABLES

While the Department continues to analyze and evaluate the many options proposed during the NES hearings, Secretary Watkins has already put seven options on a fast track, including increased use of renewable energy. These options, the Secretary said "are sufficiently mature" to be forwarded now for consideration by the Economic Policy Council.

Renewables are the only energy sources or technologies included in this group. The other options are:

- integrated resource planning
- enhanced energy efficiency
- streamlined technology transfer
- upgrading math and science skills
- modeling the U.S. energy economy
- pollution prevention and waste minimization.

Renewable energy in general -- and geothermal energy in particular -- are beginning to gain increased visibility and acceptance at the National level. It is the challenge to us in the research community to use this opportunity to demonstrate clearly to decision-makers, as well as society as a whole, that geothermal energy can help satisfy the Nation's energy needs in an environmentally acceptable manner.

EXHIBIT 1
RENEWABLE ENERGY
NES INTERIM REPORT
April 1990

CURRENT U.S. INSTALLED POWER CAPACITY OF NONHYDRO RENEWABLES

Biomass*	7,300
Geothermal	2,780
Wind	1,400
SolarThermal	270
Photovoltaics	13

* Includes wood and wood wastes, agricultural wastes, and municipal solid wastes.

EXHIBIT 2
RENEWABLE ENERGY
NES INTERIM REPORT
April 1990

PUBLICLY IDENTIFIED OBSTACLES CONFRONTING NONHYDRO RENEWABLES

- Reluctance of energy users to invest because of the lack of clear signals about future energy prices
- Inhibition of the development of currently competitive technologies -- e.g., municipal solid waste, wood burning, geothermal energy -- by existing policies and regulations
- Utility pricing practices, denial of transmission access, and high capital costs
- Diminished or vanished investments in an era of declining oil prices
- Insufficient federal tax credits, unfavorable depreciation allowances, and unfavorable treatment under PURPA
- Insufficient R&D in public and private sectors due to fluctuations in other energy prices and changing government policies

EXHIBIT 3
RENEWABLE ENERGY
NES INTERIM REPORT
April 1990

PUBLICLY IDENTIFIED OPTIONS FOR NONHYDRO RENEWABLES

- Consistent and predictable regulatory treatment
- Environmental and regulatory policies based on scientific benefit/cost analysis
- Incentives (e.g., tax credits, tax exemptions, loan programs) to accelerate use of market-ready technologies
- Requirements for use in new federal buildings
- Creation of set-asides
- Increased public attention through presidential speeches and site visits
- Expanded support for moving technology from research stage to industrial production
- Opportunities for cooperative public/private sector arrangements to advance technologies
- No governmentally-favored energy -- use of the marketplace for all energy sources to find their proper place

EXHIBIT 4
GEOTHERMAL TECHNOLOGY

Program Activity Actual	FY 1989 Actual	FY 1990	FY 1991 Request
Geopressured Research	$5.930	$5.855	$2.900
Geothermal Technology Development			
Hard Rock Penetration Research	2.250	2.233	3.400
Reservoir Technology	2.450	2.098	4.000
Conversion Technology	1.935	1.544	2.795
Hot Dry Rock Research	3.500	3.426	3.600
Magma Energy	1.635	1.663	. 0
Subtotal, Geothermal Technology Development	$11.770	$10.964	$13.795
Capital Equipment	$.795	$.444	$.405
Program Direction	.826	.814	.900
Total, Geothermal Technology	$19.321	$18.077	$18.000

EXHIBIT 5

OTHER FY 1990 GTD R&D PROJECTS

HARD ROCK PENETRATION

- Field test insulated drill pipe
- Conduct preliminary test of second generation fracture mapping tool
- Verify circulation models
- Support field evaluation of lost circulation materials
- Field test LC materials (pumpable setting fluids, cements, and foam)

CONVERSION

Heat Cycle

- Test performance of mixed working fluids in supercritical cycles
- Investigate condensation behavior of metastable hydrocarbon turbine exhausts

Materials

- Test CO_2-resistant cements downhole
- Analyze performance of polymer concrete-lined heat exchanger tubing in binary fluids

Brine Chemistry

- Develop a unique thermodynamic brine model capable or predicting scale formation
- Extend model parameters for alumino-silicates, sulfates, and H_2S

Waste Treatment

- Scale up biochemical experiments to evaluate most promising detoxification techniques for geothermal wastes

GEOPRESSURED

- Complete flow and pressure testing at the Gladys McCall site
- Conduct long-term flow test of Pleasant Bayou reservoir and operate energy conversion system
- Conduct preliminary flow testing of Hulin Well
- Continue university research on rock mechanics, reservoir modeling, logging, liquid hydrocarbons, and environmental effects

HOT DRY ROCK

- Complete procurement and installation of components for long-term flow test
- Conduct preliminary system flow tests
- Provide sufficient water to conduct LTFT

MAGMA

- Conduct research on exploratory well
- Conduct ongoing scientific experiments with other well sponsors

HYDROTHERMAL ENERGY CONVERSION TECHNOLOGY

Chairperson: Kenneth J. Taylor
Idaho Operations Office, U.S. Department of Energy

HYDROTHERMAL ENERGY - AN IMPORTANT PART OF AMERICA'S ENERGY STRATEGY

Kenneth J. Taylor
U.S. Dept. of Energy
Idaho National Engineering Laboratory

Marshall Reed
U.S. Dept. of Energy
Washington, D.C.

Howard Ross
University of Utah Research Institute
Salt Lake City, UT

ABSTRACT

The U.S. Dept. of Energy (DOE) established a Geothermal Energy Program in the mid-1970's as one response to America's need to develop alternative energy sources. One element within the Geothermal Program is Hydrothermal Energy, which includes Industrialization, Reservoir Technology, and Conversion Technology as separate tasks. The successes which have resulted from this program, combined with anticipated future progress, will increase the role of geothermal energy as a contributor to our nation's future energy needs. Geothermal energy has become an important component of the U.S. National Energy Strategy.

INTRODUCTION

During the 1970's America became increasingly concerned about its' dependence on imported fossil fuel energy. As a result, a national commitment was made to evaluate and develop alternative energy resources. Among the many alternative energy resources being considered was geothermal energy. There were, and are, several characteristics about the geothermal energy resource which make it advantageous over other resources. It's abundance in the United States and the fact that it's development poses a minimum hazard to the environment are among the many advantages. However, there were many unknowns concerning this resource. Recognizing this, the United States Department of Energy (USDOE) established a Geothermal Program which continues today.

Because of the various forms in which the Geothermal resource takes, the USDOE's Geothermal Program consists of four categories: Hydrothermal, Geopressured, Hot Dry Rock and Magma. This paper describes the Hydrothermal energy research category and indicates the status for some of its' current projects.

The hydrothermal resource consist of large reservoirs of heated fluid. The temperatures and chemical composition of the reservoir fluids vary which in turn varies the way they are utilized. Low-and moderate-temperature resources, (10 to 150 C) are used primarily in direct heat applications such as heat pumps, aquaculture, and space heating. High temperature resources, (¶150 C) are more commonly used for power generation.

There are many challenges to utilizing the high temperature hydrothermal resource. These challenges include locating and quantifying the resource, drilling into the resource, handling the brines, solving power plant development and maintenance problems, and injecting the brines. The goal of the Hydrothermal Program is to provide solutions to challenges such as these and ultimately to reduce the life-cycle cost of electricity produced from the hydrothermal resource to 3 - 7 cents / kWh by 1997.

Because of the wide range of utilization and the accompanying challenges, the Hydrothermal Program has been divided into four tasks. These tasks are Industrialization, Reservoir Technology, Hard Rock Penetration and Conversion Technology. DOE-HQ located in Washington D.C. provides the program management for all of these tasks. The project management for all tasks with the exception of the Hard Rock Penetration task, is provided by DOE-ID located in Idaho Falls, ID. This paper will only discuss those tasks managed by DOE-ID. The fiscal year 1990 budget levels for these tasks are shown in Table 1.

Task	Funding, ($K)
Reservoir Technology	2,100
Energy Conversion	1,500
Industrialization	350

TABLE 1 - FY-1990 funding for tasks in the Hydrothermal Program

Each task consists of several projects, which are being carried out by various government labs, universities and contractors. A description and status of the three tasks and their respective projects follows.

INDUSTRIALIZATION

The goal of the industrialization task is to promote the use of Geothermal Energy throughout the nation and the world. The industrialization task is broken up into two projects. These projects are State Cooperative Grants and Direct Heat Participation & Support.

State Cooperative Grants

The State Coupled Grants project consists of 12 cost shared grants to various groups to study aspects of geothermal energy that are not being studied by private industry, but which have the potential for results that will be applicable to industry. One additional grant funded by the Reservoir Technology task supporting deep scientific drilling the Cascades is also reported here. Figure 1 indicates those states with a participating state team(s) and the study areas involved. The total funding for the grants in this project is $1,524,996. The grant participants and a brief description of their projects follow.

State Cooperative Program

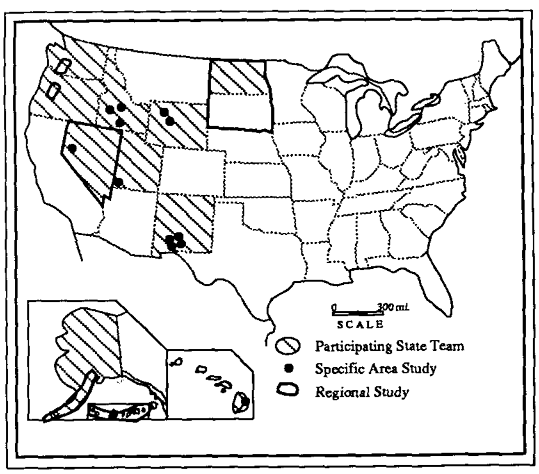

Figure 1. Participating state teams and study areas, State Cooperative Program

The University of Alaska, Geophysical Institute is performing a geologic and geochemical study of the Geyser Bight geothermal resource, Umnak Island. Results to date indicate that a zoned plutonic rock unit 9.5 (Ma) is the probable reservoir rock, and volcanic rocks range in age from 75,000 to 534,000 years. A previously unreported fumarole field, 4 km south of Geyser Bight valley, was discovered during this study.

The state of Alaska, Division of Geological and Geophysical Surveys, has completed a fluid chemistry study of the Geyser Bight area in support of the Geyser Bight geologic study. Fluid chemistry analyses indicate spring waters are derived from two separate reservoirs. Estimate reservoir temperatures, uncorrected for some dilution, are 221-228 C and 225-235 C. Much work remains to be done on the Aleutian Island - Alaska Peninsula geothermal resource map.

The state of Hawaii, Department of Business and Economic Development, is studying methods to control silica deposition from geothermal fluids of the Hawaii East Rift Zone. Mixing of 60% condensate and 40% brine, and treatment with weak acids both show great promise in retarding silica precipitation. The high surface area of precipitated silica may have some commercial value. Completion of the study has been delayed by shutdown of the HGP-A well, the only source of fluids for the study.

The state of Idaho, Department of Water Resources is completing a geochemical study of the Wood River geothermal systems and monitoring of the Banbury-Twin Falls reservoirs. The Berkeley Group, Inc., a subcontractor to ID-DWR, completed a detailed review of all existing data to constrain numerical simulations of present and future reservoir behavior under various development scenarios. All studies will be completed in 1990.

The Desert Research Institute, University of Nevada has completed a 13 month hydrologic monitoring program at the Moana geothermal system. These and other geologic data are being used to complete a quantitative evaluation and numerical model of the Moana resource. The results and the numerical model will be made available to regulatory agencies and developers to coordinate future development of the resource.

The University of Nevada Las Vegas, Division of Earth Sciences has completed a study of the genesis of geothermal fluids of the Great Basin. The study has determined a late Pleistocene age (40,000 - 10,000 years BP) for the fluids which indicates a paleo-recharge scheme. Range-bordering faults probably provide conduits for recharge of the deep geothermal systems. Pleistocene lakes probably contributed to recharge in western Nevada.

The New Mexico Research and Development Institute is using a subcontractor, New Mexico State University, in a study to evaluate the use of time-integrated radon soil-gas surveys for geothermal resource assessment in the southern Rio Grande Rift. One drill hole which tests a radon anomaly in the Rincon survey area has recorded a temperature of 65 C at depth of 90 meters. This study has advanced the radon soil-gas technique and yielded several target areas for moderate-temperature geothermal fluids.

The state of North Dakota, Mining and Mineral Research Institute, is cooperating with the Geological Surveys of North Dakota and South Dakota in a comprehensive geothermal resource assessment. Five heat flow holes have been drilled and logged in the South Dakota heat flow anomaly. Five more heat flow holes will be drilled this spring, three in South Dakota and two in North Dakota. New studies suggest the stratabound geothermal resource may be twice as large as previously reported.

The State of Oregon, Department of Geology and Mineral Industries, is drilling a deep scientific and heat flow hole at Santiam Pass on the crest of the Oregon Cascades. The projected depth of Santiam Pass 77-24 is 3000 feet. This project is jointly funded by DOE and Oxbow Geothermal Corporation. This hole was drilled to 460 feet and cased in November prior to shutdown for winter.

The state of Utah, Geological and Mineral Survey, has completed a multidisciplinary study of the Newcastle resource which currently provides space heating for three large greenhouses, a church, and several residences. Geological, geophysical, and geochemical studies have characterized this hidden resource in detail, and have determined a reservoir temperature in excess of 130C, with an anomalous heat loss of 12.4 MW. The study suggests new approaches for the discovery of other hidden Basin and Range geothermal systems.

The state of Washington, Department of Natural Resources drilled eight 152 meter temperature gradient holes to better define the southern Washington Cascade Range heat flow data. Two holes did not penetrate the effects of cold surface waters, but four holes had temperature gradients of 50 to 58 degrees C/km. A related study integrated K-Ar age dates, geochemistry and volcanic stratigraphy of the Indian Haven Quaternary volcanic to evaluate volcanic production rates.

The state of Washington, State Energy Office is finalizing a computer program (GEODIM) which optimizes the design of wells, pipes, pumps and heat transfer systems.

The University of Wyoming, Department of Geology and Geophysics is developing an improved three-dimensional computational scheme for solving the combined heat conduction and forced convection equations for determining subsurface temperatures. A model will be developed for one of the Bighorn Basin hydrothermal systems.

A review of the interim and final results so far indicates that the current state team grants have been extremely productive in terms of developing new resource information (Washington Cascades; Newcastle, Utah; Rio Grande Rift), reservoir monitoring and evaluation data, and in addressing production problems (Hawaii silica studies).

Information and reports pertaining to these projects can be obtained by contacting Dr. Howard Ross at the University of Utah Research Institute. The majority of these grants will be completed by December, 1990. If additional funding becomes available for this project, it will be continued with new grants being issued.

Direct Heat Participation & Support

The Direct Heat Participation and Support project is made up of activities which have been or are taking place under two grants. The two grantees are the Oregon Institute of Technology and the National Geothermal Association.

The grant with the Oregon Institute of Technology, (OIT) is to perform research and development assistance in areas of geothermal direct-use development, and moderate temperature (90 - 150 C) wellhead electric generating systems. Direct-use development assistance ranges from answering technical questions and consultations on methods, equipment and applications to providing technical and engineering economic feasibility studies. Applications areas include space and district heating, geothermal heat pumps, greenhousing, aquaculture, and industrial processing.

Recipients of technical assistance include individual home and business owners, district heating systems operations and maintenances personnel, and consulting engineers. Work consists of consultation during initial design phases of projects, trouble shooting and failure analysis, and recommendation for corrections.

The Geo-Heat Center also provides information services in the forms of: a quarterly Bulletin (2000 subscribers), special technical papers and presentations, Geothermal Direct Use Engineering and Design Guidebook, published feasibility studies, a geothermal library, computer programs to aid in design, and tours of geothermal facilities.

Current research activities include: (1) ascertaining optimum exploration and assessment strategies for hydrothermal and geopressured resources collocated with cities and potential greenhouses and aquaculture sites; (2) investigation into the use of uninsulated piping for geothermal district heating systems; and (3) reservoir/well interaction research involving the downhole heat exchanger.

Anyone interested in the technical assistance or information pertaining to this work should contact Paul Lienau, OIT.

The grant with the National Geothermal Association is intended to promote U.S. geothermal technology world wide. A number of the projects taking place in this grant have had significant cost share from state governments and industry. To date, the grant has resulted in a number of accomplishments. Among them are: (1) conferences between foreign geothermal developers and U.S. power plant companies to allow foreign developers to see first hand the services which exist in the U.S.; (2) giving the World Bank a briefing on geothermal energy; (3) developing a report titled "A National Strategy for the Export of U.S. Geothermal Technology"; and (4) sending a team of U.S. geothermal developers to the Magati Soda Company located in Kenya and to Central America to assess the U.S. geothermal industries opportunities.

Activities currently underway include the development of world wide power plant data base and a Geysers Monograph.

The work done under this grant has been extremely productive in helping U.S. geothermal industries assess their opportunities world wide. A report has been developed for each project which has taken place under this grant. These reports can be obtained by contacting Dave Anderson, National Geothermal Association.

RESERVOIR TECHNOLOGY

The goal for the Reservoir Technology task is to improve the technology for geothermal energy resource utilization by developing and testing analytical and interpretive methods to more effectively locate, develop and utilize hydrothermal resources. By obtaining this goal, it is thought that:

> Industry will be enabled to maximize energy recovery from a resource through more realistic predictions of reservoir performance.
>
> The adverse thermal and chemical effects of injection on geothermal reservoirs will be reduced.
>
> New techniques will be developed to identify fractures in geothermal reservoirs and to locate geothermal reservoirs.

The task is broken into five projects: Reservoir Analysis, Exploration Technology, Brine Injection, Geothermal Technology Organization, and Geysers Related Research.

Reservoir Analysis

The Reservoir Analysis project is intended to provide analytical and interpretive tools for determining reservoir characteristics and reservoir performance with greater certainty. The objectives for the project are to improve production well siting and decrease the uncertainty associated with long-term reservoir decline. Several activities are currently taking place in this project.

The Lawrence Berkeley Laboratory (LBL) and the University of Utah Research Institute (UURI) are developing new geophysical equipment and field testing its' use for monitoring fluid flow in reservoirs. LBL continues the testing of vertical seismic profiling and microseismic monitoring for detection and mapping of fractures in geothermal systems. Finally, LBL and UURI are developing and verifying computer modeling methods to evaluate the use of borehole geophysical techniques for locating fractures and permeable zones in geothermal systems.

Stanford University, the Idaho National Engineering Laboratory (INEL) and LBL are analyzing field data from individual production well tests and interference tests. They will refine computer modeling techniques for identifying reservoir processes and evaluating their impact on the response of hydrothermal systems to development. In addition, UURI, LBL and INEL are interpreting field data and attempting a synthesis of knowledge about reservoir processes.

Stanford and LBL are continuing their efforts to develop theoretical and computer models to predict reservoir performance from combined well testing and production history. They are using laboratory physical models to develop techniques for simulating the response of geothermal systems to different reservoir management programs and evaluating the usefulness of these techniques for estimating the generating capacity and longevity of these systems.

Brine Injection Technology

The Brine Injection Technology project addresses industry needs for effective and environmentally acceptable injection systems which reduce adverse impacts on geothermal reservoirs. The objective for this project is to decrease the uncertainty associated with injecting brines into producing reservoirs. The project is focusing on three specific areas: fluid migration, fluid-rock chemical interactions, and injection well placement.

UURI is evaluating potential geothermal tracers in laboratory experiments which simulate natural geothermal systems. They are developing, with industry, field operations techniques for tracer injection, sampling, and interpretation to track the transport of injected fluid. INEL and Stanford are applying computer modeling techniques to the tracer return field data for the determination of reservoir physical properties and fluid interactions in the reservoir. UURI, Stanford, LBL and INEL are participating in a field test with Oxbow Geothermal Company in the Dixie Valley system to verify tracer usefulness and to develop interpretative methods to analyze tracer results.

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

INEL is continuing to develop computer models with the capability to analyze and predict the flow of injected fluids through reservoirs. INEL researchers are investigating the potential for coupling the fluid flow computer model with models of chemical interactions between rocks and the injected fluid. The INEL fluid flow model FRACSL is available for simulation of injection into commercial geothermal systems.

Exploration Technology - The Exploration Technology project is designed to develop techniques to locate and characterize geothermal resources. The objectives for this project are to increase the success ratio of wildcat wells and to devise better methods of discovering hidden geothermal systems. The following work is currently being done in this project.

UURI is collecting and analyzing existing data from geothermal exploration projects and is integrating it with geological, geophysical and geochemical data from field and laboratory investigations to develop conceptual models for exploration of geothermal systems. UURI is also utilizing this data to prepare case studies of resource exploration for the industry.

UURI and LBL are performing numerical analysis to determine theoretical geophysical responses from fluid filled fractures and are designing and conducting field tests of surface geophysical techniques to verify the responses expected. They are investigating the use of new interpretation methods for locating fractured hydrothermal systems. They are concentrating on electromagnetic and passive seismic methods of exploration and will combine the observed geophysical data with laboratory measurement of physical properties and existing geologic data to provide exploration plans for regions like the Cascades volcanic province for which the data sets are available.

Geothermal Technology Organization

The Geothermal Technology Organization (GTO) has been formed by the DOE and Industry to sponsor geothermal technological development. The geothermal industry works with the DOE through a cooperative research agreement between the DOE Idaho Operations Office and the GTO. The DOE is represented in the GTO by the INEL.

Research selected for funding by GTO has a high likelihood of yielding near term benefits.

Geysers Related Research

At the last Geothermal Technology Division annual review meeting, several operators asked for research directed toward the problems at The Geysers geothermal field. After discussions with operators and researchers, a number of proposals were compiled to study various aspects of The Geysers reservoir. Several of the proposals were selected for initial funding under the Reservoir Technology Program because of industry interest and the immediate need for the research. The remaining proposals are still under consideration for funding. Industry cost sharing will be an integral part of the support for these remaining projects.

The research projects will be conducted by various laboratories and universities. A strong management team has been designated to coordinate the research projects and to facilitate communication between researchers and industry. Dr. John E. Mock, Division Director, has designated Lawrence Berkeley Laboratory as the "Lead Laboratory" for the The Geysers Research, and he asked Dr. Marcelo Lippmann to act as coordinator and to provide the geothermal operators with a point of contact for joint projects in The Geysers. Mr. Joel Renner, coordinator for the Geothermal Technology Organization, will provide additional contact for the research projects cost-shared with industry. Federal management for the research is provided by Mrs. Peggy Brookshier at the Idaho Operations Office, and by Mr. Marshall Reed in DOE Headquarters.

Initial funding has been provided for research activities relating to geochemistry. Mike Simonson and Don Palmer at the Oak Ridge National Laboratory will begin a thermodynamic investigation of hydrogen chloride in steam to determine the thermodynamic parameters. Mike Adams at the University of Utah Research Institute will initiate the development of vapor phase tracers to track injected fluid through the reservoir. Al Truesdell at the U.S. Geological Survey will continue his investigation of chemical indicators that show the changing conditions in The Geysers reservoir. Ray Solbau of Lawrence Berkeley Laboratory will modify the LBL downhole sampler for vapor collection in the reservoir.

Two geophysical research projects have received initial funding. Ernie Majer of Lawrence Berkeley Laboratory will conduct microearthquake studies at The Geysers to determine the stress system around injection wells. Jay Zucca of Lawrence Livermore National Laboratory will continue the seismic attenuation study to locate steam in undrilled areas.

Several projects dealing with reservoir engineering and modeling received initial funding. Hank Ramey and Frank Miller at Stanford University will renew their investigation of water adsorption in porous rocks to determine the initial saturation of The Geysers. Roland Horne also of Stanford University will work with the data collected by the operators to analyze previous tracer tests conducted in the field. "Bo" Bodvarsson at Lawrence Berkeley Laboratory will continue to develop a general data base that will be available to operators and researchers and will develop a model to evaluate injection. Karsten Pruess also at Lawrence Berkeley Laboratory will provide new documentation of geothermal modules for the numerical model MULKOM that will be available to industry.

One of the geological studies received initial funding. Joe Moore of University of Utah Research Institute will conduct fluid inclusion studies of Geysers rocks to determine fluid compositions and temperatures of trapping.

ENERGY CONVERSION

The goal for the Energy Conversion Task is to develop concepts which will allow better utilization of Geothermal energy at a reduced cost. The task is broken into three projects: Heat Cycle Research, Materials Development and Advanced Brine Chemistry.

Heat Cycle Research

Several recent studies have indicated that geothermal developers are very concerned with power plant technology. In particular, developers have expressed an interest in binary plant technology and cooling systems. The Heat Cycle Research Project is primarily concerned with advancing binary power plant technology. The main objectives for the project are as follows:

Increase net geothermal fluid effectiveness of binary plants by incorporating concepts which reduce cycle irreversibilities and increase availability.

Increase net geothermal fluid effectiveness of binary plants through the utilization of supersaturated vapor expansions in the turbine.

Reduce heat rejection system cooling water make-up requirements for geothermal power plants, while retaining performance comparable with conventional wet cooling.

The Heat Cycle project is carried out by the Idaho National Engineering Laboratory, (INEL). The project utilizes a Heat Cycle Research Facility to generate experimental power plant data. This facility is a small (60 kW) power plant located at the B C McCabe Binary Power Plant in California's Imperial Valley. Data received from this facility is analyzed by the INEL.

During the 1980's a number of concepts were developed to increase the overall efficiency of geothermal power plants. Three of these concepts included using an optimized mixed hydrocarbon working fluid, countercurrent flow paths in heat exchangers and integral phase changes in the condenser. These concepts have been tested at the Heat Cycle Research Facility over the past 6 years. These tests have confirmed that, relative the Heber Binary Power Plant, a 20% improvement in brine utilization can be realized by applying the concepts. This improvement results in a 12 to 18% in reduction in cost of electricity. Currently, the final field tests are being completed and the data summarizing the tests is being organized for formal reporting.

The Heat Cycle Research Facility is preparing for the supersaturated turbine expansion tests which can provide an additional 8% improvement in geofluid effectiveness to begin in 1991. In the expansion, the working fluid vapor passes through the "two-phase" region as it is expanded in the turbine. Although these expansions can be shown theoretically to improve the geofluid effectiveness, they are not totally utilized because of concern relative to liquid condensate formation and the potential for damage to the turbine blades. The INEL has developed a 2-D nozzle which will be used to determine the limits regarding supersaturated turbine expansion and condensate formation.

In addition to the activities taking place at the Heat Cycle Research Facility, work is also being done to evaluate more advanced cycles and to test materials which may result in heat exchanger scale reduction. For more information on the work taking place in this project contact Mr. Greg Mines or Dr. Carl Bliem, both of EG&G Idaho.

Materials Development

Geothermal brines are often extremely difficult to work with. High temperatures and corrosiveness make the selection of materials to use for drilling a well, producing a well, and operating a geothermal power plant very difficult. The objective for the Material Development project is to reduce the costs associated with lost circulation; develop well cementing materials which have a lifetime of 30 years at 400 - 600 C; develop corrosion resistant, low fouling heat exchangers; and development of elastomers which can be used in the drilling applications. This project is currently broken into four activities described below. All these activities are being conducted out of Brookhaven National Laboratory, (BNL).

Chemical systems for lost circulation control are currently being developed at BNL in a collaborative effort with Sandia National Laboratory's Hard Rock Penetration Task. Efforts at BNL consist of developing chemical systems which are tested at the Sandia National Laboratory. At this time both the formula for the lost circulation material and the pumpability have been established.

The development of advanced high-temperature cements is being conducted in three phases. First, light weight cements are being tested in low CO2 containing brines. The testing was completed in 1989. Second, ceramic-like cements which can be used for well completions at temperatures up to 500 C are being developed. Third, CO2-resistant high-temperature cements are being developed.

A thermally conductive polymer concrete coating has been developed at BNL. This coating is being tested in a heat exchanger apparatus which was built and will be tested by the Idaho National Engineering Laboratory in Hawaii. The results of this experiment will be analyzed and reported in a collaborative effort by both laboratories.

Advanced elastomers for downhole drill motors are currently being developed. These elastomers are being optimized for sealing applications and for use as a stator in a downhole drill motor. To date the work has been focused on developing and doing laboratory tests. If these tests are successful, the elastomers will be fabricated and field tested.

This project has resulted in a large amount of interaction between BNL and industry. Individuals interested in this work should contact Larry Kukacka, BNL

Advanced Brine Chemistry

Handling and disposing of geothermal brine can be difficult because of the brine chemistry. Brine scaling results in handling difficulties. Brine chemical content often results in disposal problems which arise for environmental reasons. The advanced brine chemistry project is attempting to reduce these obstacles. The project consists of two activities: modeling and waste disposal.

The modeling activities are taking place at the University of California at San Diego, (UCSD). The objective for this activity is to reduce the costs associated with scale deposition on production well casing and power plant equipment. UCSD is carrying out research involving aqueous chemical models for geothermal process design. The University has developed a variable temperature model which predicts calcium carbonate, calcium sulfate, and amorphous silica scale formation as a function of brine composition and partial pressure of CO_2.

The model has a temperature range of 0 to 250 degrees C. Current modeling activities are focusing on the addition of gas model parameters, such as hydrogen sulfide and methane solubility. Individuals interested in this model should contact John Weare, Univ. of California at San Diego.

The waste disposal activities are taking place at Brookhaven National Laboratory, (BNL). The objective for this activity is to reduce costs of surface disposal of sludge from geothermal brines. In cooperation with industry, BNL is developing low-cost biochemical processes to concentrate or solubilize toxic materials from geothermal brine residues. A number of bioreactor designs have been constructed. Studies dealing with the optimization of sludge concentration and the use of thermophilic and thermo-adapted microorganisms are in progress. Furthermore, experiments using calcium and flat-bed bioreactors with different sludge loading and mixing times are being conducted to study subsequent bioreactor designs capable of accommodating larger volumes (0 - 350 gallons). People interested in more information on this work should contact Gene Premuzic, BNL.

CONCLUSION

It is evident that in the Hydrothermal program, a significant amount of work is being done on a large range of subjects. This work is being done to solve the problems which may inhibit industry from fully developing hydrothermal resources. In order for this work to be effective, industry must provide the government with input regarding their specific concerns. While this input is ongoing in many of the projects, more industry input and involvement is always needed.

With continued research in the Hydrothermal program, ultimate objective of reducing the cost of electricity produced from the hydrothermal resource will be achieved. As this takes place, it will be a positive step in our country's search for alternate energy sources. More importantly, it will allow our nation to reduce its' need for foreign energy products.

ACKNOWLEDGMENT

I wish to thank Joel Renner, Idaho National Engineering Laboratory for providing information on the Reservoir Technology section; Larry Kukachka, Brookhaven National Laboratory for providing information on the Geothermal Materials project, Paul Lienau, Oregon Institute of Technology for providing information on their Industrialization project, and Gladys Hooper, U.S. Dept. of Energy for providing information on the Advanced Brine Chemistry project.

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ADVANCED BINARY GEOTHERMAL POWER PLANTS LIMITS OF PERFORMANCE

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ABSTRACT

The Heat Cycle Research Program is currently investigating the potential improvements to power cycles utilizing moderate temperature geothermal resources to produce electrical power. Investigations have specifically examined Rankine cycle binary power systems. Binary Rankine cycles are more efficient than the flash steam cycles at moderate resource temperatures, achieving a higher net brine effectiveness. At resource conditions similar to those at the Heber binary plant, it has been shown that mixtures of saturated hydrocarbons (alkanes) or halogenated hydrocarbons operating with a supercritical Rankine cycle gave improved performance over Rankine cycles with the pure working fluids executing single boiling cycles.

Recently, in addition to the supercritical Rankine Cycle, other types of cycles have been proposed for binary geothermal service. This paper explores the limits on efficiency of a feasible plant and discusses the methods used in these advanced concept plants to achieve the maximum possible efficiency. The advanced plants considered appear to be approaching the feasible limit of performance so that the designer must weigh all considerations to find the best plant for a given service.

INTRODUCTION

The Heat Cycle Research Program is currently investigating the potential improvements to power cycles utilizing the moderate temperature geothermal resources to produce electrical power. The technology being considered either improves the performance of the power cycle and reduces the cost of electricity, or it provides a means of utilizing a resource which might otherwise not be used because of institutional or technical barriers. Although geothermal energy is provided by nature, it is generally expensive to produce, and compared to fossil fuel is a low grade energy source. Because of the low quality and high cost of the energy, optimized systems for the generation of electrical power should utilize as much of the energy contained in a unit mass of the fluid as possible. This optimization was confirmed with both a "value analyses" study and a "market penetration" study which examined the impact of performance improvements on the cost of electricity and on the future utilization of geothermal produced electrical power if these improvements could be realized (1,2). The net brine effectiveness, or the net electrical energy produced by the plant per unit mass of geofluid, is used as a primary indicator of the improvements in the cycle performance.

The Heat Cycle Research Program investigations have specifically examined binary power cycles because for the moderate temperature resources of interest, the binary cycles are more efficient than the flash steam cycles, achieving a higher net brine effectiveness. In these investigations of the binary power cycle, advanced concepts such as supercritical heating, integral countercurrent condensation, appropriate choice of working fluid, and metastable turbine expansions were explored. At resource conditions similar to those at the Heber binary plant, Demuth (3,4) found that mixtures of saturated hydrocarbons (alkanes) with these advanced concepts gave improved a 29% performance improvement over the Heber plant. Bliem (5) in subsequent studies showed that the same results were true if halocarbon mixtures (Freons) were used.

With the projected improvements in performance from the concepts identified in these analytical studies, the program has initiated field investigations to further examine the potential performance gains with these concepts (6,7,8). The field investigations of the concepts are being conducted at the Heat Cycle Research Facility currently located in the East Mesa of California's Imperial Valley. These field studies examined the validity of the predicted performance improvements through the verification of the assumptions used in the predictions, and the adequacy of the "state-of-the-technology" design methods, as well as fluid transport properties. Methods to insure that assumed conditions such as integral, countercurrent phase change have been explored and verified.

Recently, a number of new concepts for power cycles for geothermal use have been introduced and published performance data for these systems is available. For this paper, the operating conditions for the supercritical Rankine cycle have been adjusted for direct comparison with the other systems. In January of 1989, Exergy Inc. introduced the Kalina System 12 for geothermal use (9). Polythermal Technologies Corporation is considering their Low-Temperature Engine System for power production from a flashing well (10). This system employs a heat-driven heat pump and two separate heat engine cycles. One engine's heat input is from the heat rejected by the other engine and this engine rejects heat to the heat pump at a temperature lower than atmospheric which is pumped to atmospheric by the heat pump. In the United Kingdom, the Trilateral Wet Expansion System is being proposed for a binary application with a hot-dry rock resource (11). These new concepts rely on similar considerations to those studied in the Heat Cycle Research Facility (HCRF). One of the primary prerequisites for the achievement of the predicted performance of each of these systems which utilize mixtures as working fluids is that phase changes (boiling and condensation) be carried out close to equilibrium with the phases mixed. This has been studied in the HCRF in detail for the condensation process. In addition, the use of supercritical vaporization allows the generation of vapor without the problems associated with boiling a two-component mixture.

For all such cycles, there is a cycle performance limit for given resource and sink temperatures and practical assumptions relative to rotating equipment efficiencies and heat exchanger approach temperature differences or log mean temperature differences (LMTD's). This paper examines this performance limit and reviews the performance of some of the advanced systems.

The Heat Cycle Research program is being conducted by the Idaho National Engineering Laboratory. The work is supported by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technologies, under DOE contract No. DE-AS07-76ID01570. Mr. Raymond LaSala of the Geothermal Technology Division is the program manager and Mr. K. J. Taylor directs the program through the Idaho Operations Office.

CYCLE PERFORMANCE LIMITATION

Background

A Second-Law-of-Thermodynamics analysis is useful in determining the limitations of performance of power generation systems. Briefly, the second law allows for the definition of available energy, defined by Obert (12):

> "Available energy is that portion of energy which could be converted into work by ideal processes which reduce the system to a dead state--a state in equilibrium with the earth and its atmosphere."

If a system is at a different pressure from the atmosphere, work can be obtained by expansion to atmospheric pressure. If a system is at a different temperature than the surroundings, work may be obtained by transferring heat to a work producing cycle (heat engine). If chemical reactions are possible, for example, if the substance is a hydrocarbon; a reaction which oxidizes the hydrogen to water and the carbon to carbon dioxide or carbonate has the potential to produce work. (In this paper, chemical reaction will not be considered.) Available energy is essentially the same as availability, exergy and essergy.

The available energy, $\dot{A}$, of a stream in steady flow is:

$$\dot{A} = \dot{m}\,[(h - h_o) - T_o\,(s - s_o)]$$

where $\dot{m}$ is the mass flow rate; h, enthalpy ; T, absolute temperature and s, entropy. The subscript o represents the value at the pressure and temperature of the environment, the dead state.

The irreversibility of a process or physical component, $\dot{I}$, is the sum of all of the increases and decreases in available energy occurring and can be shown to be equal to:

$$\dot{I} = -\,T_o \sum \dot{m}\ \Delta s$$

where T_o is the absolute ambient temperature; $\dot{m}$, the mass flow rate and Δs the change in entropy for a given stream. Kalina (13) has shown that if the cooling water is assumed to be the sink instead of the ambient temperature or ambient wet bulb temperature, an effective ambient temperature can be defined as:

$$T_o = T_e(2 - T_e[\ln(T_i/T_e)/(T_i - T_e)])$$

where T_i and T_e are the inlet and outlet temperatures of the coolant sink in absolute units. For temperatures encountered in normal power production, T_o can be approximated within hundredths of a percent by:

$$T_o = (T_i + T_e)/2,$$

the mean temperature. Note that, for a process, the outlet available energy is the inlet available energy plus the irreversibility.

For example, for a process transferring heat from a stream at T_h to a stream at T_c in steady flow, the irreversibility will be:

$$d\dot{I}/dq = (T_o\ \Delta T)/(T_h\ T_c)$$

where all of the temperatures are in absolute units and ΔT is the temperature difference across which the heat is transferred, that is T_h-T_c.

An important observation is that if T_h and T_c are significantly greater that T_o, the irreversibility per unit heat transfer at fixed DT is significantly lower than if they are at temperatures near T_o. If Th and T_c are about 1.5 times T_o (typical of the heat addition process) the irreversibility per unit heat transferred at a fixed T_o and ΔT will be 44% that of a heat transfer process in which T_h and T_c are approximately equal to T_o such as the heat rejection process. This would imply that closer approaches are advantageous (increase efficiency more) in the heat rejection process than in the heat addition process.

Dr. Kalina (13) graphically shows this relationship by plotting an "exergetic temperature", T_{ex}, instead of actual temperature on heat duty plots for heat exchange, where:

$$T_{ex} = 1 - (T_o/T).$$

Then,

$$d\dot{I}/dq = \Delta T_{ex}$$

the difference in the hot and cold exergetic temperatures. For a more complete discussion see a basic engineering thermodynamics text such as (10).

Methodology

A realistic maximum can be placed on the work produced for a given resource using the ideas discussed in the previous section. If one assumes logical values for heat exchanger pinch-point temperature differences or log-mean temperature differences (LMTD's) and for rotating machinery isentropic efficiencies, the irreversibilities associated with the heat transfer and work processes in a cycle with the optimum match between working fluid and heat source and heat sink can be calculated. The work produced by a given cycle can be determined by subtracting from the available energy in the geofluid source, the irreversibility associated with each of the cycle devices: the heater, the turbine, the condenser (heat rejection) and the pump.

This analysis attempts to be generic in its application. The efficiency produced by this analysis is for the plant only. It does not include parasitic power associated with the heat rejection system, or the geothermal supply and injection system. These systems are separate and the impact of each will vary considerably depending on the particular application. The plant is a separate unit and can be considered separately. The choice of the type of heat rejection system and impact of the supply and injection system are left for a site-specific analysis.

Results

Restricting the analysis to liquid resources, a working fluid is postulated which will give close to the minimum irreversibility in each component with a realistic temperature difference in heat exchangers and realistic isentropic efficiency for turbines and pumps. Figure 1 shows the heat addition and heat rejection curves for the ideal working fluid, "unobtainium". For a given pinch point temperature difference, the minimum heat exchanger irreversibility occurs with a constant temperature difference. With a fixed log temperature difference (LMTD) for the exchanger, the minimum irreversibility occurs with a slightly smaller temperature difference on the end of the heat exchanger nearer to T_0. For heater temperatures in the range of this study, for an LMTD of 10 ^{o}F, a temperature difference on the cold side of the exchanger of 8 to 9^{o}F (on the hot side, 11 to 12.1^{o}F) gives slightly lower heater irreversibility than a uniform 10^{o}F difference. That increase is between 0.6 and 1.2 % of the heater irreversibility, and is thought to be not worth considering in order to simplify the problem to one of a uniform temperature difference. All enthalpies are referenced to the geofluid mass. Note that the difference in the heat added in the heater and that rejected in the condenser is the cycle net work per unit mass of geofluid.

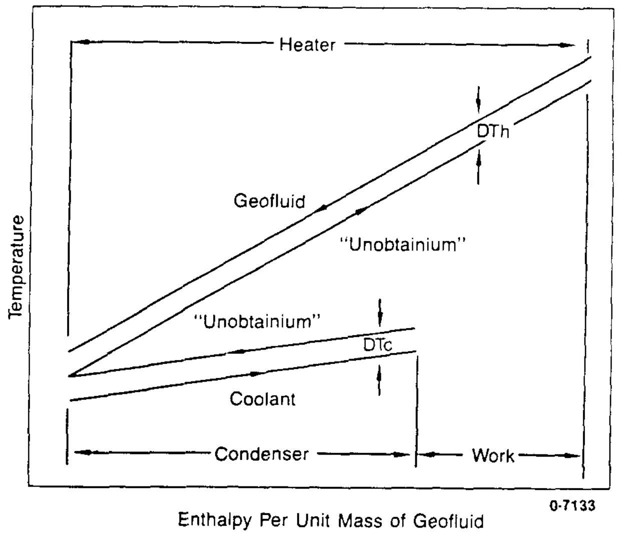


Figure 1 "Unobtainium" Cycle with Unconstrained Outlet Temperature.

It is further assumed that an "unobtainium" turbine will have an efficiency of 85% and that the pumping work will be small compared to the turbine work. With the approximation that the second law turbine efficiency is approximately equal to the isentropic efficiency, the net work is approximated by applying the turbine efficiency to the available energy in the geofluid minus the irreversibilities in the heat transfer processes.

Figure 2 shows the performance results for this system for different maximum resource temperatures. Each loss or irreversibility is expressed as a fraction of the available energy of the geofluid. (In this case with no restriction on geofluid outlet temperature, it was assumed that the geofluid could be reduced to ambient temperature.) These results are for a uniform temperature difference in both heat exchangers of 10 ^{o}F. That is, the pinch point and the log mean temperature difference are each 10 ^{o}F. At lower resource temperatures the fraction of the available loss due to heat exchange increases, indicating that smaller pinch points would be justified for lower temperature resources. Note that the condenser irreversibility is larger than the heater irreversibility because the heat exchange fluid temperatures are closer to T_0 as explained in a previous section. This would indicate the effectiveness of lower pinch points in the condenser than in the heater. This point has been explored from a cost-effectiveness point for the supercritical Rankine cycle (14). When the heat exchange irreversibility and the rotating machinery irreversibility fractions are subtracted from unity, the second law efficiency (net plant work divided by the available energy in the geofluid) remains. For this system, the efficiency varies from about 65 to 75% depending on the resource temperature for this LMTD and rotating machinery efficiency.

In many cases, the minimum temperature to which the geofluid can be cooled is limited by concerns over deposition of silica. For this case, the

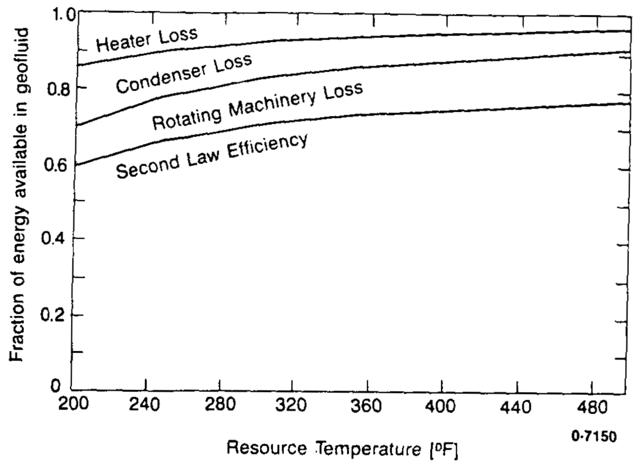


Figure 2 Efficiency of "Unobtainium" Cycle with Unconstrained Outlet Temperature.

minimum geofluid outlet temperature increases as the resource temperature increases. Figures 3 and 4 depict this case with a single heater and single condenser. Here the temperature difference in the heater is not uniform. Therefore, the temperature difference on the hot end of the heater is changed to obtain LMTD's of 10 °F. The net plant second law efficiency with this restriction was between 55 and 60%. The heater irreversibility is increased over the case with no limit. The breaks in the curves in Figure 4 result from the fact that at low temperatures there is no limit and the limit temperature increases as the resource temperature increases. (At resource temperatures lower that 280 °F, the results are the same as in Figure 2.)

In the case of a restricted minimum geofluid temperature, adding internal recuperation allows the heater irreversibility to be decreased substantially (although there is an added irreversibility associated with the recuperative heat transfer.) These results have been shown by

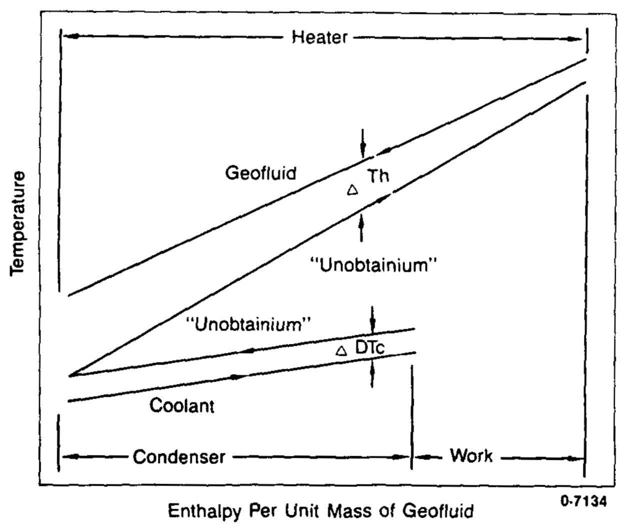


Figure 3 "Unobtainium" Cycle with Constrained Outlet Temperature.

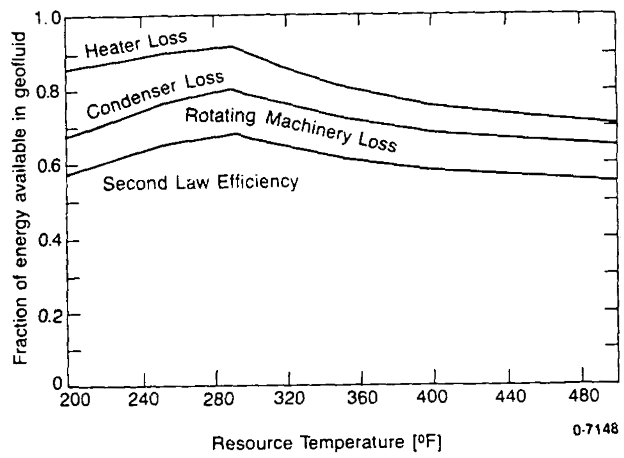


Figure 4 Efficiency of "Unobtainium" Cycle with Constrained Outlet Temperature.

Demuth and Kochan (6) for a Rankine cycle using turbine exhaust to recuperatively heat the working fluid. Figure 5 shows a schematic diagram of such a system. Another recuperative scheme used in utility steam plants is feedwater heating with steam bled from intermediate turbine stages. Demuth and Kochan considered this method of recuperation but found in general results were no better than with the turbine exhaust recuperation which is somewhat less complex.

Figure 6 shows the temperature enthalpy (heat duty) diagram for an "unobtainium" cycle with internal recuperation. The hot "unobtainium" in the recuperator would come from the expansion process say as hot turbine exhaust or a small turbine bleed stream. This heat is used to perform enough preheating of the working fluid to give an ideal match of heating and cooling curves in the heater. The match in the recuperator may not be as good. For this analysis, the

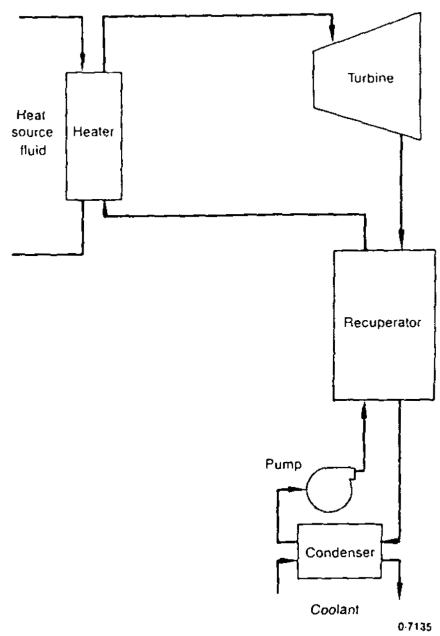


Figure 5 Recuperated Rankine Cycle.

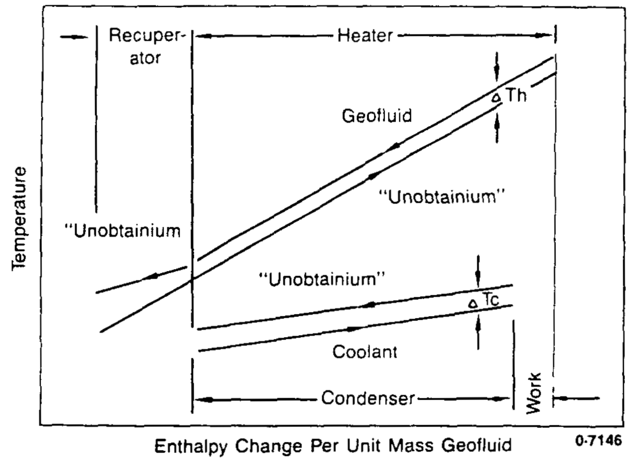


Figure 6 Recuperated "Unobtainium" Cycle with Constrained Outlet Temperature.

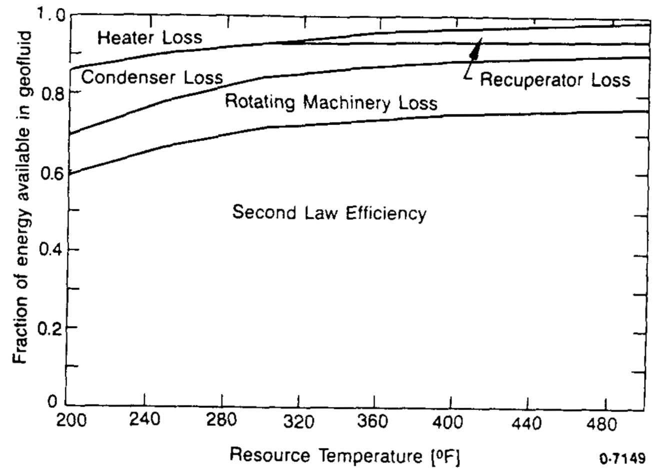


Figure 7 Efficiency of Recuperated "Unobtainium" Cycle with Constrained Outlet Temperature.

temperature difference at the hot end of the recuperator is adjusted to maintain a 10_0F LMTD.

Figure 7 shows the performance results for the recuperated cycle with a geofluid outlet temperature limit. Here, again the LMTD for each exchanger is 10 °F and the rotating machinery isentropic efficiency is 85%. Note that there is an added loss for this system, the recuperator irreversibility. However, the heater and condenser irreversibilities are decreased giving approximately the same second law plant efficiency as for the case with no outlet temperature restriction as found in Reference (6). The recuperator takes some of the heating duty from the heater and some of the heat rejection duty from the condenser. (Compare the heater and condenser irreversibilities in Figure 2 with the heater, condenser and recuperator irreversibility in Figure7.) Generally, the second law efficiency varies from 65 to 75% depending on the resource temperature.

ADVANCED SYSTEM PERFORMANCE

How close do the latest advanced cycles approach the maximum plant efficiency defined in the previous section? In this paper the systems with limited geofluid outlet temperature will be considered. The reason for this is that most of the systems which have been optimized for operation under this constraint. In a later report, the Trilateral cycle and the Heat Cycle concept of turbine expansion "through-the-dome" (16) will be considered.

Three actually proposed systems are considered to illustrate the methods which use real fluids to approach the behavior of "unobtainium". A supercritical Rankine cycle with exhaust gas recuperation and a Kalina System 12 are discussed in some detail and the Polythermal Technologies Low Temperature Energy System is also discussed, but not to the same degree because there is less in the literature concerning specific state-point data. State points for the supercritical Rankine cycle and the Kalina System 12 are given in Reference 13 where the two systems are compared under the same assumptions. More detail on individual processes in the Kalina System is given in Reference 7 and the supercritical Rankine cycle illustrated here is discussed in earlier work from the Heat Cycle Research program (4,6).

The path pursued in the Heat Cycle program has been to use a Rankine cycle as depicted in Figure 5 and approximating the near linear heating curve of working fluid by operating at pressures above the critical point. The use of a mixture allows for critical pressures and temperatures to be matched with the given resource maximum temperature and remain at moderate pressures (for example below the rating for 600 psi flanges).

Figure 8 show a temperature-enthalpy plot for the heat exchange processes of the cycle. This representation is used rather than the exergetic temperature-enthalpy because it is more familiar to designers. If the exergetic temperature had been used, the area between curves would be directly proportional to the heat transfer irreversibility. In this diagram, as discussed in the background section, a temperature difference at the hot end of the heater represents approximately half the irreversibility of the same temperature difference in the condenser because of their relation to T_0. Note that the largest temperature differences are near the hot and cold ends of the heater. The enthalpy change of the condenser is lined up with the heater because the difference in heat transferred is the net work for the cycle. The temperature difference in the condenser is practically constant. This is a result of using a mixture for a working fluid and achieving integral condensation in countercurrent flow. The recuperator, which heat the working fluid by using turbine exhaust is relatively small and the temperature difference is nearly constant. The primary inefficiency is the large temperature difference near the cold end of the heater.

Another advanced system operating under the same constraints is the Kalina System 12. Figure 9

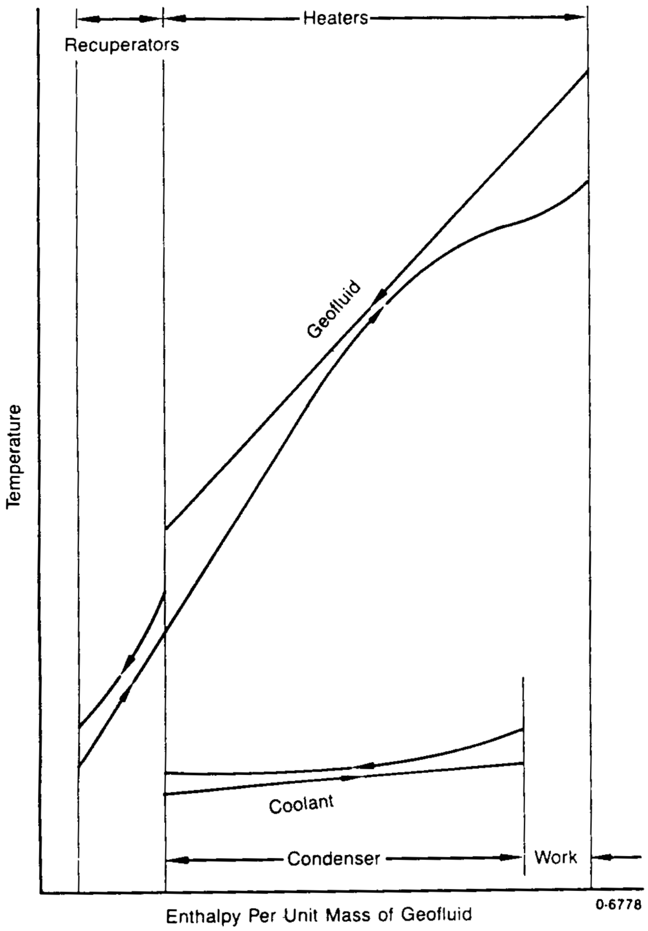


Figure 8 Temperature-Enthalpy Diagram for Supercritical Rankine Cycle.

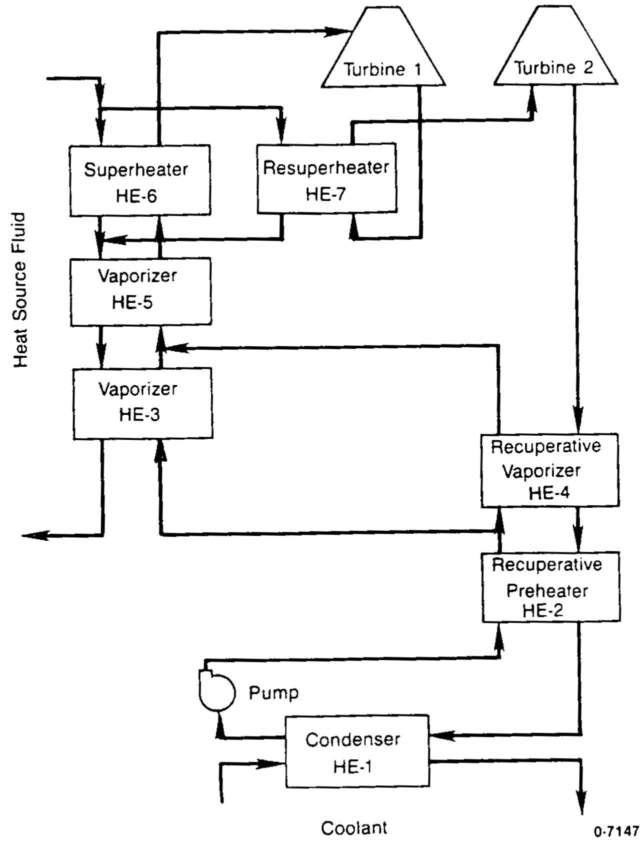


Figure 9 Kalina System 12.

shows a schematic diagram of this system. This system was unveiled in January 1989 and Exergy, Inc. has, since that time, developed a newer system which with higher performance and more complexity which might be desirable for a large installation. The Kalina system uses a mixture of water and ammonia for a working fluid. Because the working fluid becomes wet as it expands, a reheat stage and second turbine are required. Figure 10 shows a temperature-enthalpy diagram for this system. Note that because the superheater and reheater heat the working fluid through a similar temperature range, irreversibilities are minimized by splitting the geofluid flow between these units. (This is the rightmost part of the figure. Note that the individual heat exchangers are identified on both figures.) The initial vaporization of the working fluid is split between the geofluid in HE-3 and turbine exhaust in HE-5. (The discontinuity in slope of the heating curve of the working fluid is a result of the flow split.) This is necessary to maintain small temperature differences in HE-5 while avoiding a temperature pinch in HE-3. Again the condenser is lined up with the external heater train and the net work is shown as the difference between the heat transfer in and out.

Comparing Figures 8 and 10 show that there is little difference in heat exchange irreversibility

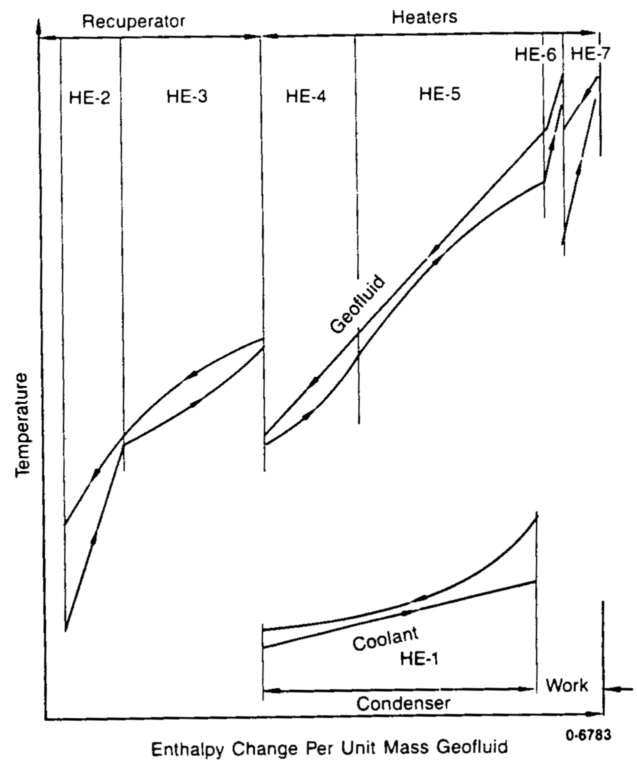
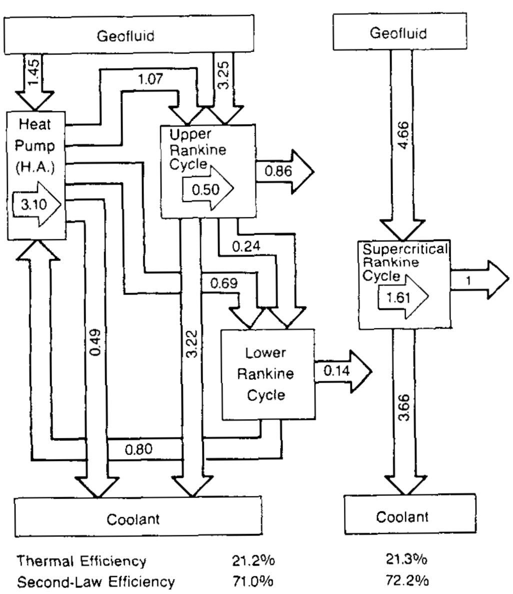


Figure 10 Temperature-Enthalpy Diagram for Kalina System 12.

between the two systems. Temperature differences in the heating processes are similar for the two systems. In the System 12, more of the heating duty is done recuperatively, to avoid temperature pinch at the cold end of the heater. It is interesting to note that per unit of work produced approximately 25% more heat is transferred in the System 12 than in the supercritical Rankine system. This does not automatically indicate a larger heat exchanger area because the heat transfer coefficients may be different enough to offset the increased heat load for recuperation.

The other system which was designed for a heat source with a restricted outlet temperature is Polythermal Technologies' Low Temperature Engine System (LTES). This system consists of three separate subsystems: receiving primary heat from the heat source is a heat-driven heat pump (heat amplifier) which produces a sink below ambient temperature, a Rankine cycle heat engine which also receives heat from the heat source as well as from the heat pump and rejects heat to ambient and to a second heat engine, and a second Rankine cycle which receives heat around ambient temperature and rejects heat to the heat pump below ambient. The heat pump proposed is an ammonia-water absorption system. Figure 11 shows this system schematically along with a supercritical Rankine cycle for the same service. The arrows within the boxes represent internal recuperation within the individual cycles. The numbers represent energy flows for a net work output of one energy unit. Notice again, that there is a large amount of recuperative heat transfer for the LTES compared with the Rankine cycle.



	Low Temperature Engine System	Supercritical Rankine Cycle
Thermal Efficiency	21.2%	21.3%
Second-Law Efficiency	71.0%	72.2%
Net Geofluid Effectiveness (Including Heat Rejection)	15.40 whe/lb geo	16.74 whr/lb geo
Total Heat Transfer/Net Work	14.81	9.93

Low Temperature Engine System (Polythermal Technologies Corporation) Supercritical Rankine Cycle

0-7144

Figure 11 Low Temperature Energy System and Supercritical Rankine Cycle.

The primary result of this study is that there is a practical limit to the plant performance. In addition, it is shown that many of the advanced systems are approaching this limit. Each system has advantages and disadvantages. The power plant designer/operator must weigh these advantages and disadvantages and in combination with economic and site-specific constraints, and select the power system which best meets the requirements for that application

CONCLUSIONS

Figure 12 summarizes the second law efficiencies for these systems along with estimates from References 7 and 8 for flash steam plants and for a plant with the Heber Binary technology at a slightly higher resource temperature. The theoretical curves are for heater LMTD's between 12 and 16 $_0$F; condenser LMTD's between 8 and 10 ^{0}F and recuperator LMTD's 12 to 13 ^{0}F. Within these ranges, the results do not change appreciably. This is the range of the LMTD's for the systems pictured in Figures 8 and 10. These results indicate that all of these advanced technologies have the potential to significantly improve on current technology and each has the potential to approach the reasonable expectation of maximum second law plant efficiency.

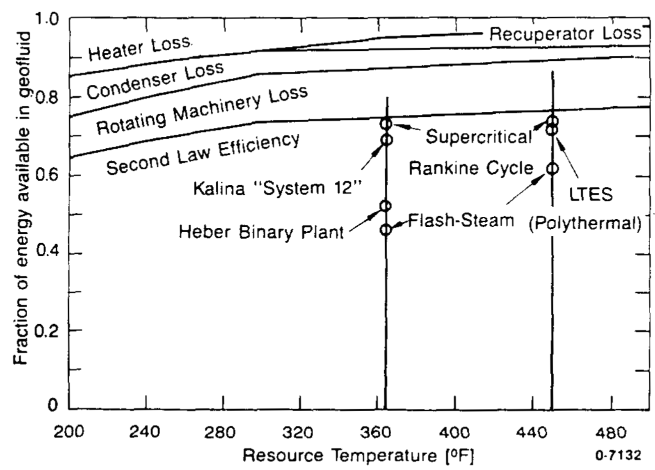


Figure 12 Results for Advanced Systems.

Summarizing the results of this paper:

With LMTD's around 10^{0}F (close to a practical limit) and turbine efficiencies of 85%, net plant second law efficiencies of 65 to 75% are possible.

Increasing these efficiencies are expected to be difficult without large increases in heat exchanger · size or improved turbine efficiencies.

Small approach temperature differences and LMTD's in the heat rejection heat exchange process reduce irreversibilities more than small approach temperature differences in the heating process. Similarly, in the heating process, smaller temperature differences on the cold end of the unit will reduce irreversibilities more than small temperature differences on the hot end.

The advanced system considered here appear to be approaching this limit and investigation for a particular application may favor one system over another. The design engineer must decide on the most cost-effective alternative.

This does not include effects of heat source delivery systems or heat rejection systems. The geofluid supply and injection systems should be similar for all binary alternatives, however the heat rejection systems may be different because of the optimum cooling water temperature rise (or air temperature rise for dry cooling). These effects must be addressed separately.

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ADVANCED MATERIALS FOR GEOTHERMAL APPLICATIONS

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ABSTRACT

Before geothermal energy can make a significant contribution to the nation's energy supply, improvements in its economic and technological viability must be made. The continued development and utilization of advanced materials of construction will help to attain these goals. To address these needs, emphasis is being placed on materials which will substantially reduce the cost of drilling and completion, and for energy conversion. Successful developments will also result in improved safety and lessen the environmental impacts of geothermal development. High priority needs are for advanced high temperature lost circulation control materials, carbon dioxide resistant lightweight cement well completion materials, and tools such as drillpipe protectors, rotating head seals, blow-out preventors, and downhole drill motors. The lack of suitable hydrolytically stable chemical systems that can bond previously developed elastomers to metal reinforcement is a critical but as yet unaddressed impediment to the development of these tools.

The availability of low cost, thermally conductive, corrosion and scale-resistant tubular lining materials for use in shell-and-tube heat exchangers and other components, would greatly enhance transport and energy extraction processes utilizing hypersaline brines, and possibly increase the exploitable low temperature geothermal energy reserves for commercial development. Work to address all of these materials needs is underway at Brookhaven National Laboratory. Recent developments, and plans for the coming year are summarized in the paper.

INTRODUCTION

Improvements in the economic and technological viability of geothermal energy must be made before this resource can make a significant contribution to our nation's energy supply. To meet these needs, advanced technology must be developed and utilized commercially before substantial reductions can be made in the cost of drilling, well completion, heat extraction, power production, and reinjection of spent brine. Although significant progress has and is currently being made, the lack of suitable high temperature corrosion resistant materials of construction continues to constrain technology development. For example, one of the Geothermal Technology Division's (GTD) Level III Program Objectives is to reduce the cost of deep wells and directionally drilled wells by 10 percent by 1992. To meet this objective, high temperature drillpipe protectors, rotating head seals and blow-out-preventors are needed. Although elastomeric materials that meet most of the design criteria are now commercially available as a result of earlier GTD-sponsored R. & D., and a successful technology transfer program, the lack of suitable hydrothermally stable chemical coupling systems needed to bond the elastomers to required steel reinforcement is preventing the successful development of these high priority tools. The attainment of other GTD Level III Program Objectives such as 1) reducing the costs associated with lost circulation episodes by 30 percent by 1992, 2) reducing well cementing problems for typical hydrothermal wells by 20 percent by 1991, and 3) development of a corrosion resistant and low fouling heat exchanger tube costing no more than three times the cost of carbon steel tubes by 1991, are similarly dependent upon successful materials development. Specific materials include lightweight (<1.2 g/cc) CO_2-resistant well cements, pumpable high temperature chemical systems for lost circulation control, and corrosion and scale-resistant thermally conductive composites which can be used as protective liners on fluid transport and heat exchange equipment.

As noted above, the GTD-sponsored Geothermal Materials Program being performed at Brookhaven National Laboratory has resulted in many materials advances which are now used commercially by the geothermal industry. The most significant has been in high temperature elastomers. Developed under GTD sponsorship by L'Garde, Inc., the Y-267 elastomer can be classified as a technology breakthrough.[1,2] Three major U.S. seal manufacturers acquired the technology from the Department of Energy in 1982, and molded parts are now commercially available from many firms. The elastomers are widely used in well logging tools, packers, valves, and other equipment. GTD-sponsored work has also been performed to modify the Y-267 EPDM to enhance its performance in drillpipe protectors, rotating head seals, and blow-out preventers, and these results are being utilized in the Geothermal Drilling Organization (GDO) programs on these components.[3]

Another successful materials advance was the development of high-temperature polymer concrete formulations. These materials are now available for use as corrosion resistant linings at temperatures up to 260°C.[4]

Cements represent another area where considerable progress has been made. The results from this effort currently serve as the basis for the selection of cements used for geothermal well completions throughout the world. There is still, however, a major need for improved lightweight CO_2-resistant cements.[5,6]

Handbooks summarizing the performance of materials in above-ground and downhole geothermal environments are other widely used outputs from the materials program.[7,8]

Results from recent GDO efforts on dynamic seals and ongoing work on lightweight well cements may be used by industry this year or next. Other efforts on CO_2-resistant cements, lost-circulation control materials, and nonmetallic heat exchanger tubing are expected to be successfully completed within the time frame FY 1991-92 when field demonstrations are performed. The program is coordinated with Hard Rock Penetration projects at Sandia National Laboratories, and the Conversion Technology project at the Idaho National Engineering Laboratory, and is the subject of cost-shared activities with U.S. industrial firms and the New Zealand Department of Scientific and Industrial Research (DSIR). Organizations currently collaborating in the program and their topics of interest are summarized below.

CURRENT COLLABORATIVE EFFORTS

Organization	Activity
Unocal	GDO Elastomer Activities
Geothermal Resources Int'nl	GDO Elastomer Activities
Gas Research Institute	Nonmetallic Heat Exchange Materials
Consolidated Edison of NY	High Temperature Composite Liners for Steam System Utility Vaults
Martin Marietta	MgO Encapsulants for Lost Circulation Control
International	
New Zealand DSIR	Downhole Testing of Cements
National Laboratories	
Sandia	Cements, Lost Circulation Control Materials, GDO Elastomer Activities
INEL	Heat Exchanger Tubing

Major accomplishments during FY 1989 and the thrust of the current efforts are summarized below.

1. Advanced Lightweight Cements

   o Completed laboratory evaluations in low CO_2-containing brine.

   o Identified promising CO_2-resistive formulations.

   o Pumpability of formulations established.

   o Downhole testing initiated with DSIR.

2. Chemical Systems for Lost Circulation Control

   o Optimization of promising formulations.

   o Microencapsulation of reactive components.

   o Pumpability of formulations established.

   o Laboratory-scale placement tests under simulated downhole environments.

3. Thermally Conductive Heat Exchanger Materials

   o Properties verified after 24-month laboratory test at 150°C, 2 month at 175°C.

   o Confirmed technical feasibility for scale retardation.

   o Technology transfer to Gas Research Institute.

Detailed descriptions of each of these task elements are given below.

RESULTS

1. Advanced High Temperature Lightweight Cements

In order to meet the GTD Programmatic Objectives of reducing well cementing problems for typical hydrothermal wells by 20 percent by 1991, improved well cements must be developed. The R&D strategy seeks to improve the effectiveness of geothermal well completion procedures and to reduce the occurrence of lost circulation problems by the development of CO_2-resistant lightweight high temperature cements. These improvements will help to transfer well-life limitations from materials to reservoir constraints in a cost effective manner. The work is being performed as a cooperative research effort with the New Zealand DSIR. BNL develops the cement formulations and performs physical, chemical, and mechanical evaluations. DSIR conducts the downhole tests in wells at their Mokai and Rotokowa geothermal fields.

Scheduled FY 1989 milestones for this effort were the completion of laboratory evaluations of lightweight cements after exposure to low CO_2-containing brines, the performance of pumpability measurements to verify the ability to place the cements, and completion of a one year downhole test in New Zealand as part of the ongoing cooperative effort with DSIR. The first milestone was attained and the results were published in three peer-review papers.[9-11]

The results from the laboratory studies to develop cements resistant to CO_2-containing hydrothermal fluids indicated that all conventional cement systems decompose very rapidly. The most promising advanced formulation developed at BNL consists of a calcium aluminate cement modified by the addition of a carboxylated styrene-butadiene copolymer. Upon exposure in an autoclave to Na_2CO_3-laden water at 300°C, this formulation was found to be the most effective for minimizing strength degradation and carbonation reactions.[12] These improvements are due to the formation of a calcium-complexed polymer structure resulting from the addition of the acrylic polymer. It was also determined that the degradation of cements in geothermal fluids containing CO_2 is due not only to severe carbonation of the hydrated cement products, but also to alkali metal-catalyzed hydrolysis of the cement hydrates caused by the attack of sodium cations present in the brine. The latter results in the formation of a porous microstructure as the $CaCO_3$ formed by carbonation is converted into water-soluble $Ca(HCO_3)_2$.

Pumpability tests on these cements in accordance with American Petroleum Institute (API) standards are being made. The results to date indicate that calcium aluminate cement pastes modified with organic or inorganic polymers can be made pumpable for 4 hr at 150°C, thereby permitting placement using conventional techniques, and have excellent mechanical properties.[13-14] Furthermore, the inclusion of acid-type retarders decreases the reactivity of the calcium aluminate cements, resulting in increased pumping time and decreased carbonation. Reductions in the early strength of the cement pastes also occur, but the values still exceed API requirements. This work is continuing, with the emphasis being placed on making further improvements in the resistance to carbonation in high-temperature hypersaline brines containing CO_2.

The cost-shared cooperative program with the Department of Scientific and Industrial Research in New Zealand is continuing, and as part of this effort, BNL fabricated and shipped several series of samples to the test site for installation by the well operators. Testing is currently in progress at the Rotokowa geothermal field where the downhole conditions are as follows: temperature 320°C, pH 2.2, and CO_2 concentration 20,000 ppm. To date, none of the specimens have been returned to BNL for evaluation.

2. Chemical Systems for Lost Circulation Control

Currently, the cost of correcting lost circulation problems occurring during well drilling and completion operations constitutes 20 to 30 percent of the cost of a well. The GTD Objective is to reduce well drilling costs for typical hydrothermal wells by 10 percent by 1991. Therefore, our goal is to develop an advanced high-temperature chemical system that can be introduced through the drill pipe into the lost circulation zones. Elimination of the need to remove the drill string will greatly reduce down time and aid in the location of the fractured zone, resulting in considerable cost savings.

During FY 1984 and 1985, BNL developed two promising chemical formulations, but due to budget constraints, the task was then suspended. Work was resumed in FY 1988.

The most promising formulation is composed of bentonite, ammonium polyphosphate (AmPP), borax, magnesium oxide (MgO), 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 has a compressive strength >500 psi at 2 hour age, a permeability to water $<2.0 \times 10^{-4}$ darcy, and a linear expansion >15 percent. Consistometer tests performed at Sandia confirmed the pumpability of the material at high temperature and pressure.

Ongoing work is directed towards optimizing the MgO-AmPP-based formulation with respect to pumping and placement temperature, measuring the pumpability of the slurries, and after curing, measuring the resultant physical and mechanical properties. Since the pumpability and curing times for the system can be controlled over a wide temperature range (20° to 200°C) by varying the MgO concentration, methods for the microencapsulation of the MgO in several polymers and waxes are being investigated. The MgO-containing capsules are then mixed with the other constituents and pumped down the drillpipe. Depending upon the thickness and thermal stability of the encapsulant, the combination of high temperature and shear forces at the nozzle can be sufficient to rupture the capsule, thereby allowing mixing of the highly reactive MgO with the other materials. Curing can take place within seconds if desired. For use in these experiments, a small bench scale unit which simulates a drillpipe, nozzle and the downhole fluid environment, was designed and constructed by Sandia National Laboratories, and placed in operation at BNL.

Currently, emphasis is being placed on the use of two encapsulants, an epoxy and a natural wax. Consistomer tests performed at temperatures up to 150°C and 10,000 psi indicate that with these materials, pumping times in excess of 4 hr can be obtained. After curing in simulated downhole environments at temperatures between 200° and 300°C, the specified property criteria are met. These studies will be continued throughout FY 1990. The compatibility of the cementitious binders with fiber and particulate bridging materials, will also be evaluated. Larger-scale drilling fluid displacement tests, and contingent upon the results, a field demonstration, are scheduled for FY 1991.

3. Materials for Nonmetallic Heat Exchangers

One of the Level III Goals of the Energy Conversion Task is to reduce the cost of binary power cycles by the development of low cost corrosion and scale-resistant materials of construction for heat exchanger tubing. This project investigates the use of thermally conductive composites for this application.

Corrosion of the brine side of tubing in shell and tube heat exchangers can be a major problem in binary plants unless a very expensive high alloy steel (AL 29-4C) is used. Even then, excessive fouling prevents the economic use of binary processes with hypersaline brine reservoirs. Both problems may be solved with the development of thermally conductive corrosion and scale-resistant polymer concrete liners for steel tubing. The work consists of determinations of the effects of compositional and processing variables on the thermal and scale-resistance characteristics of the composite, and measurements of the physical and mechanical properties after exposure to hot brine.

Methods have been developed for centrifugally applying polymer concrete liners on the inner surfaces of steel tubing with diameters ranging from 1.0 to 0.375-in. Corrosion and thermal conductivity measurements were made after autoclave exposure for 24 mo to a simulated binary-plant geothermal fluid at 150°C and for 2 mo at 175°C. Liners with a thickness of 0.020-in. were found to provide excellent corrosion protection for the steel substrate, and no deterioration or disbondment of the liner was apparent. Based upon the successful laboratory results, GTD and BNL made arrangement with the INEL to perform cooperative field tests in flowing brine. An 80-ft long single tube counter-current heat exchanger using water as the shell side fluid will be tested initially. INEL completed the design and fabrication of the unit. Corrosion rates, scaling factors, and heat-transfer coefficients will be measured in these tests. Lined tubing was fabricated by BNL for use in the field tests, and the Idaho Falls Operations Office initiated contractural procedures for selecting a test site. This selection process has not yet been completed.

Basic research studies have been initiated at BNL in an attempt to modify the surface characteristics of thermally conductive polymer concrete liners to make them less susceptible to scale deposition. It is well known that the deposition of alkali metals such as Na, Ca, and K on polymeric surfaces relates directly to oxidation of the polymer. Oxidation results in the formation of acidic-type pendent groups such as carboxylic acid (COOH) on the polymer surface, and these react preferentially with the alkali metals through acid-base reactions, resulting in the deposition of insoluble alkali metal compounds on the surface.

Experiments conducted in FY 1989 confirmed the technical feasibility of incorporating high temperature anti-oxidants into polymer concrete formulations as a means of reducing scale deposition. Tests were performed on samples after expoure to highly concentrated brines at 150° and 200°C. Contingent upon the results from the field testing of unmodified surfaces, a modified surface will be tested, and if successful, testing in higher salinity brine will be conducted in FY 1991.

CONCLUSIONS

The Materials Development Program continues to make major contributions to the attainment of GTD's programmatic goals. Significant advances have been made in the areas of lightweight cements and lost circulation control materials. With respect to the former, when the work commenced in 1978, little was known about the characteristics of normal density well cements at temperatures <200°C, and lightweight cements (density ~1.2 g/cc) capable of performing above 120°C were unknown. Now, GTD-sponsored work has resulted in lightweight cements which are durable at 300°C, being available to industry, and lightweight cements resistive to CO_2 attack may be available within a year.

With lost circulation control materials, a formulation which has the potential for placement in wells without the necessity of removing the drill string and which should allow the resumption of drilling within 2 hours is being optimized. Small-scale placement simulation tests and API standard pumpability tests are being made. Contingent upon these results, and those from a subsequent drilling fluid displacement test, a field demonstration could be performed in FY 1991. If successful, dramatic reductions in the cost of lost circulation control will result.

The feasibility for the use of corrosion and scale-resistant thermally conductive polymer concrete liners for heat exchanger applications has been demonstrated. Field tests are scheduled in FY 1990. Laboratory work to make the composite more resistant to fouling is in progress. If successful, the use of binary technology with hypersaline brines will be possible, with resulting reductions in the cost of electricity up to 48% possible, and considerably lower quantities of solid toxic wastes generated.

While dramatic improvements have been produced in the performance of elastomers for static and dynamic seal applications, the use of these hydrothermally resistant materials is now limited by the lack of hydrolytically stable coupling systems needed to bond the elastomers to steel reinforcing substrates. This is a critical, and as yet, an unaddressed need. Without a successful development, many of GTD's goals for reducing well drilling costs will not be reached.

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DEVELOPMENTS IN GEOTHERMAL WASTE TREATMENT BIOTECHNOLOGY

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ABSTRACT

Technical feasibility of a technology based on biochemical processes for the conversion of geothermal wastes from hazardous to non-hazardous wastes has been demonstrated. Laboratory-scale studies have shown that biotechnology for detoxification of geothermal wastes is versatile and is applicable to a variety of geothermal sludges containing few or many metals whose concentrations may exceed limiting threshold concentrations as recommended by regulatory agencies. Metals, such as chromium, copper, manganese and others, can be removed with 80-90% efficiencies. Continuing studies aimed at optimization and scaling-up of processes used in the emerging biotechnology indicate that there are several essential process variables which have to be considered in the development of geothermal waste treatment biotechnology. Some recent studies dealing with process variables will be discussed.

INTRODUCTION

Over the past several years, research effort in the area of advanced biochemical processes for geothermal waste treatment has focused on the utilization of acidophilic microorganisms in the development of environmentally satisfactory detoxification technology.[1-3] Programmatically, the goals and the objectives of this effort are to reduce the cost of geothermal power production.[4] In terms of the chemical composition of geothermal sludges, the toxic metal content varies from a few to many metals,[5] therefore, technology for the removal of these metals must be flexible as well as technically and economically feasible. Biochemical processes have been chosen as potential candidates on which such a technology can be based, because they seem to fulfill the environmental, technical, and economic requirements associated with the detoxification of a waste by-product generated in large volumes, containing low but environmentally significant quantities of toxic metals. The overall experimental approach is shown schematically in Figure 1.

Laboratory studies with a number of different species and strains of acidophilic, thermophilic, and toxic metal resistant microorganisms[6,7] have led to several conclusions.

In addition to the feasibility of a bioprocess, the actual number and concentration of the metals present in the geothermal waste influence the process. Furthermore, mixed cultures of different microorganisms are more efficient in the removal of toxic metals. A number of different bioreactors have been constructed[6] which include continuous flow, as well as column and agitated tank type batch bioreactors. Increases in the bioreactor capacity, say from liters to thirty to fifty gallons, introduce a set of additional variables, ranging from reactor type to temperature. These variables and their influence in the process development will be discussed in the light of most recent findings.

EXPERIMENTAL

Scaled-up bioreactors,[6] as well as their modifications involving batch and continuous processes, have been used throughout for kinetic studies. These studies were designed so as to generate data which describe the effect of known variables on the detoxification bioprocesses. The known variables include (a) reactor size, (b) agitation, (c) single or mixed cultures, (d) growth of microorganisms in the presence of residual sludge or addition of biomass at maximum growth, (e) effect of pH and dissolved oxygen, (f) effect of pH on cell growth, (g) initial concentration and loading, (h) minerals/metal salts, and (i) temperature.

A typical working configuration for a bioprocessing plant is shown in Figure 2. In all experiments this configuration was assumed to be operative in a manner in which an agitated tank can be interchanged with a fluidized-bed type bioreactor. The stream numbers are described in Table 1. Laboratory-scale models, ranging from two to thirty liters, have been used throughout.

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OBJECTIVES OF "ADVANCED BIOCHEMICAL PROCESSES FOR GEOTHERMAL BRINES" ACTIVITY

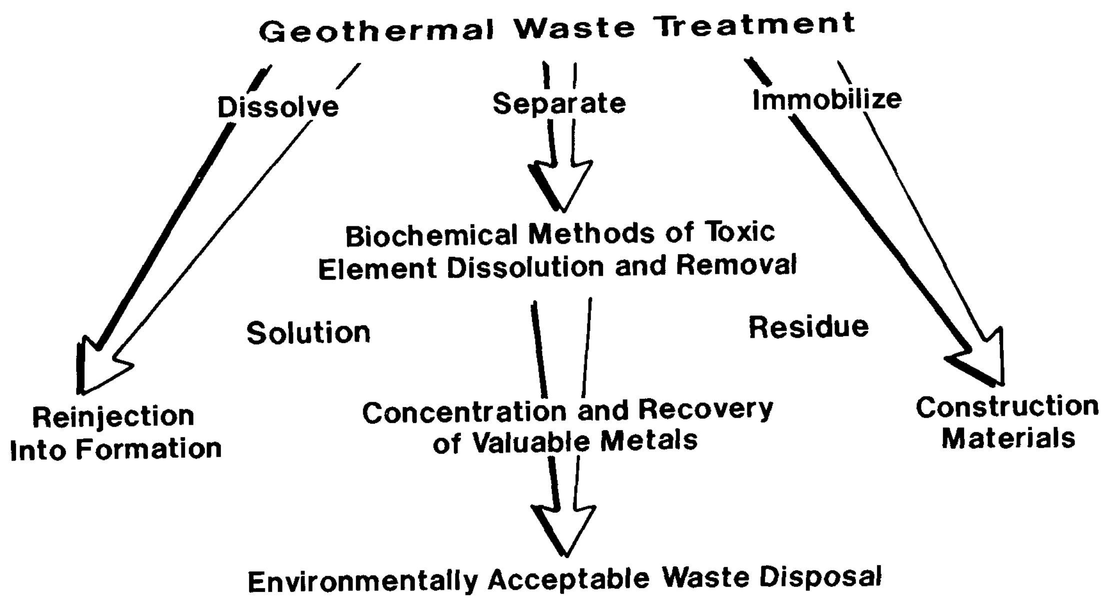


FIGURE 1

BIOLOGICAL WASTE-TREATMENT PLANT USING AGITATED TANK BIOREACTOR

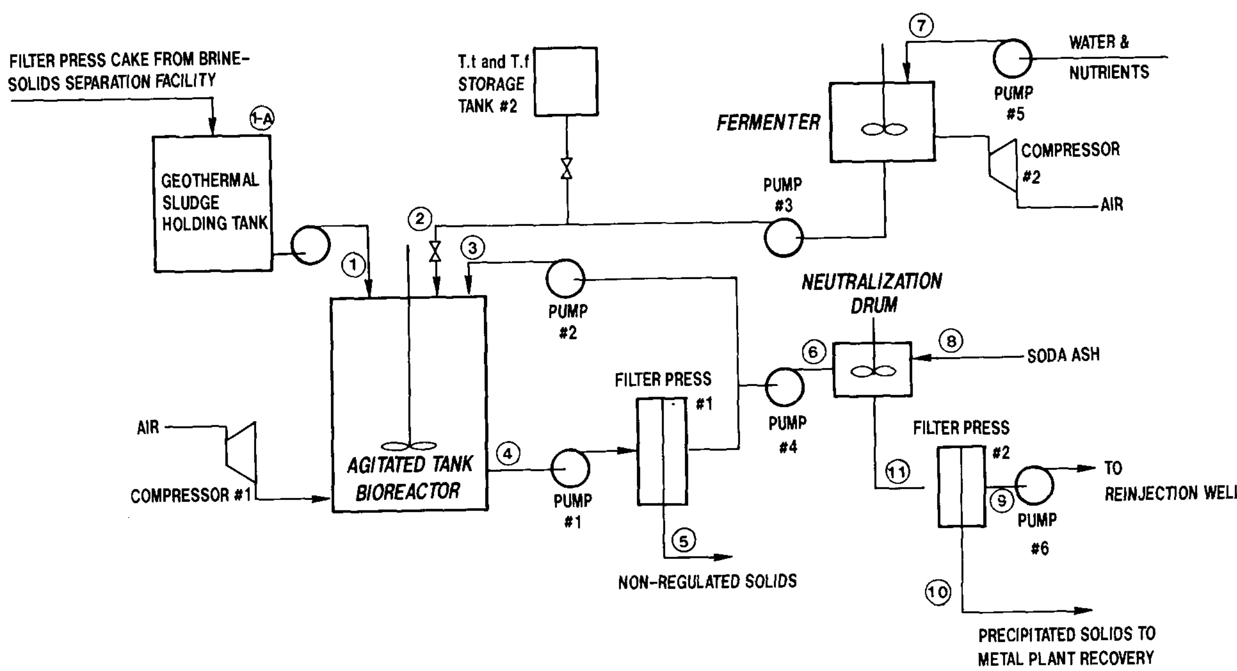


FIGURE 2

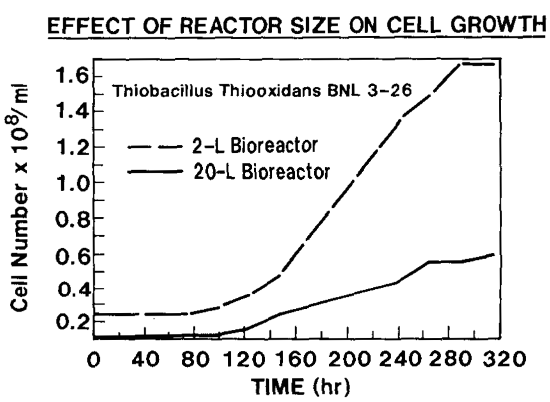
Stream Number	Description
1	Filter press cake from brine–solid separation
2	Nutrients and bacteria
3	Filter press recycle
4	Reactor outlet
5	Filter press cake
6	Filter press recycle (neutralization)
7	Water
8	Soda ash
9	Reinjection liquid
10	Precipitated solids
11	Neutralization exit

TABLE 1

RESULTS AND DISCUSSION

Reactor Size

The importance of the reactor is shown in Figure 3. There is a significant delay in achieving maximum growth ($1.7\text{-}2\times10^8$ cells/ml) as the size of the bioreactor increases, without any agitation.



No Agitation

FIGURE 3

Effects of Agitation

The effect of agitation becomes more evident in time as shown in Figure 4. Other factors to be discussed later also influence growth, and together make agitation an important aspect of the process.

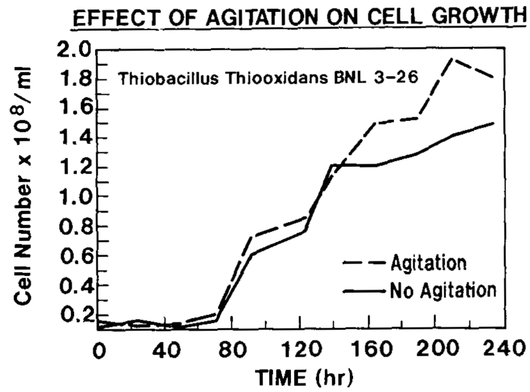


FIGURE 4

The Efficiency of Single and Mixed Cultures

Extensive studies with different strains of microorganisms[5,8] from the BNL collection have shown that there is selectivity in the efficiency of metal removal by different Thiobacilli. A typical example is shown in Figure 5, where T.T. stands for Thiobacillus thiooxidans and T.F. stands for Thiobacillus ferrooxidans. These experiments have clearly demonstrated that mixed cultures of selected strains of T.T. and T.F. are the most efficient toxic metal removers.

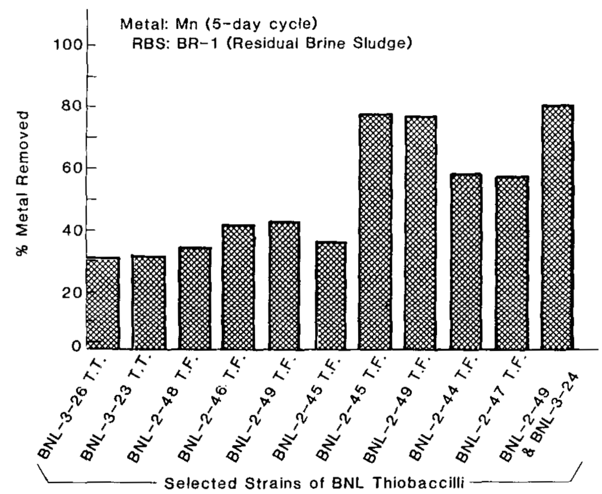


FIGURE 5

The Effect of Pregrown Biomass

The experiments in which the effect of reactor size was considered have also suggested that the long period of growth may be due not only to the size of the reactor but also to larger concentrations of the geothermal residual sludge. A series of experiments led to the conclusion that growing microorganisms in a separate bioprocessor and then adding the biomass at maximum growth to the bioreactor containing the sludge was the most efficient process.[6,7,8]

pH and Dissolved Oxygen

Results of a typical experiment in which pH and oxygen concentrations change in the presence of residual brine and sludge are shown in Figure 6. Initial pH increases with time after the addition of the sludge and microorganisms. Addition of the sludge decreases the oxygen concentration from 4 to about 1 mg/l under the experimental conditions used. The concentration of oxygen gradually increases to about 3 mg/l. Favorable optimization of these processes is currently under investigation.

Changes in pH and Dissolved Oxygen

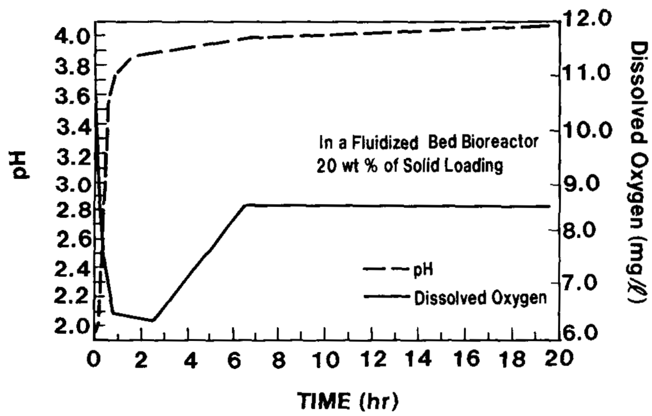


FIGURE 6

Effect of pH on Cell Growth

The effect of pH on cell growth plays an important role in the optimization of the bio-processes used in this study. Figure 7 shows the variations in pH, and the number of cells with time. Thus, pH decreases with time, while the number of cells increases with time. Therefore, optimization may be achieved by growing the cells separately (at low pH) to maximum growth of ~2.6 x 10^8 cells/ml and then adding the biomass to the bioreactor containing sludge at a pH of 1.2 - 2.0

Concentration of Residual Sludge

Earlier experiments[3] have indicated that the initial concentration of the residual sludge may influence the efficiency of metal removal. Typical results of these studies are shown in Figure 8. These effects could be due to loading itself and the influence of the chemical nature of the sludge upon the pH of the medium. This indeed is the case as shown in Figure 9. An increase in concentration of geothermal sludge increases the pH from ~2.4 at 10 wt% loading to ~4.5 at 30 wt% loading. Thus,

Cell Growth and Changes in pH

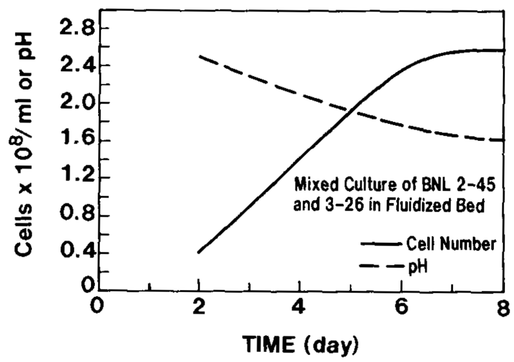


FIGURE 7

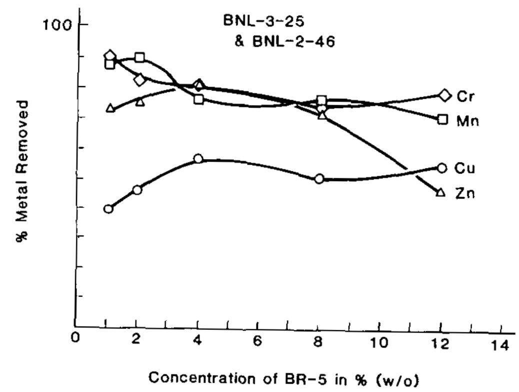


FIGURE 8
Variations in metal removal efficiency as a function of residual brine sludge (BR-5) concentration for the mixed cultural biosystem BNL-3-25 and BNL-2-46.

Changes in pH of Geothermal Sludge

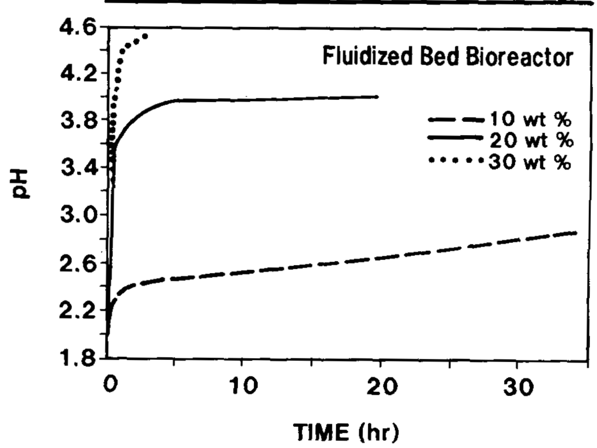


FIGURE 9

with other factors, such as, for example, oxygen, agitation, pH variation, and the microbial growth rates which also have to be considered, a process for the efficient removal of metals has to optimize these parameters. Using the 10 wt% information (Figure 9) where pH does not change as rapidly in the first thirty hours, a reasonably good efficiency of metal removal is easily achievable, as shown in Figure 10. In this case the initial pH of 2 gradually increased, but much more slowly than at 20% and 30% loading. Consistent with other observations, these data also suggest that a low pH (~2) favors a faster removal of metals. There are some variations among individual metals which have to be also considered.

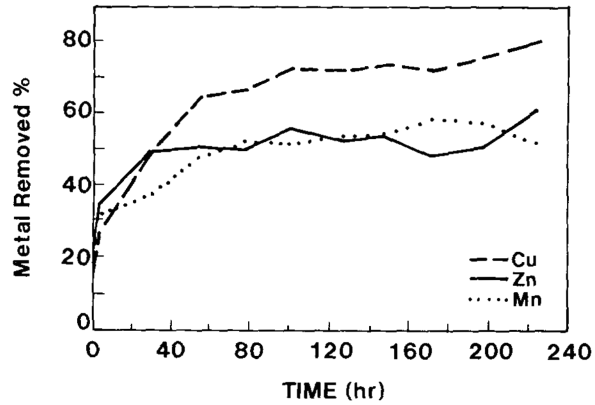


FIGURE 10
Rates of copper, zinc, and manganese removal in an agitated bioreactor at 10% loading.

Minerals/Metal Salts

In Figure 11, there is a rapid removal of metals within the first 40 to 60 hours, then a slow-down, with a much smaller increase in the rate of metal removal until a steady state is reached. This may be due to several factors. The bioprocesses are most efficient in the conversion of sulfides to sulfates. Therefore, it is possible that the initial step may be the conversion of sulfides. There may be other salts of the same metal present, which may also be oxidized and/or reduced, however, at a much slower rate. Alternatively, other enzymes present in the organisms used may become active and require different matrices and/or experimental conditions. Simultaneous analysis of many metals will allow a better understanding of the influence of trace metal concentrations on the rates of metal removal at low metal concentrations. An additional aspect to be considered are the products present in the aqueous phase, most of which will be in the form of soluble salts. However, there are exceptions, notably lead sulfate (solubility, 0.00425 g per 100 cc at 25^{o}C). The lead sulfate generated during bioprocessing will precipitate out if the solubility has been exceeded within that particular biotreatment. For example, Figure 11 shows a typical comparison of copper, zinc, and lead removal. A limiting concentration of lead sulfate in the solution is reached in about

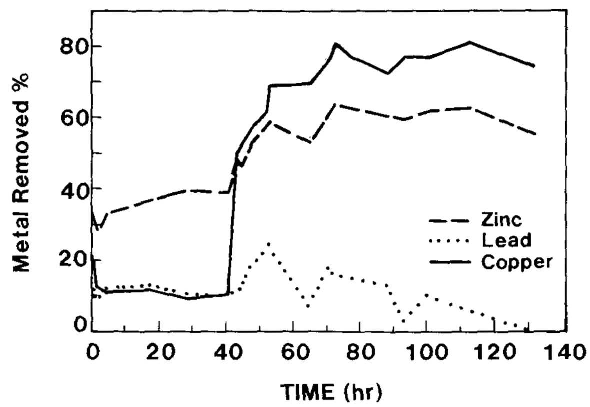


FIGURE 11
Removal of zinc, lead, and copper in a fluidized bed bioreactor at 20% loading.

50 hours, when the precipitation increases. At the present time, exploratory work is aimed at allowing all the reactions to proceed, i.e., remove other metals to within allowable threshold limit concentrations, and then recycle to remove lead.

Temperature

In the early phases of this program, exploratory work has been carried out at ambient temperatures, i.e., ~ 20^{o}C. It has been brought to our attention[9] that there is a significant amount of heat available during geothermal operations, which may be used to heat up bioreactors. If higher temperature tolerant microorganisms could be found which would be as efficient as the existing ones, then much faster detoxification rates might be achieved. Our experience, gained in other programs where biotechnologies are being developed which use thermophilic microorganisms, has proved to be helpful. Through the use of thermophiles, or temperature-adapted microorganisms (a BNL patented process)[10], we were able to develop metal removal bioprocesses at elevated temperatures. Preliminary experiments have been very successful and the results for the removal of copper and chromium, for example, are shown in Figures 12 and 13. It is to be noted that fast removal rates are evident. Addition of a mixed culture to a residual sludge causes an immediate removal of metal. For example, in the case of copper (Figure 12) there is an immediate release of metal (~30%) at 25^{o}C which increases to ~80% at 55.5^{o}C. An increase in temperature also produced favorable conditions for shorter periods of time needed to reach a steady state and a high metal removal rate.

CONCLUSIONS

Current studies indicate that a number of variables listed in Table 2 influence the efficiency of biochemical processes which serve as the basis of the emerging biotechnology for the detoxification of geothermal residual brines.

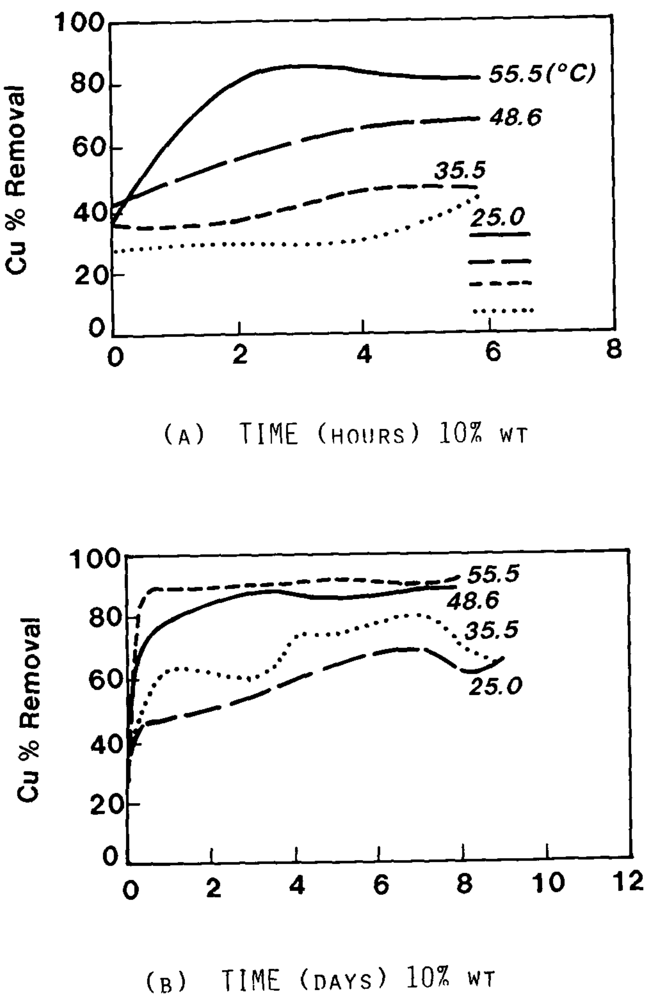


FIGURE 12
Removal of copper showing a rapid initial (a) removal with decrease in the rate of removal after approximately 90% of copper has been removed (b).

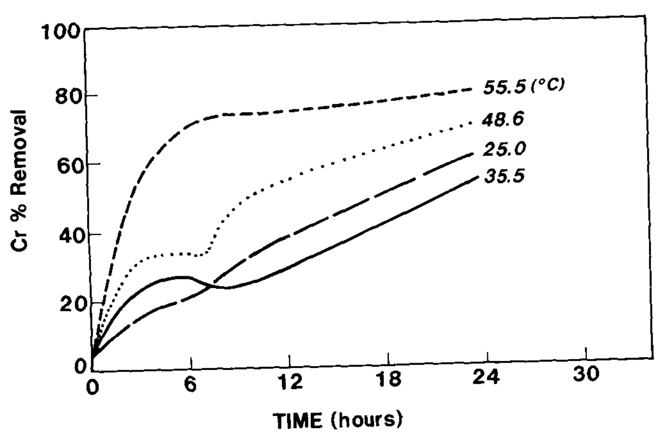


FIGURE 13
Removal of chromium as a function of temperature and time.

ESSENTIAL PROCESS VARIABLES

- **Reactor Size**
- **Effects of Agitation**
- **The Efficiency of Single and Mixed Cultures**
- **The Effect of Pregrown Biomass**
- **pH and Dissolved Oxygen**
- **Effect of pH on Cell Growth**
- **Concentration of Residual Sludge**
- **Minerals/Metal Salts**
- **Temperature**

TABLE 2

Studies dealing with the optimization of sludge concentration and decrease in the residence time in a variety of bioreactor designs should lead to significant savings in process design and operation. Similarly, the use of mixed cultures at elevated temperatures, based on most recent data, should also lead to considerable savings in the overall cost of the new biotechnology.

ACKNOWLEDGMENTS

This work has been supported by the U.S. Department of Energy, Division of Geothermal Technology, under Contract No. AM-35-10. We wish to acknowledge the assistance of B. Sylvester of BNL for the development and maintenance of microbial cultures used in these studies.

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Chemical Models for Optimizing Geothermal Power Production

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ABSTRACT:

The purpose of the UCSD Brine Modeling Program is to develop technology which will improve the efficiency of geothermal operations. We are constructing computer models which can evaluate the energy content and the likelihood of scale formation of geothermal brines with their associated gas phases under a wide variety of operating conditions (species, temperature, pressure). Our present model, with a temperature range of 0°-250 °C, can predict calcium carbonate, calcium sulfate, and amorphous silica scale formation as a function of brine composition and partial pressure of CO_2. It can also predict the presence of other less common scales, such as sodium chloride. This model is now ready for testing on industry problems. A Macintosh version, which will be available to the geothermal community, is under development.

New developments include improvement of the representation of mixed gas phase behavior in high pressure formations. We now have modeled the thermodynamic behavior of gaseous mixtures in the $CO_2(g)$–$CH_4(g)$–$H_2O(g)$ system from 0° - 1000 °C and from 0 - 3500 atm. These ranges in P and T allow application to geopressured systems. This model can be used to calculate the energy content (dissolved methane) and scaling tendency under the high pressures experienced in these systems.

Progress has also been made in modeling the behavior of the H_2S (g)–H_2O (g) system. Using a reliable representation of the gas phase (Redlich - Kwong), a model which predicts the solubility and gas phase thermodynamics for this system for temperatures from 0° - 90°C and for pressures from 0 - 60 atm has been developed. The T and P ranges are limited by the lack of high temperature data. This preliminary model may be used in engineering studies of the abatement of H_2S and will eventually be part of a model of sulfide scale deposition.

We are continuing efforts to incorporate more species that are important for geothermal applications. In addition, we are adapting our codes for dissemination to the geothermal community. The theoretical developments necessary to include nonideal gas phases (highly pressured gas phases) in the total system free energy expressions, which are necessary to predict breakout in high pressured systems, are progressing. Models of the solubility of the gases, methane and carbon dioxide, in concentrated brines should be available soon.

INTRODUCTION:

The economical production of power from a geothermal reservoir often depends on the ability to predict and control the chemistry of the formation brines from which the energy is extracted. For example, in many water dominated resources the formation of mineral scales in the powerplant or in the well bores severely limits the efficient extraction of power by elevating the operating costs of the system. For geopressured systems, the chemistry of the brine affects the solubility of the desired energy product, methane gas. Prediction of the amount of dissolved gas and its behavior under various formation water compositions, pressures and temperatures is necessary to determine the economic value of the resource.

Because the chemical behavior of brines is of such widespread importance to the industry, it is essential that methods be developed for modeling geothermal brine chemistry. Unfortunately, predicting the behavior of production fluids with the required accuracy is difficult. Typically, these fluids contain many species in high concentration, and they may be produced from various wells with large ranges of temperatures and pressures (even within the same resource). Moreover, during various phases of the energy extraction process an individual brine experiences large changes in its intensive parameters. Furthermore, changes in the brine composition are expected to occur as a result of the reservoir aging.

In order to provide a means to understand the chemistry of a wide variety of brines under various operating conditions and to predict the effects of changes in these conditions on resource production, the DOE has supported a program to develop a model of the thermodynamics of geothermal brines. This model will provide the geothermal industry with a cost effective means of assessing the energy content of a resource, predicting and identifying chemical problems and investigating strategies for solving these problems. This model will also be a flexible aid in interpreting reservoir data and laboratory simulations.

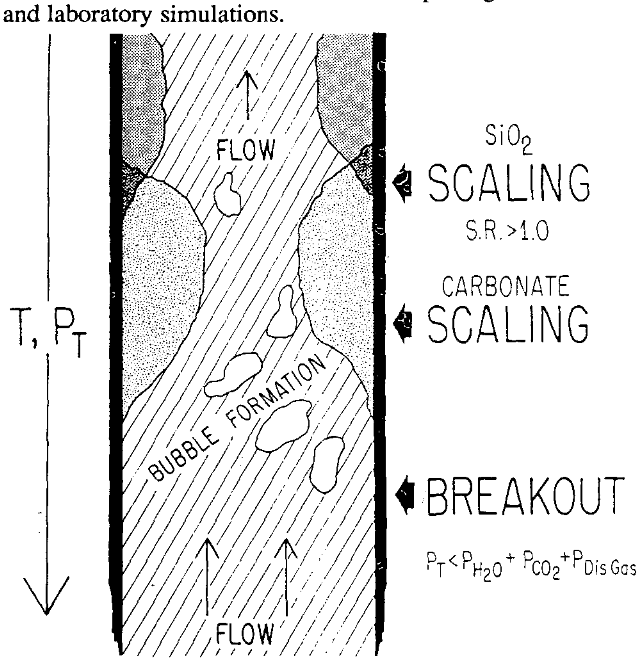

Fig.1 An illustration of a process stream with breakout and scaling in response to changes in temperature and pressure.

Figure 1 is a cartoon illustrating a typical operating problem that our model can address. A process stream is presumed to be flowing in the well bore or power plant in response to a pressure drop. There is a temperature drop in the direction of flow reflecting either energy removal or natural cooling. The formation fluid is typically a concentrated brine with NaCl as a major constituent and a number of other constituents, including dissolved gases, in lesser concentration. The response of the formation fluid to the changes in temperature and pressure are shown as the formation of gas bubbles (breakout) and the precipitation of solid phases (scaling) which, as illustrated in the figure, may drastically decrease the diameter of the well bore or pipeline causing costly downtime for removal. The primary scales are formed from the minor constituents and are generally $CaCO_3$ and amorphous silica. Lesser scales may also be formed from the sulfide minerals. In some systems (geopressured systems) economically valuable amounts of methane gas may be recovered from the gas breakout.

Both scaling and gas breakout depend in complex ways on the composition of the fluid phase. Therefore to predict either the amount of scale formed or the amount of gas recovered requires a computer model of the chemistry of the brine. Our group has made considerable progress in constructing such a model. A model which treats some of the more important problems encountered in geothermal energy production is now ready for testing by the industry. This model predicts the formation of the common carbonate and amorphous silica scales as a function of the partial pressure of CO_2 and of brine composition for a temperature range from 0°-250 °C. A summary of the present capabilities of this model is given in Table 1. A description of its parameterization is being prepared for publication. The model predictions have been validated by extensive comparison with laboratory data. Model calculations agree with measurements within experimental error. The model has also been applied to analyze field problems with considerable success. Predictions have been compared not only to geothermal data but also to highly accurate data from downhole samples supplied by the oil industry. These results demonstrate conclusively for the first time that the chemical processes in formations which contain petroleum correlate well with the formation water chemistry. They will be published in detail elsewhere.

Table 1. CAPABILITIES OF PRESENT MODEL
-Predicts Behavior of Calcium Carbonate Scale Formation in NaCl Brines for T = 0° to 250°C (Preliminary PC Version Available)
-Predicts Solubility of CO_2 in NaCl Brines for T = 0° to 250°C (Preliminary PC Version Available)
-Predicts Solubility of Amorphous Silica Scale in Seawater-Type Brines for T = 0° to 250°C
-Predicts Solubility of Marine Scaling Minerals (NaCl, $CaSO_4$, etc.) to 250°C
-Calculates Dissolution-Solution Characteristics of Rock-Water Systems Containing Na, K, Ca, Cl, and SO_4 for T = 0° to 250°C
-Predicts Onset of Two Phase Behavior in NaCl Brines
-Predicts Solubility of Hydrogen Sulfide (H_2O–H_2S–HS^-) System (preliminary, 0° - 90°C; 0 - 60 atm)
-Predicts Solubility of Methane in NaCl Brines for T = 0° to 250°C
-Predicts Partial Fugacity in Mixed Gas System (CO_2–H_2O–CH_4) T = 0° to 1000°C and P = 0 to 3500 atm

The model we have developed has application to energy technologies other than geothermal. It has been widely used in the oil industry to study scaling problems similar to those experienced in the geothermal industry both in well equipment and in formations. It is being used to predict process chemistry in the mineral industry. Recently, the potash industry has also used our programs to study problems in mine flooding and solution mining. The nuclear waste program has adopted the model for application to waste isolation problems.

OVERVIEW OF THE SOLUTION PHASE MODEL:

The model under development at UCSD is based on recent progress in the physical chemistry of aqueous solutions. Unfortunately, the behavior of concentrated aqueous electrolyte solutions cannot be predicted from first principle theories. However, because of the great importance of such solutions to many industrial processes, there has been considerable effort to develop accurate phenomenological descriptions which are parameterized from experimental data. For the solution phase, the model we have developed is based on one of the most successful of these descriptions which was originally proposed by Pitzer and co-workers. Our approach has been shown to describe complex natural waters with sufficient accuracy for most geochemical, industrial and energy-related problems (see, for example, Moller and Weare 1986, Weare 1987).

The phenomenology is based on modeling the free energy of an aqueous system. If the free energy is minimized, at a fixed temperature, pressure and total composition, the distribution of species in the system, including the amounts of solid scale, may be predicted. The aqueous solution model which is parameterized from laboratory data was discussed briefly in last year's report (Weare and Moller 1989). More detail is given in papers by Weare (1987) and Moller (1988). Because this model must be reliable in highly complex mixtures, the fitting process requires a very large data base. Our final models generally agree with laboratory data within experimental error. While the parameterization of the model requires only data from binary (e.g., NaCl-H_2O) and ternary (e.g., NaCl-KCl-H_2O) systems, the model may be reliably applied to the much more complex mixtures typical of geothermal systems. For example, in last year's report results were given showing that the model predictions of breakout in East Mesa geothermal brine are essentially identical to the measured values (Weare and Moller 1989). The capabilities of the present version of the model are given in Table 1. Presently, other models with these capabilities do not exist.

Table 2. COMPOSITION AND FUGACITIES FOR VARIOUS WELLS

Name of well		Pleasant Bayou #2	Gladys McCall #1	Willis Hulin #1
Depth(ft)		13000	15160	20670
T(°F)		279	292	380
P (psi)		10286	11105	17850
Brine (m)	NaCl	1.63	1.35	2.26
	$CaCl_2$	0.21	0.094	0.50
Gas (%)	CH_4	85	86	93.1
	CO_2	10	10	4.31
	C_2H_6	3	2	2
	others	2	2	0.56
partial fugacity coefficient	CH_4	1.1082	1.1546	1.5999
	CO_2	0.7131	0.7429	1.0766

Recently, our modeling effort has focused on the last entry in this table. For the geopressured systems, downhole pressures may be very high. Pressures, temperatures and dissolved gas compositions for a representative set of geopressured wells are given in Table 2. These temperatures and pressures are somewhat unusual for geothermal formations, but are common in oil production wells. Therefore, the research reported here will also expand the application of the model to oilfield problems. Preliminary models have already been used to study formation damage in oilfields.

A MODEL OF GEOPRESSURED GAS PHASES:

The prediction of the behavior of geopressured systems is considerably complicated by the effects of high pressure. For the pressures of the wells in Table 2, the gas phase mixtures will act very nonideally. In order to predict the behavior of such systems, we have initiated a program to model gaseous mixtures in the CO_2–CH_4–H_2O system at high pressures and temperatures.

The most succinct way to summarize the thermodynamic behavior of a gas phase system is in terms of an equation of state (EOS). This equation gives the relation between the temperature, volume, and pressure (PVT) of the gas mixture. Most of the problems that are of interest to the geothermal community, for example breakout and gas solubility, require free energy information and cannot be predicted directly from the EOS. The free energy may, however, be obtained from the EOS by integration and appropriate differentiation.

With the theory of gas phases available at this time, it is not possible to establish a purely theoretical EOS. The PVT relationship is, therefore, determined by fitting an assumed form of the EOS for a range of experimental PVT data. As in the case for aqueous solutions, the importance of gas phases to industrial processes has prompted the suggestion of several empirical forms for the EOS, which may found in the chemical engineering literature. In our research, we tested a number of the most successful of these with the objective of finding an equation that would describe the large amount of data in the pure gas phase systems (for example, CH_4) within experimental accuracy. We finally selected the Lee - Kesler form:

$$Z=\frac{PV}{RT}=\frac{P_rV_r}{T_r} \tag{1}$$

$$=1+\frac{A_1}{V_r}+\frac{A_2}{V_r^2}+\frac{A_3}{V_r^4}+\frac{A_4}{V_r^5}+\frac{\alpha}{T_r^3V_r^2}(\beta+\frac{\gamma}{V_r^2})\exp(-\frac{\gamma}{V_r^2})$$

where,

$$P_r=\frac{P}{P_c} \tag{2}$$

$$T_r=\frac{T}{T_c} \tag{3}$$

$$V_r=\frac{P_cV}{RT_c} \tag{4}$$

$$A_i=a_{i1}+\frac{a_{i2}}{T_r^2}+\frac{a_{i3}}{T_r^3} \tag{5}$$

T_c and P_c are the pure system critical parameters. These definitions will be important to the mixing model to be discussed below.

The EOS of Eq's.(1)-(5) can be parameterized to describe the available data sets for the CH_4, the CO_2 and the H_2O pure systems for the temperature range from 0°-500 °C and for the pressure range from 0-3500 atm within experimental accuracy. An example of the data fit as a function of pressure for the CH_4 system is given in Fig. 2.

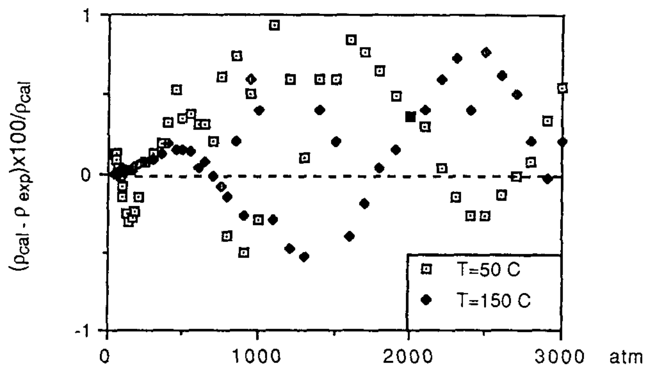

Fig 2. Comparison of the density of CH_4 calculated by our EOS with the experimental data.

Having good agreement in the pure systems is not sufficient for our purposes. Just as in the aqueous solution case, the test of the usefulness of a model is in the ability to predict the behavior of mixed systems. We have developed a mixing model for the entire CH_4(g)–CO_2(g) -H_2O(g) system. The model is based on a novel approach which involves mixing in the critical parameters. The details of this work will be presented elsewhere (Duan, Moller and Weare, in preparation). The predictions for the CH_4(g)–CO_2(g) subsystem, which is important in geopressured resources, are compared to the experimental data in Fig. 3. The model predictions are again within the experimental error.

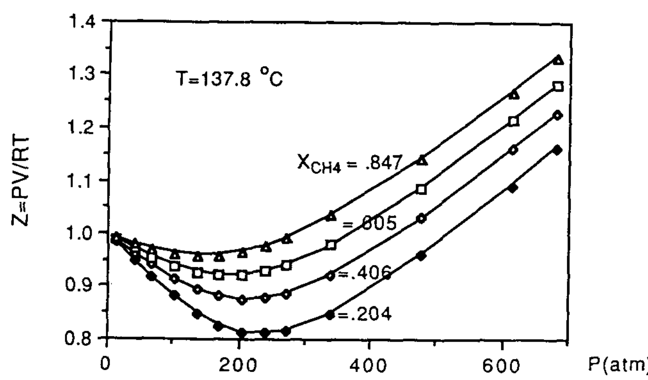

Fig.3 Prediction of the compressibility factor in the $CH_4 + CO_2$ mixture and comparison with experimental data. The solid line is the EOS of this study and the symbols are experimental data.

At this point, we have a model which can reproduce the available PVT data set for the CH_4(g)–CO_2(g)–H_2O(g) system within experimental accuracy. However, as we mentioned above, the thermodynamic information necessary for our purposes is the free energy, G. For convenience, this quantity is defined in terms of the partial fugacity coefficient for species i, ϕ_i, given by the equation:

$$\ln\phi_i=\frac{f_i}{x_iP} \tag{6}$$

In Eq.(6) the fugacity, f_i, is defined by

$$\mu_i=(\frac{\partial G}{\partial n_i})_{T,P,x_j}=\mu_i^o+RT\ln f_i \tag{7}$$

In the low total pressure limit, the fugacity of species i, is defined such that it is equal to the partial pressure, x_iP, where x_i is the mole fraction of species i. The fugacity of species i can be calculated from the EOS via a series of integrations and differentiations. The important point is that for an ideal system the fugacity always equals the partial pressure. But for a real gas the fugacity may be very different. The fugacity coefficient for each component is a function of the gas composition, temperature and pressure. The fugacity coefficients for some geopressured brines under downhole conditions are also given in Table 2. Note that the fugacity coefficient values in the table may be considerably different from one, indicating nonideal gas behavior.

APPLICATION OF THE MODEL TO THE WILLIS HULIN NO.1 WELL:

In last year's report, we applied our solution phase model to the Dixie Valley geothermal system. Our results suggested that scale formation would be a problem for this system. Scaling has now been identified in actual flow tests of the well. Last year it was not possible to make a similar study of the geopressured systems because the capability to treat high pressure had not been developed. With the partially complete gas phase model we presented above, we can now make some predictions for these important systems.

The Willis Hulin well with a downhole pressure of 1,214 atm, temperature of 193°C and 120,000 ppm total dissolved solids is one of the most difficult to treat. The major constituents of the brine are Na, Ca and Cl. The major condensed gas constituents are 4% CO_2 and 93% CH_4. Our model predictions of the solubility of methane in the brine as a function of total pressure are given in Fig. 4. Also shown are the solubility predictions of the model using Henry's law equations (straight line). The partial fugacities of the major components of the gas phase, methane and carbon dioxide, are shown in Fig. 5. This example illustrates that it is important to consider the non ideal behavior of the gas phase when

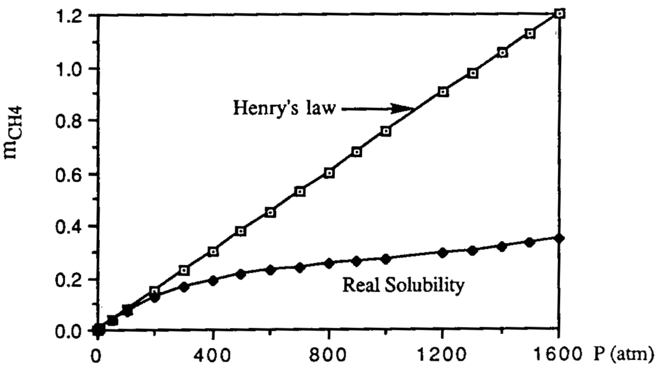

Fig.4 The solubility of methane in Willis Hulin Well No.1

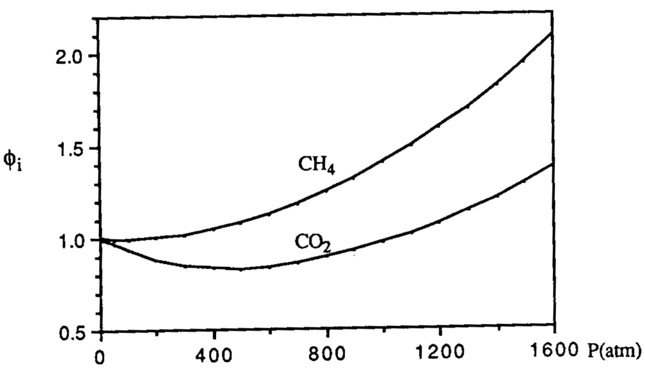

Fig. 5 Partial fugacity coefficient of the main components in Willis Hulin Well No.1

evaluating the amount of dissolved gas in a concentrated brine. Since for the geopressured systems a substantial portion of the economic value of the resource comes from the dissolved CH_4, it is important to evaluate the concentrations accurately.

As mentioned above, for many geothermal systems a determining factor in the economical utilization of the resource is the ability to control the scale precipitation. Scaling is expected to be a problem in the Hulin well. As a final example of the use of the model to predict the behavior of geothermal systems, we show in Fig. 6 the saturation ratio, S.R. ($S.R. = \frac{\prod_i a_i}{k_{sp}}$, where a_i is the activity of species i and k_{sp} is the solubility product) of calcium carbonate vs. temperature in the calcium chloride rich Hulin brine. The Hulin well has a calcium to carbonate ratio of 33.1. (The brine composition of this well was supplied by Marshall Reed.)

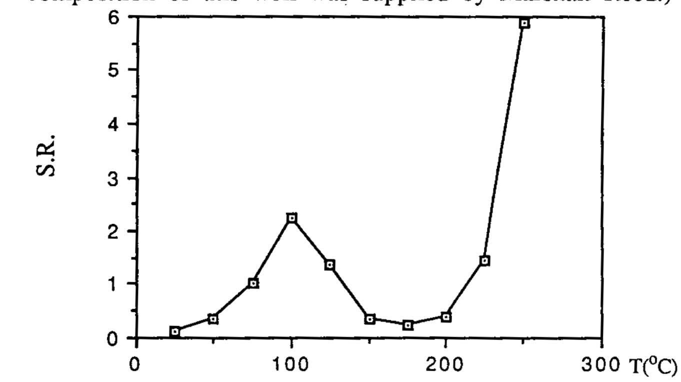

Fig.6 Calcite saturation ratio as a function of temperature in Willis Hulin Well No.1.

Fig. 7 is a similar plot for an artificial brine with a calcium to carbonate ration typical of NaCl dominated oilfield brines. The brine composition used to calculate the results of Fig. 7 was constructed by taking a calcium to carbonate ratio of 0.15 from typical Alaskan oil wells. The composition of the other species was chosen to be roughly the same as the Hulin well and the total carbonate was adjusted to give a downhole saturation ratio approximately that of the Hulin well. The compositions of the two brines are given in Table 3. We note that the behavior of the saturation ratios for the two brines vary in dramatically different ways as function of temperature. For example, the behavior in Fig. 7 is the typical retrograde behavior of calcium carbonate solubility in pure water or in NaCl brines. On the other hand, the increase in saturation ratio with temperature shown for the Hulin brine, Fig. 6, is completely contrary to laboratory experience. However, essentially all the laboratory data has been confined to the NaCl rich systems. Because this behavior is so different from what we have seen before and because it has very important implications for the operation of geothermal resources, we need to investigate this phenomenon more carefully. This investigation will be part of our program during this year.

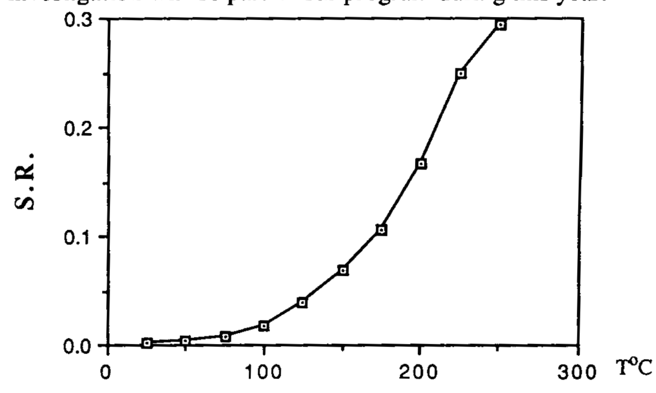

Fig.7 The saturation ratio of an artifical brine, which has about the same composition as that of Willis Hulin No.1 Well but has a Ca/HCO_3 ratio typical of oil field brines.

Table 3. COMPOSITION OF THE WILLIS HULIN WELL BRINE AND OF THE ARTIFICIAL BRINE

Composition (molality)	Willis Hulin well	Artificial brine
Na	2.258	2.258
Ca	0.488	0.00227
Cl	3.219	2.248
HCO_3	0.0172	0.0172
CO_2(aq)	0.228	0.271

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HYDROTHERMAL RESERVOIR TECHNOLOGY

Chairperson: Kenneth J. Taylor
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Reservoir Technology Research at LBL Addressing Geysers Issues

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Abstract

The Geothermal Technology Division of the Department of Energy is redirecting a significant part of its Reservoir Technology funding to study problems now being experienced at The Geysers. These include excessive pressure drawdown and associated decline in well flow rates, corrosion due to high chloride concentration in the produced steam and high concentration of noncondensible gases in some parts of the field. Lawrence Berkeley Laboratory (LBL) is addressing some of these problems through field, laboratory and theoretical studies.

Introduction

The first power plant at The Geysers came on-line in 1960. Initially the development of this vapor-dominated geothermal system was at a slow rate; not until the early 1970s did it acclerate. During the 1971–1981 period the yearly average increase in installed capacity was 67 MWe. Between 1982 and 1989 the development intensified substantially; during that period the generating capacity at the field grew at a rate of 180 MWe/year (Barker *et al.*, 1989). At the present time the total installed capacity at The Geysers is about 2000 MW.

Starting in 1987, problems with the amount and quality of the steam produced at The Geysers became evident. There was a decline in the steam supply in response to decreasing reservoir pressures. In addition, in some parts of the field the steam began corroding valves and pipes caused by the presence of HCl, and in others areas, the noncondensible gas content in the steam was high to the extent of affecting turbine performance. Because of these problems, the electrical power output is substantially below the total installed capacity at the field; about 400 MWe of the installed capacity was not being used during June, 1989 (Mock, 1989).

There is general agreement that in order to stabilize reservoir pressures, and possibly reduce the corrosiveness of the steam and its noncondensible gas content, it will necessary to expand present injection operations at The Geysers; about 20 to 25 percent of the mass extracted from the reservoir is currently being reinjected. However, some Geysers operators have had mixed results. Even though the rate of reservoir pressure decline was reduced by water reinjection, some wells started to produce a steam-water mixture (i.e., a high-permeability flow path existed between the injection and production wells).

Evidently all injection operations will have to be carefully designed to be able to recover most of the heat stored in the reservoir rocks and reduce possible negative effects on producing wells. The design will have to take into consideration the reservoir fracture network and the subsurface movement of the injectate; this information has to be determined on the basis of well log data, and tracer and other well test results.

In 1989, the geothermal operating companies requested assistance from the Geothermal Technology Division (GTD) of the US Department of Energy (DOE) in view of the serious nature of the problems at The Geysers. A significant part of GTD's Reservoir Technology is now directed toward research activities relevant to Geysers issues. During the present Fiscal Year 1990 funding for about $900,000 has already been approved for these activities. The funded projects are described in a March 16, 1990 letter from Marshall Reed (GTD) to The Geysers operators. Because of budget constraints, a number of other projects are awaiting funding (these are also described in the above-mentioned letter).

GTD is seeking industry's support in cost-sharing its Geysers research effort during this and future fiscal years. For this purpose, personnel of GTD and GTD-funded organizations have had several meetings with industry representatives to discuss the proposed research. As a result, some projects have been cost-shared by industry under the Geothermal Technology Organization. Recently, LBL has been designated by GTD as the Lead Laboratory for Geysers research and has been requested to coordinate the DOE research effort and to provide the geothermal operators with a point of contact for joint projects between industry and GTD-funded organizations. A meeting in Santa Rosa, CA, is being organized for June to further discuss the proposed research program.

LBL Research on The Geysers

About $250,000, half of the FY90 budget assigned to LBL for Reservoir Technology, is being directed toward projects relevant to The Geysers field. These include: (a) Geysers Database, (b) Injection Modeling, (c) Seismic Monitoring in the NW Geysers, (d) Development of a Downhole Fluid Sampler and (e) Fracture Studies. Other studies have been proposed and are in need of funding, such as the study of interference effects at The Geysers. We are actively seeking industry's support for these projects.

Geysers Database

LBL has developed a comprehensive computerized database of The Geysers with support from the California State Lands Commission (SLC) and the DOE.

The bulk of the data consists of production and injection histories for 221 wells, obtained from the California Division of Oil and Gas. The well histories consist of flow rates, wellhead pressures and temperatures and shut-in pressures. Other data include well locations, directional surveys, lithologic logs, steam entries, topographic data, heat flow data, pressure transient tests and geochemical data (Fig. 1). This information was obtained from SLC files and other sources. All available open file data, as well as proprietary information on State wells, are included in the database.

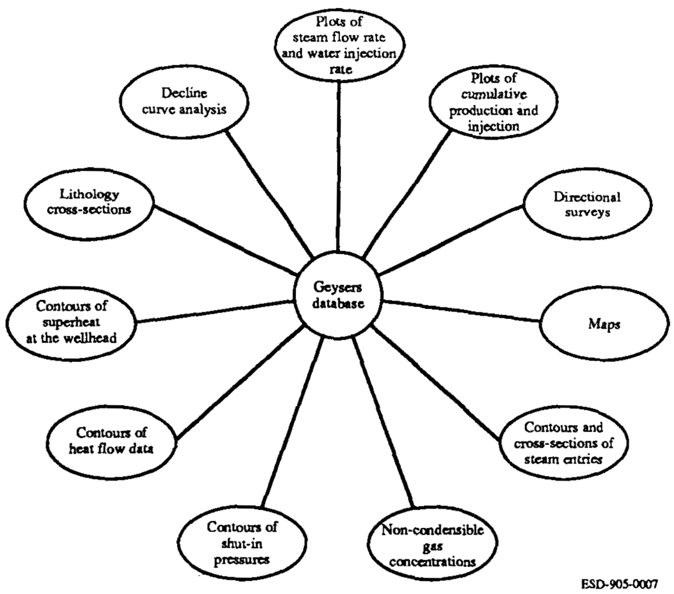

Figure 1. Capabilities of LBL's Geysers database system (from Ripperda and Bodvarsson, 1988).

A major effort was devoted to the development of a computerized base map that can display well names and locations, power plants, roads, lakes, townships, sections and county and lease boundaries. The data used in the development of the base map came from many different sources, including reports prepared by Unocal, United States Geological Survey and Geothermal Resources Council. Some of the data were digitized from SLC maps.

Other software development includes the capability to display lithologic data, steam entries and directional surveys. After specification of any number of wells, the software provides a plot of well locations with actual well tracks, and a lithologic cross section that includes steam entries, casing shoes and well directions.

Currently, the database is being expanded with data required for the DOE Geysers researchers. LBL is communicating with the operators in an effort to obtain data needed for the current research effort. Of particular interest are data on past and current tracer tests that will help quantify the beneficial (and detrimental) effects of reinjection.

Injection Modeling

As mentioned before, significant increase in reinjection may be the only possible means of reducing the current rate of pressure decline and considerably increasing the overall energy recovery from the system. One problem of primary interest is how much of the injected water is boiled off and extracted at the production wells. The operators have conducted various tracer tests and carefully monitored the isotope concentrations in producing wells. The results obtained are mixed, with a large percentage of the injected water being produced in some areas and a much smaller one in others. Therefore, it would be most useful to numerically investigate this problem in order to fully understand the effectiveness of reinjection in the past, as well as for designing future reinjection operations.

In the past few years LBL has been conducting research on fluid reinjection especially by incorporating chemical transport into geothermal reservoir studies (Gaulke, 1986; Tulinius *et al.*, 1987; and Amistoso *et al.*, 1990). Perhaps the most thorough evaluation of reinjection effects was that of Amistoso *et al.* (1990) for the Palinpinon geothermal field in The Philippines. They matched the total performance of all wells within the field in terms of flowrate decline, pressure decline, chloride concentration in the produced fluids and thermal decline in some production wells.

The Palinpinon study yielded detailed evaluation of fracture porosities, permeabilities and spacings which are the primary parameters controlling the movements of chemical and thermal fronts. This methodology will be applied to selected Geysers data sets to evaluate the dispersivities of the injected fluids and the resulting impact on the pressure decline.

Microseismic Monitoring of the NW Geysers

In a joint project with Coldwater Creek Operator Corporation (CCOC), LBL has begun collecting, processing and interpreting microearthquake (MEQ) data from the 16-station array deployed by CCOC at the Northwest Geysers geothermal field.

The first task is to bring the existing array into a state of routine operation to insure the collection of MEQ data, and to maintain the array in a routine data gathering mode. Another task is to process the existing data (Fig. 2) in order to refine the velocity model for precise location of events and designing future reinjection and calibration studies. This will help in the analysis of new MEQ data.

The main objective of the project is to demonstrate the utility of high-resolution MEQ data for (a) identifying high-permeability paths in the reservoir, (b) aid in locating future in-fill wells and (c) monitor the effects of injection. Another purpose is to develop a three-dimensional model of the reservoir showing (a) the P- and S-wave velocity structure, (b) the Poissons ratio model and (c) the structural model of the area based on the location of MEQs assumed to indicate high-permeability flow paths.

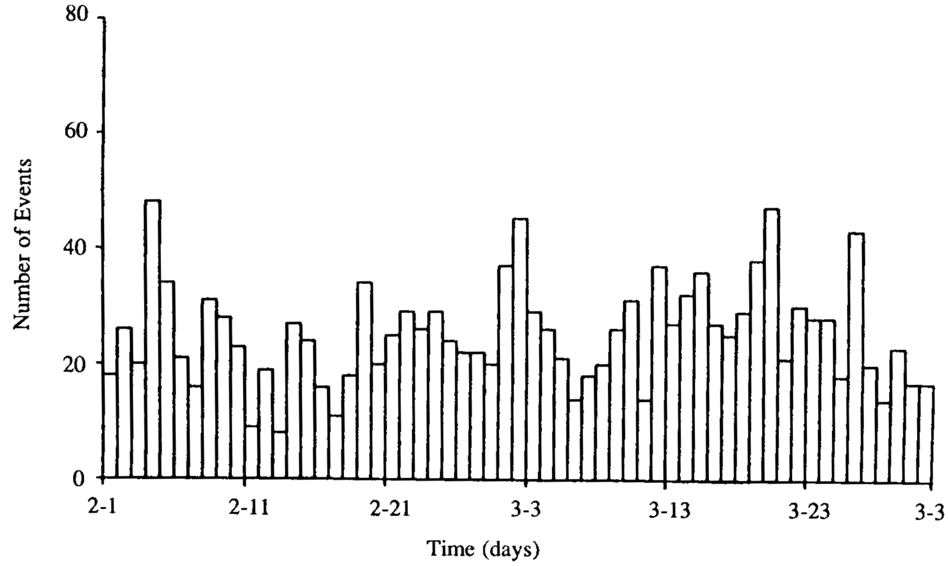

Figure 2. Microearthquake events per day in the NW Geysers during February and March 1989 (from J. Weiser, 1989, GEO internal report).

Development of A Downhole Fluid Sampler

The appearance of corrosive steam in the northern part of The Geysers field has caused serious development problems, and could be affecting others in the future. Presently, it is not clear whether the HCl in the steam has a magmatic origin (i.e. degassing of deep igneous intrusion) or is generated by the hydrolysis of chlorides present in the reservoir rocks (mainly Franciscan graywackes). The collection, chemical analysis and interpretation of downhole samples would greatly increase our understanding of the genesis and transport of HCl.

In order to obtain larger volumes of deep reservoir fluids (there is the possibility that only steam might be collected at depth), LBL has begun the design and fabrication of a flow-through six-liter downhole sampler. The design of the new instrument will be based mainly on that of existing one- and two-liter capacity samplers (Fig. 3; Solbau *et al.*, 1986). The only substantive difference will be addition of an electrical timing device attached at the top to initiate valve closure. This will allow the sampler to be deployed using a simple wireline.

The new sampler will have a 3.5 in. diameter and a length

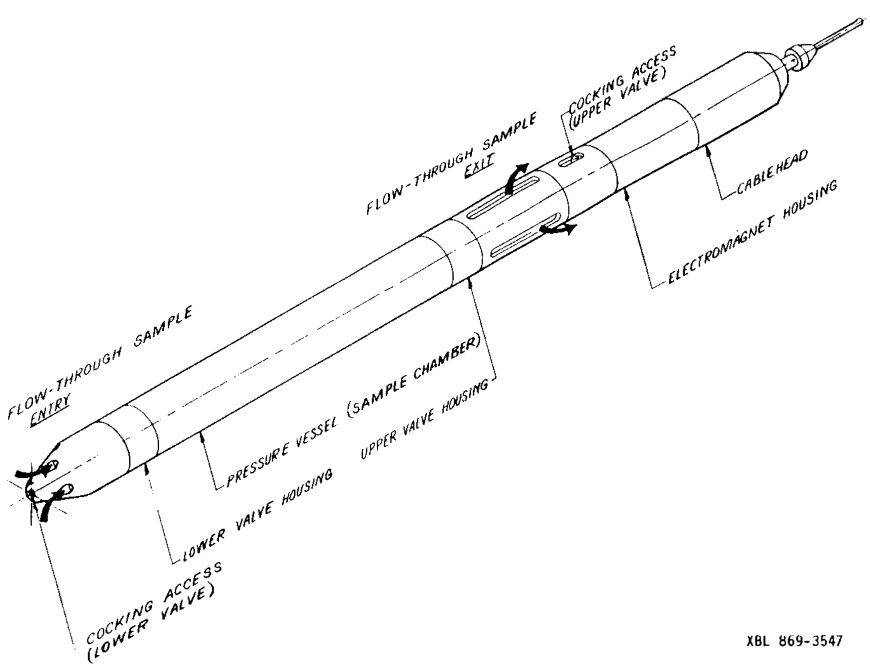

Figure 3. Downhole sampler with its major components; also shown is the flow path of the fluid during sampling (from Solbau *et al.*, 1986).

of about 10 ft. The deward timing mechanism will be designed to withstand temperatures of up to 350°C for up to three hours, time enough for the sampler to be lowered, closed and retrieved from a deep well. All parts in contact with geothermal fluids and the cooled condensate sample (possibly with high HCl content) will be fabricated from a chemically inert titanium alloy. The sampler will be rated for pressures up to 5,000 psi.

Multiphase Flow in Fractured Rocks

Fluid movement in The Geysers reservoir is predominantly through fractures; the rock matrix recharges the fractures in response to production-induced pressure drawdown. In the fractures of the "normal" upper vapor-dominated reservoir, only steam is flowing, while in the deeper hotter reservoir, a mixture of steam and brine seems to be present. On the other hand, throughout the entire system multiphase fluid flow is dominant in the rock matrix (Pruess and Narasimhan, 1982). An understanding of fracture relative permeability and fracture-matrix interflow is crucial in evaluating the response of The Geysers reservoir to steam production and liquid reinjection.

With this in mind, LBL has initiated a combined experimental and theoretical program to study multiphase flow in fractured rocks. Two-phase flow in rough-walled fractures is being visualized and measured in the laboratory. Figure 4 illustrates our experimental setup that utilizes the "Hassler sandwich" technique (Hassler, 1944; Rose, 1987) for measuring fracture relative permeabilities and capillary pressures. Assembly of this apparatus is nearing completion.

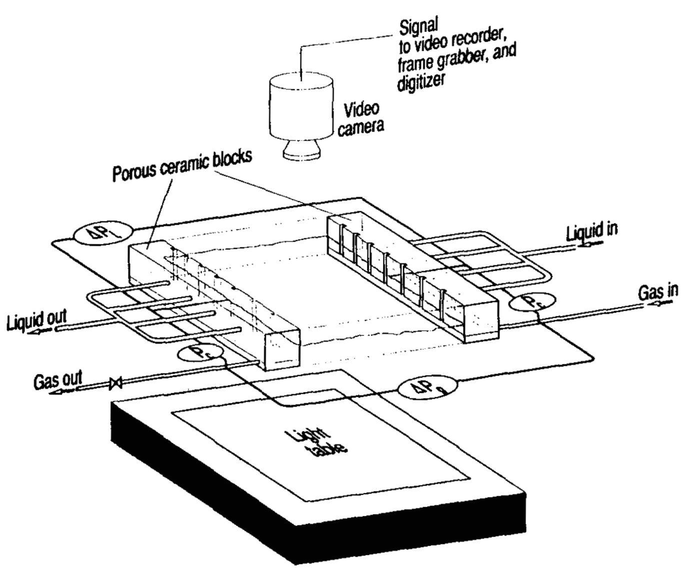

Figure 4. Sketch of the apparatus for measuring and visualizing multiphase flow in fractures (Pc: capillary pressure; Pg: gas pressure; PL: liquid pressure).

Conceptual models for determining fracture relative permeability are being developed, based on fracture void space geometry which is measured using casting techniques or obtained from statistical methods (Cox *et al.*, 1990; Pruess and Tsang, 1990). The acquired fracture geometry information

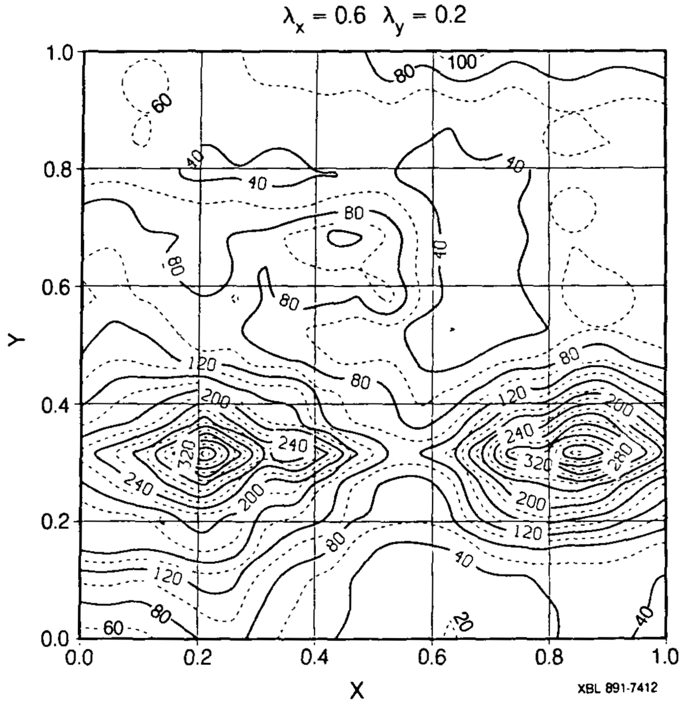

Figure 5. Contour diagram of a lognormal aperture distribution with anisotropic correlation; apertures in μm (from Pruess and Tsang, 1990).

(Fig. 5) is being incorporated into numerical models to compute fracture relative permeability parameters (Fig. 6). The resulting relative permeabilities will be useful in gaining insight into the response of fluid-depleted fractured reservoir

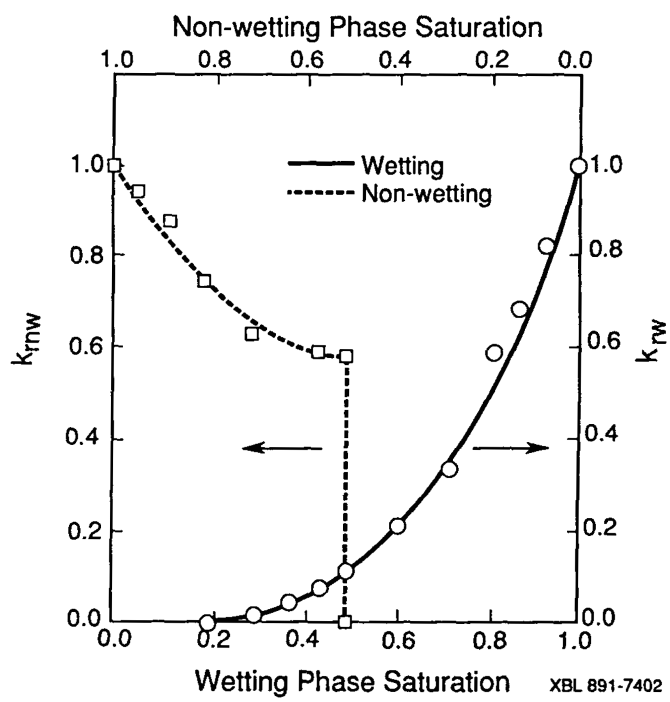

Figure 6. Simulated relative permeability curves for the aperture distribution shown in Fig. 5 (from Pruess and Tsang, 1990).

zones subjected to steam production and injection of cooler waters.

Acknowledgments

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ADSORPTION IN VAPOR-DOMINATED SYSTEMS

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ABSTRACT

Vapor-dominated geothermal systems have been produced for almost 90 years. But the storage mechanism is still in doubt. The fluid must be stored as a liquid, yet the pressure at reservoir temperature is well into the superheated steam region for flat-surface thermodynamics. One popular mechanism is that the liquid phase is a brine. Another possibility is that the liquid phase is adsorbed. A study of the Big Geysers shallow steam production indicates that adsorption is a reasonable mechanism.

INTRODUCTION

The existence of humankind is tied to the fruits of the earth. Some have been beneficial and others sometimes catastrophic. Eruption of volcanoes is an example. The earliest writings record events tied to hot fluids issuing from the earth. Thus geothermal systems have been studied for centuries. One of the oldest books on mining, de re Metallica, Agricola 1565 (Hoover translation, Dover Press, 1950) cites study of juices which issue boiling from the earth. There are references to biblical events involving hot earth fluids. Thus scientists have studied geothermal systems from recorded history. Geothermal fluids were used for space heating and cooking before recorded history without doubt.

Early geothermal theory was that geothermal fluids were magmatic. But geochemical studies proved that geothermal fluids were mainly meteoric. Surface water migrated to depths in the earth and were heated. Hot fluid then rose toward the surface because of low density. Thus geothermal systems were believed to be active hydrothermal systems subject to recharge. If a geothermal system were produced at the natural recharge rate, the system would produce at steady state and would last forever.

The first geothermal reservoir model, Whiting and Ramey(1969), coupled heat and mass balances and permitted recharge fluid to enter from a variety of aquifer geometries. This model was applied to Wairakei, New Zealand data yielding the surprising result that recharge was not significant. We thought at the time this resulted because the model had measured the reservoir and aquifer together.

Shortly afterwards, another reservoir study was made of the original producing area of the Geysers: The Big Geysers, Ramey(1968). This steamfield was drilled in the 1920's, and a few wells were allowed to blow to the atmosphere until the Thermal Power Company began the modern development of the Geysers in the late 1950's. A piece of a casing from one of the original wells was displayed in the Thermal Power Company offices in San Francisco. It appeared like new casing and the Thermal Power Company personnel cited this as proof of the non-corrosive nature of the steam. In 1967, a thorough effort was made to determine the initial state of this reservoir and to collect data and perform a reservoir engineering analysis. The reason was preparation of material for a tax trial to be held in 1968, Ramey (1968).

Although more than 20 wells had been drilled in the Big Geysers and the adjacent Sulphur Bank-Happy Jack area of the Geysers Steam Field, Wells were mainly idle and venting to the atmosphere. However a group of wells producing from shallow depths had supplied Units 1 and 2 (25 MWe total) since 1957. Data collected from this group of wells is given in Table 1. Temperature-depth data is shown in Fig. 1. The cluster of points between depths of 500 to 1000 ft represent wells producing the shallow steam zone. Data on steam pressure-temperature from the shallow zone indicated that the steam ranged from saturated to superheated. See Fig. 2.

An attempt was made to model the data in Table 1 using the Whiting-Ramey (1969) model. This attempt failed because the pressure decline per unit mass produced exceeded that permitted by the model. In view of the high enthalpy shown on Fig. 2, the data in Table 1 was modelled by the well-known dry gas p/z vs mass produced method. Figure 3 displays the result. This information was presented to the tax court and eventually aided extablishing the tax depletion allowance for geothermal steam production.

In the months following the 1968 trial, it

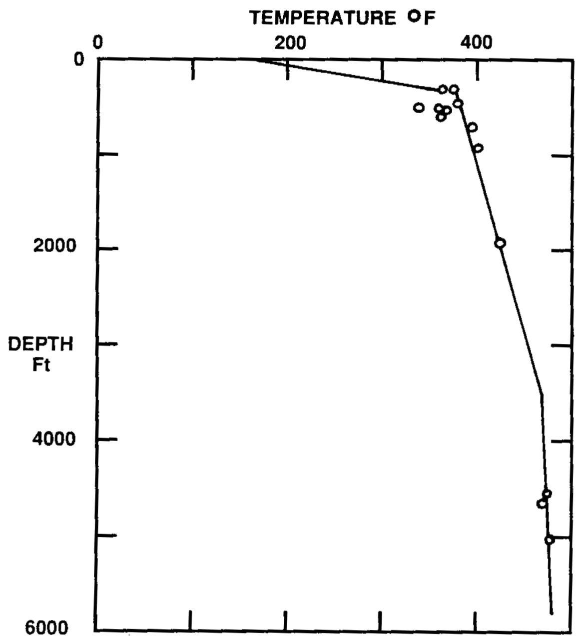

Fig.1 Temp. vs. Depth-Wells in Big Geysers Area(Ramey, 1968)

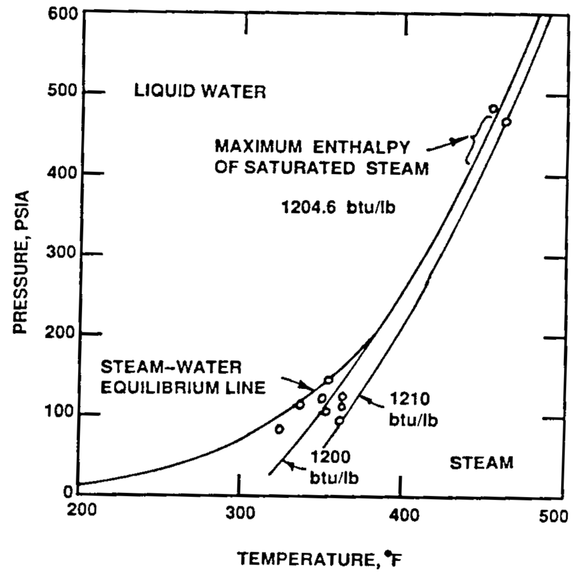

Fig.2 Pres. vs. Temp. for Big Geysers Area Well Tests Oct. 1967-Jan. 1968 (Ramey, 1968)

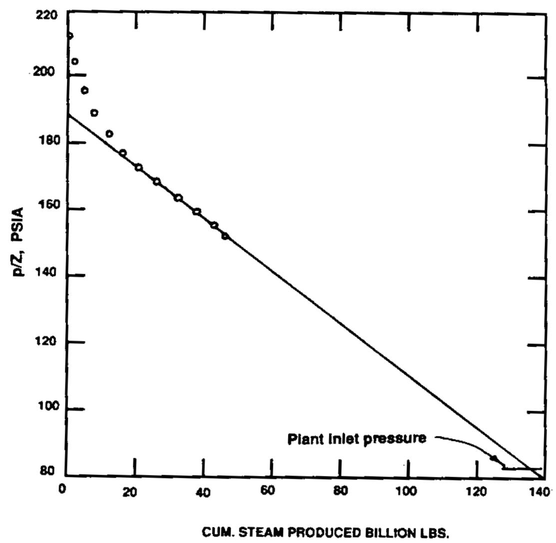

Fig.3 P/Z vs. Cum. Steam Prod. Big Geysers Area Shallow Zone (Ramey, 1968)

became apparent that the mass of steam indicated by Fig. 3, 240 billion pounds at a p/z of zero, was too great for the steam to be stored as vapor. At 400F, the density of steam is 0.5367 lb/cu ft and the density of hot water is 53.65 lb/cu ft--100 times greater than that of vapor. The paradox was that steam was stored as liquid--but liquid could not exist at the reservoir temperature and pressure, and no liquid had ever been produced. This is a simplification. Either salt in solution or a curved liquid-vapor interface may reduce the vapor pressure of water.

Two theories were proposed at that time: (1) liquid water might exist as perched liquid, or as a deep boiling interface, and (2) liquid might exist as adsorbed liquid in micropores, White(1973).

VAPOR PRESSURE LOWERING

The Whiting-Ramey study of Wairakei, New Zealand was performed in 1964-66. Results indicated that the initial state had been compressed liquid and that boiling in the reservoir would start in 1966. Future performance forecast depended on unknown factors: would liquid and vapor segregate by gravity, and would vapor pressure be less in the reservoir than for flat surfaces above ground?

These questions were studied by Cady in a doctoral dissertation at Stanford, Cady (1969). He used unconsolidated sand to experimentally study performance of geothermal systems. He found that an isothermal single-phase steam zone could exist within a few inches of a two-phase zone undergoing pressure and temperature drop. He also found no vapor pressure lowering with unconsolidated sand. Bilhartz (1971) extended this study, but found similar results for unconsolidated sand. Strobel (1973) studied an artificially-consolidated porous medium (cement and sand) and did find measurable vapor pressure lowering, but of a magnitude less than would be expected from the work of Calhoun, et al.(1949).

Calhoun et al. and the other previously-mentioned studies considered vapor pressure lowering to result from curved liquid interfaces. But Hsieh (1980) observed that the Calhoun et al data could be explained better by adsorption than by curved surface vapor pressure. Hsieh (1980, 1983) found small adsorption with unconsolidated sand, but large adsorption with consolidated sands. He attributed the difference to adsorption in micropores and observed that the mass adsorbed as liquid could be ten times greater than the mass of vapor for even high porosity sandstones.

Herkelrath et al.(1982, 1983) also studied adsorption of steam. They found that steam transmitted pressure pulses more slowly than uncondensible gases in a porous medium. They measured steam adsorption in a soil and found results consistent with transient flow experiments. The Hsieh and Herkelrath et al. adsorption results are given in Figs. 4 and 5. The adsorption shown on Fig. 4 is about 0.001 lb/lb rock, and on Fig. 5 about 0.01 lb/lb rock.

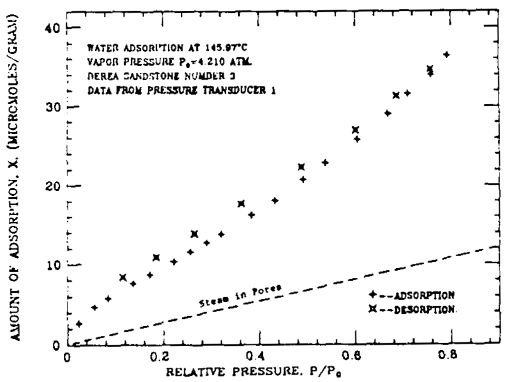

Fig.4 Water adsorption isotherm at 145.97C (Hsieh, 1980)

Economides (1983, 1985) studied the effect of adsorption on vapor-dominated geothermal systems. He used results of the Hsieh and Herkelrath et al. adsorption measurements and made the reasonable assumption that the mass adsorbed was essentially a linear function of pressure to the flat surface vapor pressure (see Figs. 4 and 5). This led him to conclude that pressure, not p/z, should be a linear function of the mass produced for field data. He regraphed the data from Table 1 and presented Fig. 6. The results for either p or p/z vs mass produced are similar. The match in Fig. 6 appears better than it actually is because the first two pressure

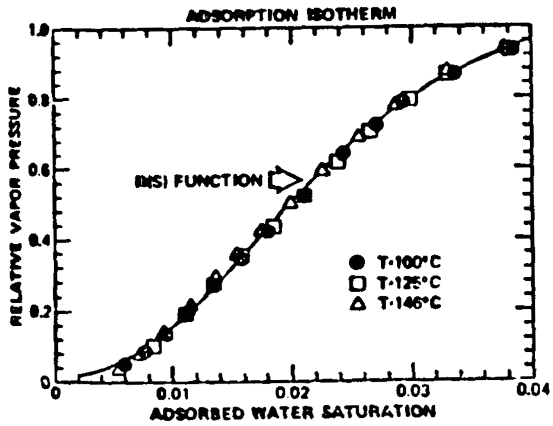

Fig.5 Adsorption Isotherm for water and silty sand (Herkelrath, et al., 1982,1983)

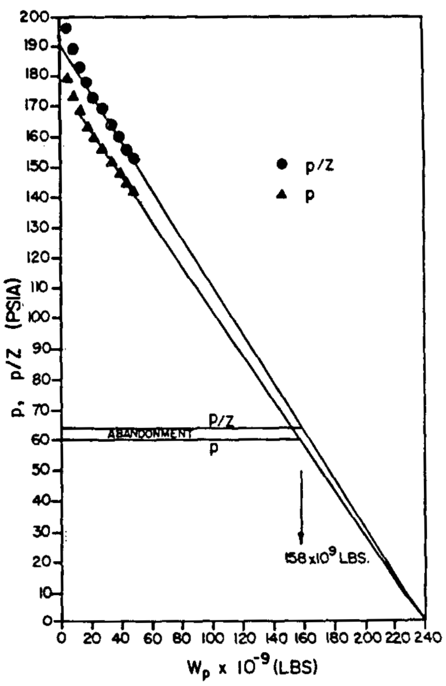

Fig.6 p and p/Z vs cum. prod. for Big Geysers Shallow zone (Economides and Miller, 1985)

points in Table 1 are not shown. Figure 7 presents the Table 1 results completely. Neither model matches the early drop in pressure.

DISCUSSION AND CONCLUSIONS

Consider that a vapor-dominated steam reservoir contains vapor and must contain liquid by virtue of convection and condensation as heat is transferred to the over-

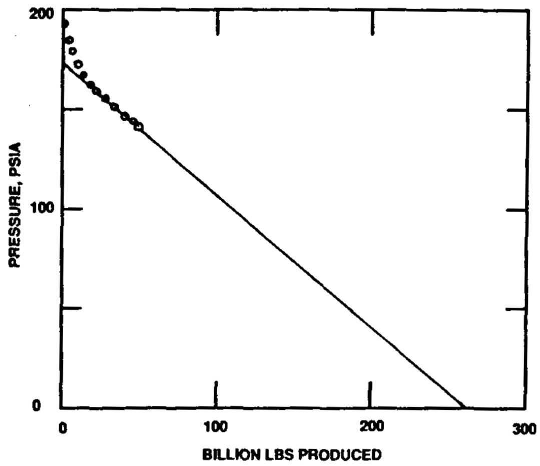

Fig.7 p vs cum.prod. for the Big Geysers shallow zone

burden, Truesdell and White (1973), White (1973). Then:

lbs vapor + lbs liquid =

$$V\phi(1-S_w)_{v} + V\phi S_{w\,l}$$

where V is the reservoir bulk volume, cu ft, ϕ is the fractional porosity, Sw is the fractional water saturation, is density, lb/cu ft, and the subscripts v represents vapor and l is liquid.

The shallow Big Geysers steam reservoir was about 400F in temperature. The density of vapor is 0.5367 lb/cu ft and the density of hot liquid is 53.65 lb/cu ft. Thus:

lbs vapor + lbs liquid =

$$V\phi[(1-S_w)0.5367 + S_w 53.65]$$

Inspection of the right-hand side indicates the larger density of liquid controls the expression, and the vapor term may be neglected. It appears the term "vapor-dominated" is ironic.

If it is assumed that the only mechanism for storage of liquid in the shallow zone is adsorption, then Fig. 7 presents the desorption curve for the entire shallow zone. This is an important and new observation. If this is true, some other conclusions are that the desorption curve for Geysers greywacke is <u>not</u> linear with pressure, and that desorption behaves as though the system has a large variation in compressibility. However, the storage mechanism is not compression. Inspection of Fig. 7 shows a large drop in pressure for a small unit of production at the start, then a gradual drop in pressure with mass produced which is nearly linear. The linear extrapolation of pressure vs mass produced assumes a linear relationship. It is not known just what the relationship is.

There is additional information which indicates that storage of liquid as micropore fluid is reasonable. The shallow zone has a limited thickness of a few thousand feet at most. This zone was developed on a very close well spacing (0.5 acres per well) but liquid was never encountered in the steam interval. Studies of changes in the gravitational field indicate that the center of gravity of the mass produced from the field should be not more than 5,000 feet below the surface, Isherwood (1977).

The rapid drop in pressure on start of production appears common to most vapor-dominated systems. Italian reservoirs typically behave this way. New areas at The Geysers typically have a high rate of pressure drop which moderates after a time. Perhaps the desorption model offers an explanation for this behavior. A key remaining problem is measurement of adsorption for geothermal system rocks to determine whether adsorption does resemble Fig. 7, and if so, what shape is proper for the extrapolation.

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TABLE 1--BIG GEYSERS FIELD SHALLOW ZONE CUMULATIVE PRODUCTION AND RESERVOIR PRESSURE* (Ramey, 1968)

year	No. Wells	Steam Produced MMlb/yr	Steam Produced Mlb/hr	Cum. MMMlbs	** p, psia	Z= pv/nRT	p/Z, psia
1957	0	0	0	0	194	0.913	212
1957	5	1109.8	126.7	1.1	187	0.915	204
1958	5	3224.4	368.1	4.3	180	0.917	196
1959	10	3426.7	391.2	7.8	174	0.919	189
1960	10	4698.2	536.3	12.5	169	0.921	183
1961	10	4246.5	484.7	16.7	164	0.922	178
1962	10	4377.6	497.7	21.1	160	0.923	173
1963	13	5299.7	605.0	26.4	156	0.924	169
1964	12	6197.5	707.4	32.6	152	0.925	164
1965	9	5509.9	629.0	38.1	148	0.927	160
1966	7	4941.4	564.0	43.0	145	0.928	156
1967	7	3847.3	439.0	46.9	142	0.929	153

* Excludes prod. from original wells drilled in 1920's and prod. from wells T-8, T-13, and T-14 after deepening.
** Measured at the wellhead.

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MANAGEMENT OF GEOTHERMAL RESOURCES

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ABSTRACT

Research at UURI concentrates on quantifying the processes taking place in geothermal systems and in developing methods to detect and monitor those systems. The past year's research has placed a greater emphasis on problems identified at The Geysers. As more geothermal systems reach a mature stage of production, production declines will become more common unless effective resource management techniques are developed.

Work is progressing on the development of vapor-phase tracers, and we are planning a tracer test with several of the operators. Mineralogical and geochemical studies to determine the origin and distribution of corrosive steam are continuing in cooperation with GEO Operator and UNOCAL.

Hydrogeochemical studies using fluid-inclusion and chemical data are continuing at Coso, Steamboat, Heber and the Valles caldera. This work is documenting fluid flow in fractured geothermal systems and in changes in fluid chemistry caused by production.

Our investigation of the application of borehole geophysics has continued with the development of two different 2-dimensional inversion algorithms for interpretation of cross borehole and borehole-to-surface data. Instrumentation is being assembled to field test the method. We believe that these techniques can be effective in mapping permeable zones and reservoir boundaries. In addition, this method can potentially be used to monitor drying out of vapor-dominated reservoirs and cold-water influx into liquid-dominated reservoirs.

Investigations of the state of stress in the Heber geothermal field suggest that borehole breakouts may be related to the proximity of major fracture zones. Concepts of stress have been used to develop a model for The Geysers system in which a structural arch effectively decouples the reservoir from the vertical stress. This model will be important in planning injection to control pressure declines.

INTRODUCTION

Research at UURI concentrates on quantifying the chemical and physical processes taking place in geothermal systems and in developing methods to detect and monitor those systems. In the past year, this effort has seen a change in emphasis to concentrate much more on The Geysers field. However, since this change has been recent, much of the work is still in the preliminary stages.

As more geothermal systems reach a mature stage of production, it is inevitable that production declines will become more common place. The solution to this problem is effective management of resources through injection. Injection strategies must consider the orientation of fluid pathways, the response of those pathways to production and injection, and the chemical interaction of injected fluids with the reservoir fluids.

With the National Energy Strategy placing more emphasis on the contribution of renewable energy resources, the future will also require a much greater emphasis on the exploration for new geothermal resources.

INJECTION RESEARCH AND TRACER DEVELOPMENT

The preliminary results of the injection test at the Dixie Valley geothermal field that involved several of the tracers developed by UURI were reported last year. That test was a cooperative effort between DOE and Oxbow Geothermal, the operators of the Dixie Valley field. Electric power production at Dixie Valley began during the summer of 1988 from a wellfield consisting of six production and four injection wells. For the tracer test, tracer slugs were injected into three of the injection wells. Benzenesulfonate (300 kg) was injected into Well 45-5, fluorescein (150 kg) and benzoate (100 kg) were injected into Well 32-18, and fluorescein (50 kg) and 4-ethylbenzenesulfonate were injected into Well 52-18. One of the six production wells that were monitored showed breakthrough of tracer-labeled injectate. The final interpretation of the test results were published in the 1989 Transactions of the Geothermal Resources Council (Adams et al., 1989). Detailed interpretations of the behavior of fluorescein during the test have been prepared and will be submitted to the journal Geothermics in April, 1990. A summary of these findings is presented below.

The Dixie Valley tracer test data were used to calculate the minimum velocities and average temperatures of the injection fluids. Velocities for the most direct path of the tracer slug were calculated using the time of breakthrough and the distance between Wells 32-18 and 76-7 (1128 m). The minimum velocity for the tracer front and peak were 5.0 and 1.4 m/hr, respectively. Because both wells are completed in basalt at similar depths, the most probable path for the injected fluid was through a basalt horizon.

The ratio of benzoic acid to fluorescein was combined with kinetic data for thermal decay of fluorescein (Adams and Davis, 1990) and used to derive temperatures along the postulated injection-production flowpath in the basalt. An effective temperature for the flowpath can be derived by comparing the time change of the tracer ratios from the field data to those calculated from the laboratory data at constant temperature. Because the injection wells at Dixie Valley had only been in use for a short time prior to the tracer test, the effective temperature along the injection-production flowpath was expected to be between the reservoir temperature, 240°C, and the pre-exploitation injection well temperature, 221°C. Figure 1 shows a comparison of the measured benzoic acid/fluorescein ratios in the production fluid to the ratios predicted from the kinetic data. This comparison yields an effective temperature of 225° to 230°C for the injection-production flow-path. The close agreement between actual and calculated temperatures implies that our kinetic data on the thermal decay rate of fluorescein are useful in the field.

One of the objectives of the Dixie Valley test was to evaluate the rock-water interactions of the geothermal tracers. For example, although fluorescein has been used often as a geothermal tracer, significant adsorbtion of the compound has been observed during groundwater tracer tests. Adsorption of a tracer throughout a long flow path can retard the arrival time of the peak, interfering with interpretation of the breakthrough data. However, when one adsorptive and one nonadsorptive tracer are injected simultaneously, the breakthrough curves will show two distinct peaks. Thus, any adsorption during the Dixie Valley test should have resulted in time separation of the arrival of the peaks of benzoic acid (a non-adsorbing tracer) and fluorescein.

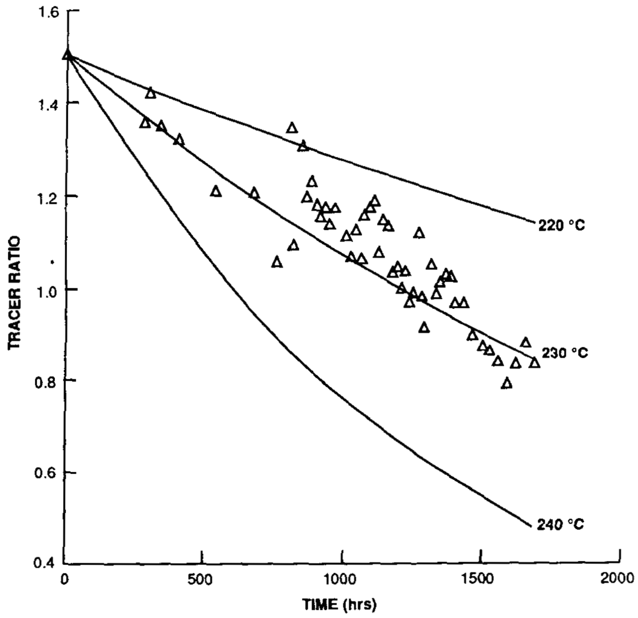

Figure 1. Actual ratios of fluorescein to benzoic acid in the Dixie Valley geothermal production fluid (Δ) compared to ratios calculated with the assumption of constant temperature along the injection-production flowpath (curves). The time shown is the time since injection of the tracers.

The normalized return curves of the simultaneously injected benzoic acid and fluorescein tracers from the Dixie Valley test are shown in Figure 2. The fluorescein curve in this figure has been corrected for thermal decay using a flowpath temperature of 230°C. These return curves show no peak separation, which indicates that fluorescein does not adsorb at these temperatures and is an appropriate tracer for these conditions.

Our current emphasis in the tracer research program is to develop and test vapor-phase tracers. Methods to monitor and evaluate injection are needed at The Geysers because of the large pressure declines being experienced in many parts of the field. In order to evaluate the mass recovery of the injected fluid and the efficiency of the current injection strategy, vapor-phase tracers must be used to follow the fluid from the injection to the production wells. An ideal vapor-phase tracer would have the same concentration in both the steam and liquid, regardless of the mass fraction of steam produced from the injected liquid. Unfortunately, only the isotopes of water even approach this behavior. Deuterium and tritium have been used in the past as tracers but are no longer suitable for various reasons. Consequently, there is a need for new tracers that can be used to quantify the mass recovery of injected fluids.

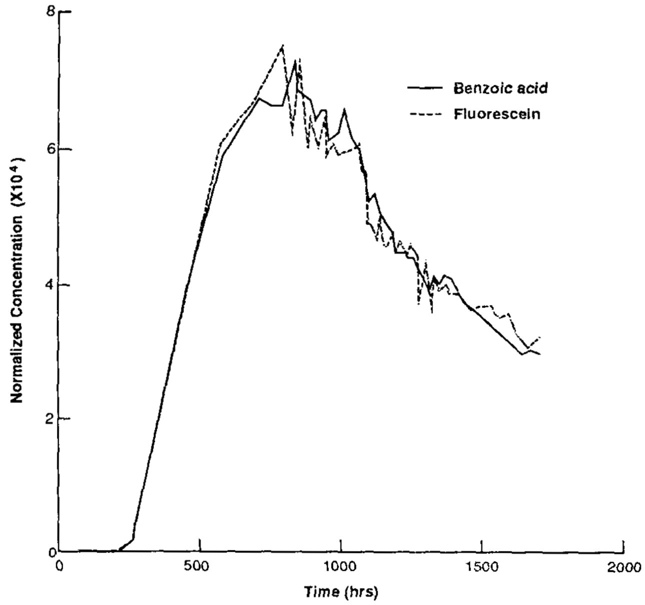

Figure 2. Normalized tracer return curves from the Dixie Valley tracer test. The concentration data was normalized by dividing the tracer concentration by the number of kilograms of tracer injected.

Suitable tracers must be stable at temperatures up to 350°C, have finite volatilities, be detectable at low concentrations, be nontoxic and relatively inexpensive, and they must be unaffected by the high levels of molecular oxygen in the injected fluid. We have identified a class of fluorocarbons that appear to be suitable as vapor-phase tracers. Some of these compounds have been tested at temperatures greater than 300°C in the presence of water and are stable for time periods exceeding six months.

We are currently setting up a vapor-phase laboratory to test the thermal stabilities and chemical properties of these compounds. Our tests will simulate geothermal conditions as closely as is possible in the laboratory. In order to test the tracers under actual field conditions, we are also planning to perform field tests that will be cost-shared with industry. One such test is planned for the spring of 1990 in the southwestern Geysers. The injection and production wells that will be involved in the test are operated by GGC and NCPA. The test will be conducted in an area that has previously been without injection wells and has been shown to display superheat. Since injection began in the fall of 1990 the production wells have shown dramatic changes in their isotopic composition. Thus, the test has a high probability of success because injection-production communication has been demonstrated. The test will determine the velocities and directions of injectate travel and the relative proportions of injectate from the two injection wells in the area.

BOREHOLE GEOPHYSICS

GOALS OF CROSS-BOREHOLE AND SURFACE-TO-BOREHOLE RESEARCH

A borehole samples a small volume of rock and the physical properties of any core which is brought to the surface can be altered by the experience. Traditional logging techniques extend the radius of investigation to perhaps several feet, while sampling rock which ideally has not been degraded seriously by the drilling. There is a great volume of rock which does not affect either traditional logging measurements or surface geophysical measurements. Unfortunately, for many purposes, this volume of rock is the most interesting and knowledge about it is needed. The purpose of cross-borehole and surface-to-borehole geophysics is to image this previously unknown zone.

Since the response of electrical geophysical methods is a function of the concentration of aqueous ions and semi-conducting ore minerals, electrical geophysics used in a cross-hole and surface-to-borehole mode is a likely candidate for giving information about geothermal reservoirs from regions which are inaccessible to traditional surface geophysics or logging techniques. Reservoir properties which would influence the measured cross-borehole response, for example, include temperature, permeability contrasts, large fractures and faults, clay alteration, the amount of pore fluid, and the salinity of the pore fluid. Such information is important in guiding drilling, assessing injection programs, and ascertaining the fluid reserves of a reservoir.

As an example of a possible application, consider the potential use of electrical borehole geophysical methods to obtain pertinent parameters of the subsurface at The Geysers for helping to mitigate decreased steam production and HCl generation. The two major problems at The Geysers are pressure decline apparently brought about by loss of water from the system and the increasingly corrosive nature of the produced steam. Reinjection is a plausible way of ameliorating both problems. However, an optimal reinjection strategy is critically dependent on a knowledge of the distribution of water in the system prior to injection and the movement of injected water in the system. The salinity of the reservoir water may also be important because it might influence the amount of corrosive hydrochloric acid contained in the produced system. Estimating the distribution and salinity of water in the system might be of great value in deciding between the Fournier and Truesdell models for hydrochloric-acid generation. Since the electrical and electromagnetic techniques are unique among remote sensing techniques in being sensitive to the amounts of reservoir water as well as its temperature and salinity, they should be considered as candidate tools for helping to design an injection strategy and for monitoring its progress.

2D INVERSION ALGORITHMS

For several years, UURI has conducted a research program on inversion of electrical data. For the cross-borehole and surface-to-borehole resistivity methods, two successful inversion algorithms have been developed for the case when the electrical conductivity structure of the earth does not vary along one spatial direction. The first algorithm, developed by Beasley (1989), can in principle represent a complex conductivity distribution in fine detail. Of course, the computational cost increases as more detail is represented. Since the algorithm is based on the finite-element method, a certain amount of expense is incurred even for simple conductivity distributions. If the exploration target is composed of a small number of discrete bodies, the second algorithm, developed by LaBrecque (1989) has clear computational advantages over the Beasley algorithm. This algorithm achieves its speed with a small number of discrete conductivity inhomogeneities by using an integral-equation technique for calculating model responses and response derivatives with respect to the model conductivities.

Wang et al., (1990) investigated an inversion technique using alpha centers. In this technique, the earth's conductivity distribution is assumed to be represented as a superposition of a number of "alpha-center" conductivity distributions. This assumption leads to an extremely fast inversion technique. The assumed conductivity distribution itself seems to adequately represent discrete geologic features such as hydraulic fractures.

FIELD SYSTEM

During the past year, UURI has progressed towards the goal of fielding a system for gathering cross-borehole or surface-to-borehole electrical and electromagnetic data in geothermal areas. We have also studied potential field experiment sites and have examined new ways of gathering and interpreting data.

The heart of a borehole electrical system is the electronic assemblage which transmits and receives the electric or magnetic signal. UURI has purchased this equipment from Zonge Engineering of Tucson. The components of this assemblage are a high-power 30KW transmitter, a motor-generator used to power the transmitter, and a six-channel receiver. The transmitter is capable of generating up to 50 amperes of current into a grounded wire or an ungrounded loop. The current waveform can be sinusoidal or repetitive boxcars, with the repetition frequency ranging from DC to 10KHz. This transmitter versatility enables UURI to conduct DC resistivity, IP and most active source electromagnetic surveys. The receiver is programmable and can be interfaced with electric field or magnetic field sensors.

Another essential component of a cross-borehole or surface-to-borehole system is the draw-works and cable assemblages. UURI is in the process of acquiring a logging truck equipped with draw-works and approximately 3000 ft. of 4-conductor armored cable. Given the successful acquisition of this truck UURI, will be able to conduct surface-to-borehole experiments in shallow, moderately hot environments.

Anticipating the successful acquisition of a complete borehole system, UURI has examined the practical logistical problems of conducting surface-to-borehole and cross-borehole surveys and has assessed the possibility of conducting field experiments at various sites. Tripp et al. (1989) discuss some experiment design criteria as applied to a possible test site at Roosevelt Hot Springs. General guidelines for field experiments are investigated in Tripp et al. (1990) and Wright (1989).

Many wells are cased with steel casing. Since the steel is highly conductive, it is nearly an equipotential body. This makes electrical potential measurements very difficult to execute. However, magnetic field measurements through casing are possible, as demonstrated by Cook et al. (1990). These magnetic field measurements can be quite diagnostic of geological features away from the borehole, as discussed by Tripp et al. (1989).

In conclusion, UURI is now well positioned to begin field tests of cross-borehole and surface-to-borehole electrical techniques given continued funding.

HYDROGEOCHEMICAL MONITORING

The integration of fluid-inclusion data with chemical analyses of spring and well fluids has proven to be a powerful means of obtaining information on the geometries and compositions of geothermal reservoirs. Our current studies have focused on 1) The Geysers; 2) geothermal systems developed in granitic host rocks, and 3) the composition of secondary steam-heated reservoirs.

A petrologic and fluid-inclusion study of hydrothermal breccias from the Northwest Geysers was conducted with GEO Operator Corp. to obtain infotmation on the early evolution of the steam reservoir (Moore et al., 1989). In this investigation, hydrothermal breccias occurring above the steam reservoir were examined. Our work demonstrated that the breccias formed from boiling fluids at temperatures ranging from 315° to 225°C. The fluids had relatively low salinities, between 0.35 and 1.7 equivalent weight percent NaCl, and variable but significant gas contents. The inclusions were found to display systematic variations in their homogenization temperatures which could have been caused by the downward movement of the water table with time. As the water table declined, slightly acidic condensate formed and altered the mineralogy of the breccias.

Our current petrologic studies at The Geysers reflect the need to understand better the origin of the corrosive steam that has been encountered. We are studying fluid inclusions from core and cutting samples that have been taken from both the normal and high-temperature reservoirs. We will use this data: 1) to determine the potential of the reservoir liquids to deposit salts within the rocks as they evolved; and 2) to help evaluate the composition of the deep liquid underlying the present steam reservoir.

Hydrogeochemical studies of geothermal systems in granitic rocks have continued with California Energy at Coso, California, and with Caithness Power Inc. at Steamboat Hills, Nevada. At Coso, we are assisting in the evaluation of chemical data obtained as part of California Energy's development and monitoring programs. Fluid-inclusion measurements have been made on samples from fifteen wells drilled throughout the field. Several additional wells have been sampled and will be analyzed this year. Variations in the temperatures and salinities of the fluids have been used to define a plume of hot water that originates in the southwestern part of the field (Moore et al., 1989 and 1990). Two-phase conditions exist in the upwelling center. As the fluids move laterally and vertically from this center, they are diluted by at least one, and possibly two, low-salinity fluids with temperatures between 120° to 170°C.

Core and cuttings from four wells at Steamboat Hills have been obtained in order to develop a better understanding of the reservoir chemistry of this important system. We plan to continue our petrologic studies of these wells and integrate the results with chemical analyses of the production wells.

Sodium-bicarbonate fluids are found on the margins of many high-temperature geothermal systems (Mahon et al., 1980). These fluids, which develop as steam and acidic gases (CO_2 and H_2S) condense into shallow groundwaters, have been shown to cause severe damage to well casings in some systems (Hedenquist and Stewart, 1985). However, because of their low temperatures, sodium-bicarbonate fluids are generally not sampled during drilling.

We have sampled and analyzed fluid inclusions from several geothermal systems to develop a general model of the chemical and thermal structure of these secondary steam-heated reservoirs. Our work has shown that CO_2-enriched fluids define umbrella-shaped caps over the deeper sodium chloride fluids and that these caps thicken outward from the main upwelling zones (Lemieux et al., 1989; Moore et al., 1990). Inclusions from the upper parts of the caps have calculated CO_2 contents that range up to 5 weight percent. Lower concentrations of CO_2 characterize the deeper portions of the steam-heated reservoirs. The high concentration of CO_2 in some of the inclusions requires trapping at pressures several tens of bars above a hydrostatic gradient. These pressures may have developed intermittently as fracture permeabilities were reduced by mineral deposition.

STRESS MEASUREMENTS

Previous studies of borehole breakouts in geothermal wells across the western U. S. have shown that, in contrast to the commonly accepted assumption that stress fields are relatively uniform over large regional areas, geothermal systems are dominated by local or secondary stresses (Allison and Nielson, 1988; Nielson, 1989). Stress orientations vary not only among wells but also within wells studied. Faults can show a range of behaviors from completely sealed and mechanically indistinguishable from the host rock to free surfaces across which stresses are not transmitted. The control of stress by faults suggests that such faults are open and active, and in hydrothermal systems, act as conduits for fluids.

The assumption is that the stress variations recognized in the geothermal wells are due to warping of stress trajectories around local faults and/or to thermal stresses generated by hydrothermal fluids in those fault zones (Allison, 1988). Thermal stresses in a fault or fracture can be up to twenty times as large as typical continental deviatoric (tectonic) stresses for every 100°C difference between the fluid and surrounding country rock. In many wells previously examined, the stress directions run perpendicular to the trends of mapped normal faults. That is, the breakout group directions lie in the least horizontal compression direction inferred for those faults in an extensional environment.

Measurements of breakouts from six wells in the Heber field have shown the presence of three distinct sets: north-, northeast-, and northwest-trending. Lengths of breakouts in each of the three sets were measured as a percentage of total breakouts within each well as a method of normalizing them. The percentages were plotted on separate maps for each stress orientation set and two patterns became evident. First, the percentages of each breakout set varied systematically across the geothermal field so they can be contoured. Second, two of the sets (northeast and northwest sets) centered on the two mapped faults in the field and each set of stress concentration contours run parallel to one of the faults. This suggests that local stress may be used to predict the location of active faults in geothermal systems.

Our initial work on stress at The Geysers has reviewed previously published studies of the structural geology. We have been struck by several contradictions. First, although the system is located in a zone of active faulting, and the reservoir is severely underpressured, it is not being recharged along the numerous faults that cut the area. Second, production of steam from the graywacke is from randomly oriented fractures, including fractures that have a flat orientation. Under calculated lithostatic pressure, flat fractures should not be maintained even in the preproduction state. We postulate that the reservoir is protected from the weight of the overlying lock by a structure that is analogous to an arch.

In order to test this model and give a first order approximation of the stress distribution around The Geysers reservoir,we have applied a numerical model designed to determine stress orientation around an underground excavation (Hoek and Brown, 1980). The application of this model is warranted by the underpressured conditions of the reservoir. This is a two-dimensional model, and it does not consider thermal effects such as cooling and contraction of the felsite intrusion. The reservoir is approximated by an ellipse (Fig. 3) and the sections are parallel the least principal stress (Fig. 3A) and perpendicular the least principal stress (Fig. 3B) in the σ_1-σ_2 plane. The lines (streamlines) plotted show stress trajectories or how the orientation of the stress changes due to the presence of the underpressured reservoir. In an elastic medium, the separation of streamlines demonstrates a low-stress environment. In contrast, areas where the streamlines crowd together shows areas of high stress.

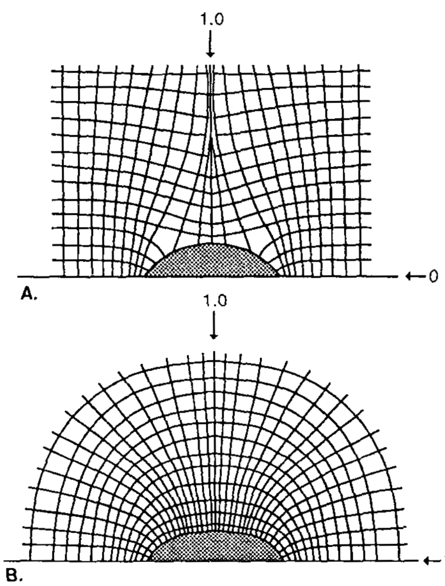

Figure 3 - Two-dimensional models of stress trajectories around a cavity. A. Greatest principle stress is vertical with least principal stress horizontal. B. Representation of stress trajectories in the $\sigma_1 = \sigma_2$ plane.

Figure 3A shows the stresses that would develop along a NW-SE section parallel the least principal stress. Note that the approximation assigns volumes of $\sigma_1 = 1.0$ and $\sigma_3 = 0$. Here the streamlines are affected considerably above the reservoir, and low stress zones are developed at the top of the reservoir.

An implication of the stress distribution on Figure 3A is that the approach to the reservoir boundary may be predictable using measurements of borehole elongation or breakouts (Allison and Nielson, 1988). Since stress orientation is changing because of the presence of the reservoir, this change should be measurable and detectable using either Dipmeter or Televiewer tools.

The situation changes considerably at right angles to this section (Fig. 3B). In this section that represents the $\sigma_1 = \sigma_2$ plane, compressional stresses are concentrated along the top of the reservoir. In addition, there is a concentric or hoop stress surrounding the reservoir. Another way of looking at this situation is that the overburden pressure must be distributed through the reservoir "cap" in order for the underpressured conditions, and reservoir permeability, to be sustained. In this section, the distributed loads will tend to close permeable channels.

It is clear from this simple representation that three-dimensional modeling of the stress environment is required to depict accurately the conditions in the vicinity of the reservoir.

The lack of natural recharge to the system can be attributed to the relative impermeability of the rocks surrounding the reservoir. However, application of a simple stress model also suggests that concentric stresses around the reservoir may be responsible for preventing some natural recharge.

The model also helps explain one of the enigmas of the system; the existence of flat, steam-producing fractures in an underpressured reservoir. As the model suggests, the reservoir is apparently protected from the lithostatic stresses in much the same manner that a tunnel is; the stresses are distributed along the reservoir margins. However, it is also clear that this structural seal is not perfect since surface subsidence is measurable and earthquakes in the reservoir are responding to regional tectonic stresses.

We postulate that the reservoir developed by contraction of the felsite pluton following emplacement and initial contact metamorphism of the country rock. Pluton contraction could have resulted from processes of cooling or tectonically induced magma withdrawal. Country rock collapsed into the space created by the withdrawal up to the point that the overburden was supported by an arch. Note that this process of roof collapse may have been responsible for the transition from the liquid- to the vapor-dominated state.

ACKNOWLEDGEMENTS

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RESERVOIR RELATED RESEARCH AT IDAHO NATIONAL ENGINEERING LABORATORY, LAWRENCE LIVERMORE NATIONAL LABORATORY, AND OAK RIDGE NATIONAL LABORATORY

J. L. Renner, INEL
P. W. Kasameyer, LLNL
R. E. Mesmer, ORNL

ABSTRACT

Idaho National Engineering Laboratory (INEL), Lawrence Livermore National Laboratory (LLNL), and Oak Ridge National Laboratory (ORNL) conduct research in reservoir engineering, geophysics, and geochemistry, respectively, in support of the DOE Reservoir Technology Research Program. INEL's research has centered on the development of a reservoir simulation code to predict heat and solute transfer in fractured, porous media. The results of that development were reported to the geothermal industry in a technical transfer workshop during 1989. In support of the initiatives for research at The Geysers, INEL will initiate in cooperation with Lawrence Berkeley Laboratory, studies of injection and related interference effects at The Geysers. Work at LLNL is centered on analysis of the seismicity associated with production and injection at geothermal systems and effects of geothermal systems on seismic signals. LLNL is continuing studies of seismic attenuation related to the presence of steam at The Geysers. ORNL conducts research to obtain the thermodynamic and kinetic data needed as input into geochemical models such as those being developed by John Weare of the University of California, San Diego that predict the phase behavior and corrosion characteristics of geothermal brines. The current program at ORNL addresses the ion interaction parameters of bisulfate ion (HSO^-) with H^+ and Na^+, the dissociation constant of HSO_4^-,OH^-, and the solubility and specification of aluminum in the system H^+-Na^+-K^+-Cl^--OH^-. ORNL is initiating studies of the distribution of HCl in steam in support of the expanded research program at The Geysers.

INEL is also involved in several other activities in support of the development of geothermal resources. INEL acts as liaison between the Geothermal Technology Organization and DOE and provides contract support for initiation of joint research. INEL also participated with several other National Laboratories in preparation of an analytical study of renewable resources in support of DOE's ongoing National Energy Strategy. As a result of this study, INEL is initiating a review of geothermal reserves.

INEL
(J. L. Renner)

Simulation Code Development

The movement of injected fluid in a fractured reservoir is being modeled in response to a primary industry concern about the effect of injection on pressure maintenance, thermal breakthrough, and water-rock interaction in a producing reservoir (Miller and Clemo, 1988). The Idaho National Engineering Laboratory (INEL) has developed the FRACSL code to simulate flow, solute transport, and heat transport in a saturated fractured-porous media. The code uses a dual permeability approach in which a common head distribution drives flow in matrix cells and in discrete fractures which lie on the edges and diagonals of the matrix cells. Solute and heat transport are modeled by moving marker particles in the matrix, in the fractures and between the two. Fractures and matrix are modeled explicitly to provide the most physically realistic models and potentially the most accurate tool for studying the movement of injected and produced fluids.

FRACSL (Miller et al., 1987, Miller and Clemo, 1988) provides a two-dimensional simulation of flow, solute transport and heat transport in a saturated, fractured-porous media. The following discussion of FRACSL is taken from Miller and Clemo (1988).

> As shown in Figure 1, a distributed flow is computed through the porous matrix cells and a discrete flow is computed in the parallel plate fractures superimposed on the edges and diagonals of the matrix cells. This approach, termed dual permeability, is different from dual porosity in which flow is computed in the fractures and a one-dimensional interchange occurs with the storage in the adjacent matrix. In dual permeability a flow can be computed from fracture to fracture through intervening matrix and in dual porosity modeling it cannot.
>
> The marker particle transport approach used in FRACSL is ideally suited to dual-permeability models since it permits explicitly addressing the fractures, the matrix, and the interchange between them in terms of the fundamental physical processes of advection, dispersion, and diffusion.
>
> Movement within a fracture is computed based on random diffusion plus the longitudinal and transverse fluid velocities at the particle lateral position. The longitudinal velocity is selected from a Poiseuille distribution across the fracture aperture while the transverse velocity depends on the fluid movement from fracture to matrix due to advection across the matrix cell and storage within it. At a junction with another fracture the particle moves into the appropriate exit fracture by advection along a stream line plus a random diffusive movement.

Particle transfers between fracture and matrix are computed due to advection and diffusion. For diffusively dominated conditions, the random walk approach used excessive amounts of computer time since a particle moving into the matrix has a 50% chance of moving back into the fracture in the next time step. A higher order model was, therefore, developed which determines the particle motion based on overall probability..

Particle movement within the matrix is computed as the sum of advective, dispersive and diffusive motions. Solute concentration or temperature within the model is computed from the distribution of particles at any particular time. Concentration or temperature is also monitored at a production well node.

The original version of FRACSL uses the Advanced Continuous Simulation Language (ACSL) (Mitchell and Gauthier Associates, 1986) for its user interface and numerics and is implemented on the INEL CDC Cyber 176 computer. This version has been phased out and the work load transferred to a UNIX based version with self-contained numerics. The new version (FRAC-UNIX) is operable on a SUN or equivalent workstation for field applications.

The FRAC-UNIX code is currently capable of modelling fluid flow and solute and heat transport in a two-dimensional, dual-permeability reservoir. Further development of FRAC-UNIX is not included in the fiscal year 1990 program.

INEL presented a two day workshop on the code to the geothermal industry in January 1989. A preliminary edition of the user's manual for the code was given to the attendees at the meeting. The final version of the manual is being edited and will be available soon. The code will be released through the National Energy Software Center.

Geysers Research

Current research at INEL is directed towards developing a better understanding of the effects of injection on reservoir performance. Two studies have been proposed. The first, which will be conducted in conjunction with Lawrence Berkeley Laboratory, proposes to study the relation between interference effects and injection. The second study will investigate modelling of injection at the Geysers and perform comparative studies of the MINC and Warren and Root approaches to simulation of fractured reservoirs.

LLNL
(P. W. Kasameyer)

Lawrence Livermore National Laboratory is developing and testing methods to image volcanic areas, gathering case-study information for geophysical monitoring of geothermal fields, and evaluating practical geothermal applications of existing geochemical modelling codes Only the development of seismic velocity and attenuation images at The Geysers to look for steam zones is discussed in this paper.

The method used at The Geysers is based on successful experiments at Medicine Lake Volcano, and at Newberry Crater. Rings of explosions provided seismic signals to produce 3-D images of these volcanic areas. At Medicine Lake, a low attenuation, normal velocity area was interpreted to be a dry or steam-saturated area beneath the water table.

Because of substantial industry interest in this method, LLNL decided to apply it at The Geysers, where the predictions of the existence of steam zones could be tested. In a cooperative project, Unocal Corporation and Lawrence Livermore National Laboratory are working together to utilize existing microearthquake data for a three-dimensional interpretation of both the seismic velocity structure and the attenuation properties of the geothermal field. In this study LLL is using natural microearthquakes as seismic sources to test the hypothesis that high seismic velocity and low attenuation occur where steam is present. If this method is successful, it could be applied to other seismic data sets collected at The Geysers.

Unocal has recorded waveforms and picked P-wave arrival times for thousands of microearthquakes recorded over a five year period, and are providing LLNL with a comprehensive set of the "best" events. LLNL is using the data from selected events to determine the apparent attenuation for each signal and to run inversion programs to produce 3-D models of attenuation and velocity. Results of the study should provide an improved ability to locate earthquakes, additional information about geologic structures, and possibly, the location of steam zones.

The study area is 10 km square and 5 km deep. The number of stations and the distribution of earthquakes provides excellent coverage of the target volume. Presently, LLNL is resolving source volumes of 1 km cubed and is examining ways to improve resolution of the inversion to better than 0.5 km. This type of study is possible in most areas that have recorded microearthquakes or artificial explosions from a wide variety of locations with stations distributed over the area of interest.

Graphic presentation of the inversion results provides a means to compare the structural interpretations with geologic maps or hypocentral locations. When final images of velocity and attenuation are completed this summer, LLNL will relate them to geologic features and make predictions about the occurrence of steam.

The Unocal contribution to this work has been substantial. By supplying LLNL with high-quality seismic data collected over several years, they have saved DOE several hundred thousand dollars, and have allowed LLNL to complete this project in one year instead of three. LLNL looks forward to other fruitful cooperative efforts with industrial operators at The Geysers.

ORNL
(R. E. Mesmer)

Geochemical Research

The object of this research is to obtain needed thermodynamic and kinetic data for input into geochemical models which predict the phase behavior and corrosion characteristics of geothermal brines. Of particular interest are reactions involving highly saline solutions, for which no adequate theoretical predictive capabilities exist. Reactions important in controlling reservoir permeability, brine chemistry, plant scaling, and corrosion are the major concerns of this program. Needed data include activity coefficients, gas solubilities, and selected rate constants in the range of 0-350°C and 0-6 molal ionic strength for components of the system H-Na-K-Ca-Mg-Fe-Al-B-C-O-S-Si-Cl and the metals Pb-Mn-Zn-Cu, etc.

The current program addresses the ion interaction parameters of bisulfate ion--HSO_4^---with $H^+$and Na^+, the dissociation constant of HSO_4^-, the solubility and specifiation of aluminum in the system H^+-Na^+-K^+-$Cl^-$$OH^-$, and the distribution of HCl to steam. Results are available as input to the computer codes being developed by J. Weare and others, which model the effects of chemical equilibria and salinity on the geochemistry and engineering chemistry of geothermal facilities.

Liquid-Vapor Distribution of HCl to 350°C:

This project addresses physical chemical measurements relative to understanding the origin and transport of chloride in superheated geothermal steam systems such as The Geysers and Larderello, Italy. In order to assess the physical and chemical conditions for production and handling of the HCl-containing steam, new information on the distribution of HCl between liquid and vapor are needed at high temperatures as a function of brine composition. The motivation for the work comes from the accelerated corrosion caused by the presence of HCl in steam in contact with well casings and parts of the steam collection and handling systems of geothermal power plants.

HCl is strongly dissociated in the liquid phase at temperatures well below the water critical temperature but is strongly associated in the steam phase. Mass action suggests an increase in the volatility with decreasing pH and with increasing chloride activity in the liquid phase. We have constructed an apparatus for equilibrating HCl solutions in a noble metal lined pressure vessel fitted with a pressure transducer, inert tubing, and valves. The K_D values are being evaluated from volatility measurements to about 350°C on solutions for which activity coefficients for HCl are known.

Thermodynamic Parameters for $NaHSO_4$ and H_2SO_4:

The electrolyte solutions encountered in real-world situations such as in geothermal brines typically contain several cations and anions, some at relatively high concentrations. The extents to which solids precipitate and various chemical reactions occur in these complex systems depend not only on the (generally known) concentrations of the individual components but also on their (generally unknown) activity coefficients. The sulfate- bisulfate ratio is an important pH buffer in many such systems and the thermodynamic information for bisulfate, as well as for the bisulfate ionization equilibrium, are lacking for a complete chemical model of these systems. We have obtained osmotic data from isopiestic measurements on $NaHSO_4$ and H_2SO_4 solutions to 250°C and to about 5 molal. These data are being analyzed in detail along with other relevant data in the literature to derive ion-interaction parameters useful in the Pitzer model. Results can be combined with other thermodynamics to develop a comprehensive model for multicomponent brines.

The osmotic coefficient is a useful thermodynamic function which is defined in terms of the activity of the solvent (water in the present case). Figure 2 compares the osmotic coefficients of NaCl(aq) and $NaHSO_4$(aq) at 100 and 200°C. Standard data for NaCl(aq) at these two temperatures are shown as the dashed lines. The points are results from ORNL isopiestic experiments on $NaHSO_4$(aq) with NaCl(aq) as the osomotic standard. Osmotic coefficients for $NaHSO_4$(aq) are stoichiometric, i.e., computed on the assumption that $NaHSO_4$ dissociates into three ions (the infinitely dilute standard-state condition), and are useful as is for calculations involving the solvent activity.

Dissociation Constant of Bisulfate in NaCl Brines to 5 Molal and 150°C:

The sulfate/bisulfate ratio is an important pH buffer in many geothermal systems and the activity coefficients of sulfate and bisulfate are needed for modeling the solubility of the sulfate minerals and calcium phases (such as calcite) in brines as a function of temperature and total salinity. The dissociation constant of bisulfate ion, $Q = m(H^+)\ m(SO_4^{2-})/m(HSO_4^-)$ was measured potentiomtrically in a hydrogen-electrode concentration cell in 0.1 to 5.0 molal

NaCl solutions from 50 to 250°C. The results have been combined with literature data and fit to a function of temperature and ionic strength over the range 0-250°C and 0-5.0 molal ionic strength (Figure 3) using a modified form of the Pitzer ion interaction model (solid lines in Figure 3).

These results demonstrate the dominant effect of salinity, as well as temperature, on this important pH buffer. Because bisulfate dissociates appreciably to sulfate and hydrogen ions at elevated temperatures and ionic strengths, independent knowledge of the dissociation constant is needed in order to model the isopiestic data discussed above.

<u>Aluminum Speciation and Gibbsite Solubility in Brines at Elevated Temperatures:</u>

A knowledge of the aqueous chemistry of monomeric aluminum species is needed in order to model the evolution of porosity and solution chemistry (pH, cation ratios, etc.) in geothermal systems, because the stabilities of aluminosilicate minerals (clays, feldspars, zeolites, etc.) control these parameters. Therefore, we have undertaken a systematic study of the solubility of aluminum oxyhydroxides as a function of salinity and temperature, coupled with novel potentiometric measurements, in order to work out the speciation and activity coefficients of aqueous aluminum. Work completed thus far (funded jointly by DOE's Basic Energy Science and Geothermal Technology Division) includes the solubility of gibbsite, $Al(OH)_3$, in: (a) NaCl-HCl brines from 30-70°C and 0-5 molal ionic strength (free energies and activity coefficients of Al^{3+}); (b) Na^+-K^+-OH^--Cl^- brines from 5 - 100°C (free energies and activity coefficients of $Al(OH)_4^-$); and (c) NaCl brines buffered in the near neutral pH range at 50°C (species intermediate between Al^{3+} and $Al(OH)_4^-$ as well as formation constants for complexes of these ions with acetate and other soluble organic compounds). We have also determined the formation constants of $Al(OH)^{2+}$ and aluminum acetate to 125°C in 0.1 molal NaCl from potentiometric titrations.

The logarithm of the total molality of dissolved aluminum in equilibrium with gibbsite at 50°C in 0.1 molal NaCl solutions is shown as a function of the negative log of the hydrogen ion molality on Figure 4. The plotted points were obtained by measuring gibbsite solubility in NaCl solutions in which the hydrogen ion molality was fixed by a variety of organic buffers. The straight lines indicate the results of other experiments in which the solubility of gibbsite was measured over a wide range of temperatures and ionic strengths in: sodium chloride plus HCl solutions in which Al^{3+} is the dominant aluminum species; and in sodium chloride plus sodium hydroxide solutions in which $Al(OH)_4^-$ is the dominant species. The curve for $Al(OH)^{2+}$ was obtained from potentiometric titrations of Al^{3+} plus sodium chloride plus HCl solutions using a hydrogen electrode concentration cell. As can be seen, the results of these earlier studies agree very well with the results from the buffer runs. The shape of the solubility curve near its minimum can now be used to extract the formation constants of species intermediate between $Al(OH)^{2+}$ and $Al(OH)_4^-$. Early in this study, it was discovered the Al^{3+} forms a strong complex with acetate, one of the buffers used in the study. This has very important implications for secondary porosity development in sedimentary basins and geothermal systems, because acetate is the most abundant soluble organic acid produced during the thermal decomposition of buried organic material in these settings.

Future work will involve boehmite, AlOOH, solubility studies at temperatures to 300°C and continued potentiometric studies of aluminum hydroxide species and complexes with chloride, other inorganic anions, and carboxylic acids. The interaction of aluminum with organic compounds is most interesting because it provides a mechanism for secondary porosity development in sedimentary basins and geothermal systems in which abundant organic material is thermally decomposing to produce carboxylic acids and other water-soluble organic compounds.

<u>Geothermal Technology Organization</u>

INEL also supports the geothermal industry's Geothermal Technology Organization, a geothermal industry group seeking to advance the state-of-the-art of geothermal technology through:

- o conducting cooperative research under the "National Cooperative Research Act of 1984,
- o sharing research costs with the DOE,
- o facilitating the industrial development of basic research results, and
- o advising the research community of the geothermal industry's needs.

The organization was formalized and entered into an agreement for cooperative research with DOE in the Spring of 1988. Membership is open to all who have an interest in geothermal development.

The Geothermal Technology Organization (GTO):

- o funds research in reservoir performance and energy conversion technology,
- o seeks research with high probability of short term benefits, and
- o shares costs -- industry 51%, DOE 49%.

GTO and DOE have completed a study of the applicability of advanced seismic techniques to monitor injection and productivity enhancement at the Geysers steam field and additional projects are under discussion. Much of the proposed cooperative research at The Geysers may be funded through the GTO.

National Energy Strategy

INEL, in conjunction with several other National Laboratories and the Solar Energy Research Institute, prepared an analytical study of the potential for development of renewable energy resources over the next 40 years. INEL was involved in the preparation of the portions of the document dealing with geothermal resources and hydropower. The geothermal section attempted to take a reasonable approach to the development of hydrothermal resources and the advanced geothermal resources such as geopressured, hot dry rock and magma. However, the anticipated growth in utilization of hydrotherml resources, in particular, may be too conservative.

One outcome of the preparation of this is the realization that there does not exist a suitable data base on which to estimate future geothermal production relative to increases in cost of electricity and little data is publically available with which to estimate undeveloped reserves or undeveloped, nearly economic resources. INEL is initiating a program to develop such data bases and is seeking the support of industry. In order to protect proprietary interests of the geothermal industry, reserve estimates will be made publically available only as a national aggregate.

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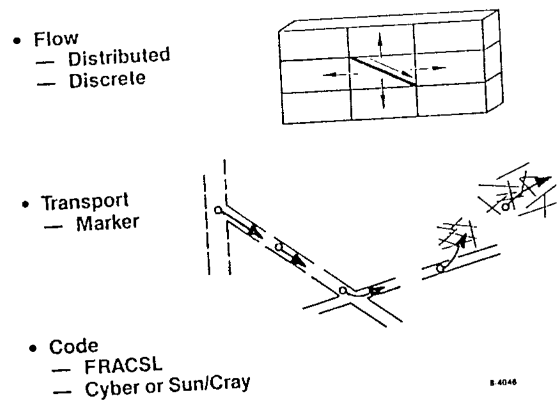


Figure 1. FRACSL approach: matrix dual permeability.

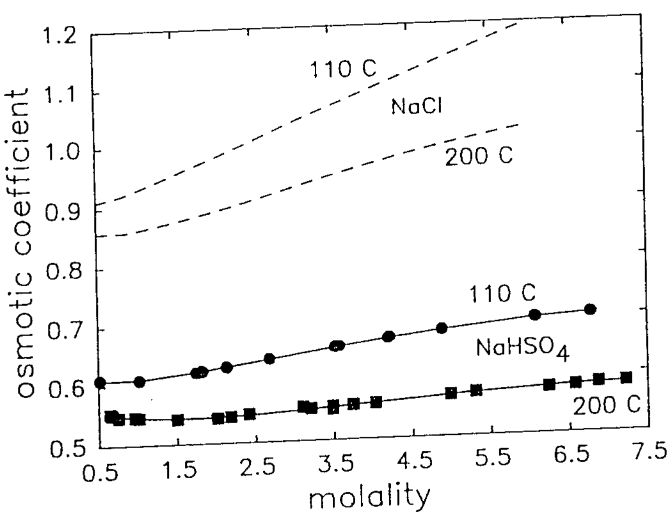


Figure 2. Osmotic coefficients of sodium chloride and sodium bisulfate.

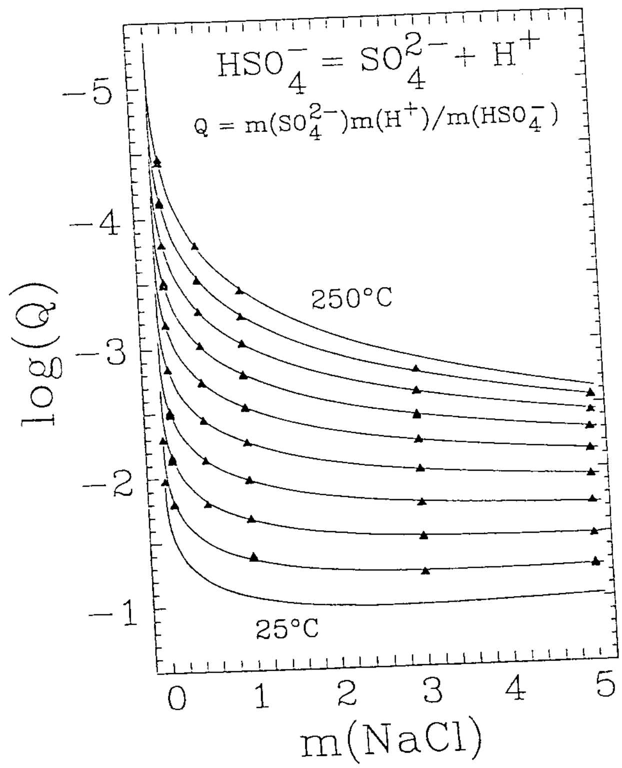
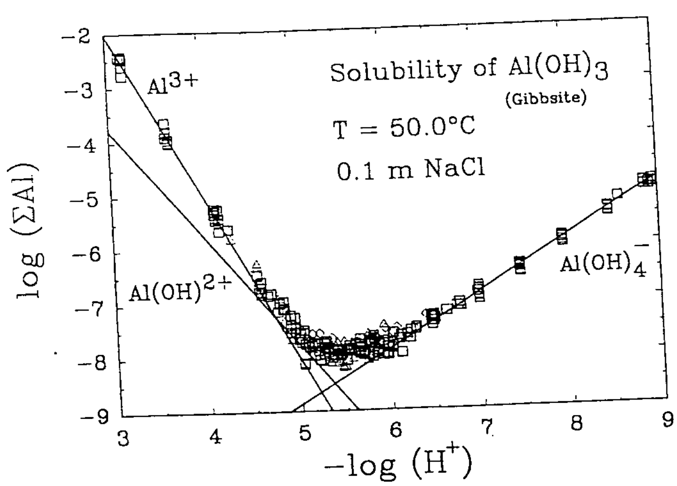


Figure 3. Bisulfate dissociation constant relative to molality of sodium chloride and temperature.



Figue 4. Solubility of gibbsite.

HYDROTHERMAL HARD ROCK PENETRATION TECHNOLOGY

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

OVERVIEW: HARD ROCK PENETRATION

James C. Dunn
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

The Hard Rock Penetration program is developing technology to reduce the costs of drilling and completing geothermal wells. Current projects include: lost circulation control, rock penetration mechanics, instrumentation, and industry/DOE cost shared projects of the Geothermal Drilling Organization. Last year, a number of accomplishments were achieved in each of these areas. Laboratory test equipment was designed and built to evaluate cementitious muds and polyurethane foams for lost circulation control in major fracture zones. Models for particulate plugging of loss zones were developed and used to summarize extensive laboratory data collected for a wide variety of material additives.

Scale-model transmitting and receiving transducers were fabricated and tested for acoustical data transmission through drill pipe. Active noise and echo suppression was demonstrated and the drill pipe transmission concept was verified. Final testing of our prototype borehole directional radar was completed and an extensive redesign was initiated. The surface data acquisition system was completed for the GDO high-temperature borehole acoustic televiewer and logs were successfully obtained in the Salton Sea at temperatures up to 293°C. New drill pipe protectors that use a higher temperature elastomer were manufactured for geothermal applications and tested in the Geysers.

INTRODUCTION

The Hard Rock Penetration task is composed of the following four projects: Lost Circulation Control, Rock Penetration Mechanics, Instrumentation, and The Geothermal Drilling Organization. Major activities in each of these areas are shown below.

LOST CIRCULATION CONTROL

- Loss Zone Characterization
- Minor-Fracture Loss Control
- Major-Fracture Loss Control

ROCK PENETRATION MECHANICS

- Acoustical Data Telemetry
- Insulated Drill Pipe
- Advanced Drilling Concepts

INSTRUMENTATION

- Borehole Directional Radar
- Downhole Memory Tools

GEOTHERMAL DRILLING ORGANIZATION

- Borehole Televiewer
- Downhole Air Turbine
- Drill Pipe Protectors
- Rotating Head Seals

The Hard Rock Penetration task has a technical review panel which is composed of the following members:

James B. Combs
Geothermal Resources Int'l., Inc.

Neal Davis
Chevron Service Co.

Robert Deputy
ARCO Oil & Gas Co.

Charles George
Halliburton Services

Barry Harding
Ocean Drilling Program
Texas A&M University

A. P. S. (Tony) Howells
Atlas Wireline Services

James W. Langford
Security Division
Dresser Industries, Inc.

Bill Lyons
New Mexico Tech.

George McLaren
Tonto Drilling Services

Nic Nickels
Eastman Christensen

Steve Pye
Unocal Geothermal

Robert D. Tibbs
CE Exploration Co.

Dick Yarter
Northern CA Power Agency

Tommy Warren
Amoco Production Center

The panel met in February 1990 to review the current program mix and provide guidance for future activities. The seventeen sub-activities in Lost Circulation Control were reviewed in detail and several recommendations reached for continued development. The panel recommended futher investigation of high resolution borehole seismics currently under development in a Oil, Gas/DOE partnership. Application of this technology to fracture detection in geothermal reservoirs will be evaluated. The panel also recommended development of a new project in core drilling for geothermal exploration. Initial work should focus on evaluation of reservoir properties from a slim core hole.

Two project areas in Hard Rock Penetration are covered in following presentations. This talk will provide an update on the Geothermal Drilling Organization by giving project status and recent accomplishments.

GEOTHERMAL DRILLING ORGANIZATION

- Five Joint Project Undertaken
  - One complete
  - Two near completion
- Initiate new project FY90

HIGH TEMPERATURE BOREHOLE TELEVIEWER

Total Project Cost $948K

Industry Contribution (cash) $474K

Participating Members

- Unocal
- Geo Operator

Status

- Contractor Squire Whitehouse declared bankruptcy
- Sandia completed commercial version (with M & W Instruments)
- Full system field test - Spring 89
- RFQ issued to logging companies was unsuccessful
- Unocal will take possession

PNEUMATIC TURBINE

Total Project Funding $418K

Industry Contribution (in kind) $294K

Participating Members
- Rift Engineering
- Geo Operator
- Geysers Geothermal
- Unocal
- Eastman Christensen
- Grace Drilling
- H & H Tool

Status
- First prototype turbine drilled 400 feet of sand and shale sequences at penetration rates up to 180 ft/hr
- Four field tests completed at the Geysers
- Several modifications completed
- Third prototype has been designed
- Project waiting for commercialization

HIGH TEMPERATURE DRILL PIPE PROTECTORS

Total Funding $80K

Industry Contribution (cash) $40K

Participating Members
- California Energy Co.
- Geo Operator
- Unocal

Advisor: Larry Kukacka (BNL)

Status
- Thirty-five materials were screened
- Laboratory testing is completed
- Full scale protectors were manufactured and successfully tested in air to 550°F
- New material added to product line
- Geysers testing showed minor improvements
- Reports in preparation

GDO ELASTOMER PROJECT

ACTIVITY: High Temperature Drill Pipe Protector Development

FY89 PROGRESS: L'Garde Y-267 EPDM used as reference material
- Contractor developed three formulations
- Several iterations of molding and bonding
- Upper use limit of 400°F, improved from 250°F
- Field tests at UNOCAL-Geysers with uncertainty
- Second field test soon

PROJECT SUPPORT/TECHNOLOGY TRANSFER:
- SNL applying BNL expertise developed with L'Garde, Inc.
- L. E. Kukacka, BNL consultant to SNL

FY89 MEETINGS: GDO Membership Update--Fall 89 GRC; San Francisco
- Project Representatives--Several meetings, Regal Plant; Corsicanna

GEOTHERMAL PIPE PROTECTOR FIELD TEST PROGRAM
UNOCAL - TOM HAAS

Location 1 - 100' below table
This location was selected so the protectors could be tripped out for inspection at 10-hour intervals.

Location 2 - 180' above liner top
This is an area of high side loads and a severe test for the protectors.

Location 3 - 180' above kick-off point
This is an area of high side load and also a severe test for the protectors.

FIELD TEST CONDITIONS SUMMARY

Maximum Temperature	350°F
Maximum Side Load	4000 lbs
Maximum Time in Hole	13 Hrs
Air Flow Rate	2400 SCFM
Rotary Speed	65 RPM
Steam Flow Rate	10,000 lb/hr

POST-TEST OBSERVATIONS

Location I

L1P1 (Regal EPDM, 6-3/4" OD)
6-5/8" final OD, worn 1/8"
Little sign of wear

L1P3 (Regal Nitrile, 6-3/4" OD)
6-5/8" final OD, worn 1/8"
Minor chunking, rubber looked good

L1P4 (Regal EPDM, 6-3/4" OD)
6-5/8" final OD, worn 1/8"
Protector looked good

Location II

L2P2 (Regal EPDM, 6-3/4" OD)
No visible disbonding
Rubber cracked around pin slots
Hinge bent, maybe broken
Protector slipped from original location

L2P4 (Regal Nitrile, 6-3/4" OD)
3/4 of rubber chunked off
No disbonding
Minor hinge damage (stretched, hinge pin bent)

L2P6 (Regal EPDM, 6-3/4" OD)
No disbonding
Minor OD gouge
Hinge pin bent
Protector slipped
6-3/4" Final OD

Location III

L3P2 (Regal EPDM, 6-3/4" OD)
Almost total rubber removal
Abrasion damage, some bond left

L3P4 (Regal Nitrile, 6-3/4" OD)
Near total rubber removal
Some rubber may have melted

L3P6 (Regal EPDM, 6-3/4" OD)
Near total removal
Some areas abraded to metal
Some bond good
Hinge failure (spot welds failed on one hinge tab)

HIGH TEMPERATURE ROTARY HEAD SEAL

Total Funding	440K
Industry Contribution (in-kind + cash)	220K

Participating Members
- Unocal
- Geo Operator

Advisor: Larry Kukacka (BNL)

Status
- Contract placed with A-Z Grant (Drilex)
- Field test fixture fabricated
- Several compounds developed and cycle tested (ambient temp)
- New stripper rubber configuration developed and will be added to product line
- Field testing in fall of 1990

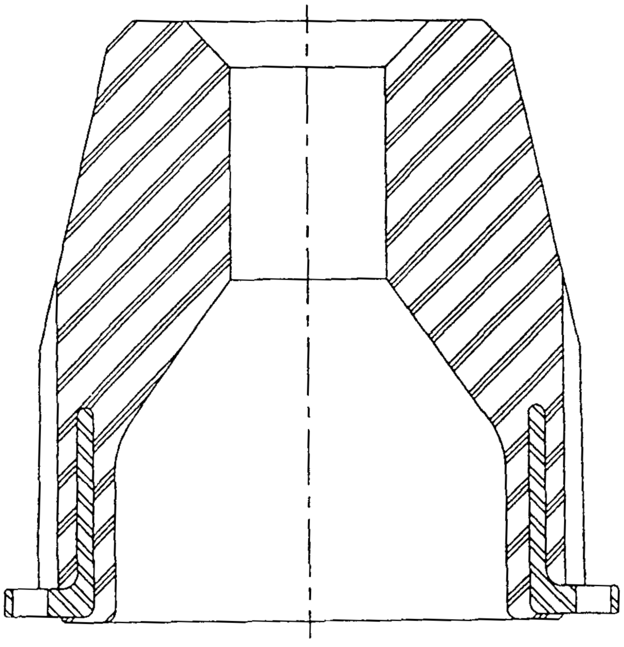
GDO ELASTOMER PROJECT

ACTIVITY: High Temperature Rotary Head Seal Development

FY89 PROGRESS: L'Garde Y-267 EPDM used as reference material
Extensive lab testing of several proprietary materials
Several production iterations of full scale seals
Field testing delayed until late spring of 1990

PROJECT SUPPORT/TECHNOLOGY TRANSFER:
SNL applying BNL expertise developed with L'Garde, Inc.
L. E. Kukacka, BNL consultant to SNL

FY89 MEETINGS: GDO Membership Update--Fall 89 GRC; San Francisco
GDO project sponsors--Several meetings, A-Z/Grant plant; Houston



NEW PROJECT PROPOSALS

- PDM technology for geothermal air drilling (Eastman Christensen)
- Geothermal Wellhead Packer System (A-Z Grant)

PDM AIR DRILLING

- EPDM stator
- 430°F temperature limit
- Build and test 2 prototype motors

WELLHEAD PACKER

- Temporary plug reworking wellheads
- Current prototype system for 400°F and 1000 psi
- Propose development for 600°F/2000 psi

This work was supported by the Geothermal Technology Division, under the Assistant Secretary for Conservation and Renewable Energy of the U. S. Department of Energy at Sandia National Laboratories under Contract DE-AC04-76DP00789.

BOREHOLE DIRECTIONAL RADAR

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ABSTRACT

A directional radar tool is being developed for application in high resolution imaging of structure near a borehole. Previously, a prototype tool was constructed and tested in both laboratory and field environments. Targets in fractured media were successfully detected, however, the overall system dynamic range was found to be only about 40 dB. During FY89, work on the borehole radar focused on both mechanical and electrical redesign of the initial prototype. Also, in an effort to better define the operating characteristics that will be required of the eventual field system, a numerical model was developed that predicts the magnitude of reflected radar signals as a function of the host rock electrical properties and the fracture characteristics. Model studies indicate that a significant improvement in system dynamic range (40 to 60 dB) will be necessary for the borehole radar to be of practical use in locating fractures in most geothermal reservoirs. The electrical and mechanical modifications initiated in FY89 should achieve much of the needed improvement in dynamic range with changes in the antenna design achieving the remainder and possibly more.

PROGRAM STATUS

- **Completed Treaty Verification Tests Nevada Test Site 9/88**
- **Completed Mechanical Redesign and Fabrication 6/89**
- **Completed Contract with Southwest Research Institute Tool and components returned to Sandia 11/89**
- **Completed Component Checkout Identified Three Areas for Electrical System Upgrades 2/90**
- **Initiated Antenna Alternative Design 10/89**
- **Completed New Antenna Construction and Anechoic Chamber Testing 3/90**

CURRENT PROGRAM EMPHASIS

- **Bring Performance of the Overall System up to Standard of Current Radar Technology (>100dB dynamic range)**
    - **alternative antenna design**
    - **improved electronic system performance**
- **Develop Analytical Model and Signal Processing Capability**

MECHANICAL SYSTEM IMPROVEMENTS

- **Modular design using slotted shaft coupler to greatly reduce assembly/disassembly time**
- **30 mil stainless steel sleeve**
- **Completed hydrostatic pressure testing to 10,000 PSI, phenolic 2500 PSI**
- **Reduced isolator section length went from metallic to phenolic**
- **Commercial centralizers**
- **Modular design permits the receiver/transmitter antenna separation to be varied**
- **Reduced diameter from 8" to 5-1/2"**
- **Reduced weight from 465 to 300 lbs**

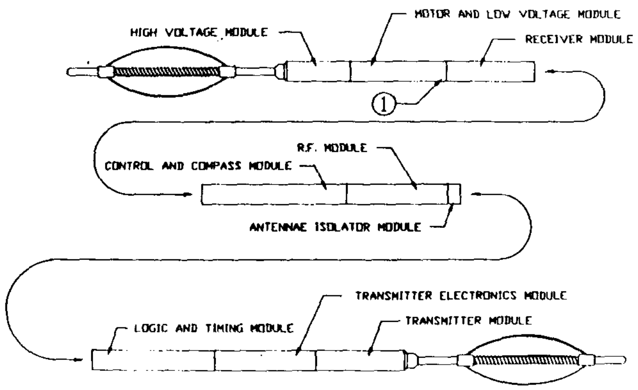


FIGURE #1

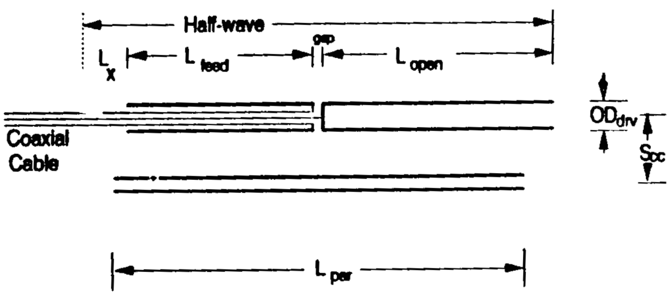
CORNER REFLECTOR ANTENNA

- **Smaller Diameter Lowered Directionality**
- **Radiating Efficiency Too Low Requiring Large Pulse Strengths**

ALTERNATIVE ANTENNA DESIGN

- **Center Fed Dipole Array (1/2 - 3/2 wave dipole)**
- **Forward Gain 6dB over Isotropic**
- **Front to Back ratio 10-15 dB**
- **Frequency 40-120 MHz**
- **Compatible with current driver circuits and mechanical components**

Antenna Design: Center Fed Half-Wave Dipole with Parasitic HW Dipole



Optimal tuning for F/B ratio: Set Lpar so that $|HW - L_{par}| \cong S_{cc}$

ELECTRICAL SYSTEM IMPROVEMENTS

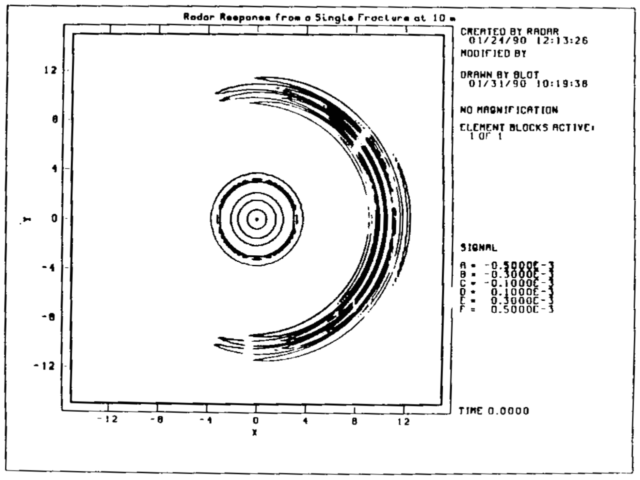
- **More robust transmitter circuit capable of driving into any impedance, completed avalanche transistor component evaluation eliminating failures**
- **Improve isolation more transmitter inside transmitting antenna section, utilize filtered bulkhead feed thru and external choking**
- **Modify receiver circuitry to achieve improved response to overload**

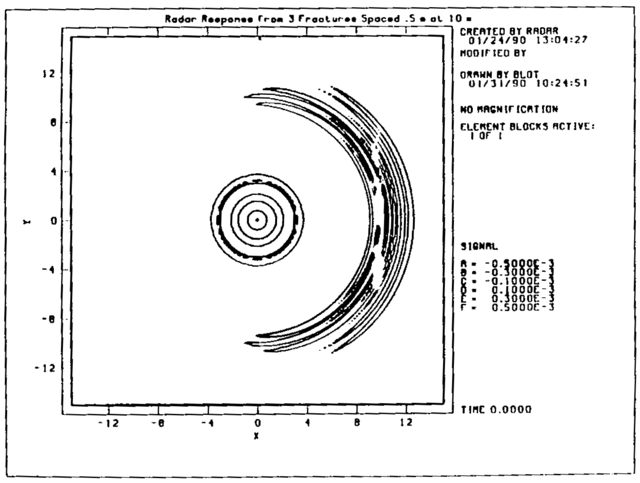
NUMERICAL MODEL

- **1-D Boundary value solution with closed form expressions instead of the usual solution in terms of Bessel functions**
- **Frequency dependencies of the dielectric constant, K and conductivity σ are included**
- **Solutions are calculated in the frequency domain and then transformed to the time domain using FFT routine**

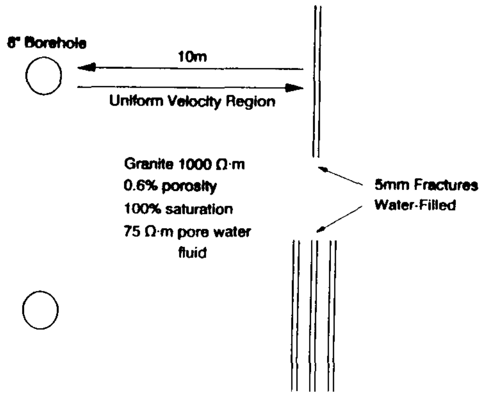
EXAMPLE MODEL CALCULATIONS

- **Input signal is 3 half-sine waves with fundamental frequency of 50 MHz**
- **Calculations include "losses" due to**
  - **borehole reflection**
  - **target reflection**
  - **attenuation in formation**

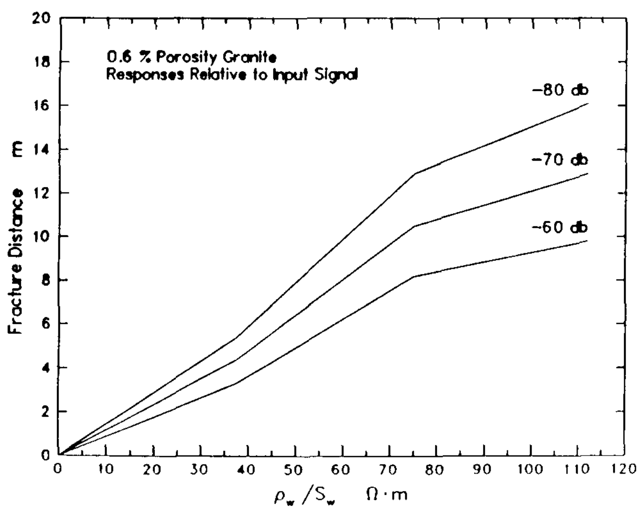




Geometry for Numerical Calculations



Fracture Detectability



MATERIAL PROPERTIES FOR RADAR RESPONSE

CENTER FREQUENCY 50 MHz

Pore Water Resistivity	ppm NaCl	Attenuation	Resistivity
75 Ω -m	100	-2.3 dB/m	270 Ω -m
37.5 Ω -m	150-175	-5.4 dB/m	106 Ω -m
7.5 Ω -m	1,000	-28 dB/m	14 Ω -m
0.75 Ω -m	12,000	-109 dB/m	1.2 Ω -m

CURRENT SCHEDULE BOREHOLE DIRECTIONAL RADAR PROGRAM

FY 90

- **Electronics assembly and testing - 5/90**
- **Antenna design and fabrication - 6/90**
- **Preparation shallow borehole test facility - 5/90**
- **Component testing - 7/90 - 9/90**
- **Model and signal processing development thru 9/90**

FY 91

Full tool testing at hard rock and treaty verification sites

LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROJECTS

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ABSTRACT

Lost circulation is the phenomenon where circulating drilling fluid is lost to fractures or pores in the rock formation rather than returning to the surface through the wellbore annulus. In geothermal drilling, lost circulation can be a serious problem that contributes greatly to the cost of the average geothermal well. A DOE-sponsored program is underway at Sandia National Laboratories to develop new technology for solving lost circulation problems. The Lost Circulation Technology Development Program currently consists of twelve projects in three areas: technology to plug porous and minor-fracture loss zones; technology to plug major-fracture loss zones; and technology to characterize loss zones. This paper describes the program and highlights recent progress.

BACKGROUND

The most costly problem routinely encountered in geothermal drilling is lost circulation. This occurs when the drilling fluid, pumped downhole to cool the bit, carry rock chips out of the borehole, and in some cases control the well, is lost to the rock formation rather than circulating back to the surface. Such a loss of circulation is caused by an incompetent or permeable rock formation (characterized by a porous matrix, fractures, vugs, or caverns) which does not have adequate physical integrity or pore-fluid pressure to support the hydrostatic pressure inside the wellbore.

Although drilling can continue under lost circulation conditions, it is generally imperative that the fluid loss be stopped as soon as possible after it is discovered, for several reasons:

* Drilling fluid is expensive (typically $5/bbl), so pumping thousands of barrels into the formation can significantly increase drilling costs;

* Changes in the rock formation being drilled cannot be easily detected if rock chips are not circulated out of the wellbore; rock chips lost to the formation can also flow back into the wellbore when drilling stops, thereby sticking the drillstring in the hole;

* The well may be difficult or impossible to control if a high-pressure zone is encountered with the wellbore only partially filled with drilling fluid;

* Drilling fluid invasion of the surrounding rock formation alters in-situ conditions and therefore affects the logging response of the formation;

* Freshwater aquifers associated with loss zones can be contaminated by drilling mud and connate fluids produced at other wellbore intervals; and

* Loss zones not treated during the drilling phase can cause casing cement to to be lost to the open formation during completion operations, resulting in a poor or incomplete bond between the casing and the rock formation and requiring expensive remedial action to prevent inter-interval flow and possible casing collapse when the well is put on production.

Lost circulation problems tend to be more severe in geothermal drilling than in oil and gas drilling because of the highly fractured and underpressured nature of many geothermal formations. Bridging materials used as drilling mud additives for lost circulation control in oil and gas drilling are ineffective in plugging large fracture apertures, particularly under high-temperature conditions.

As a result, the standard lost circulation treatment in geothermal drilling is to fill the loss zone surrounding the wellbore with cement. This is an expensive operation in terms of both material costs (typically several hundred cubic feet of cement at $15/ft^3) and rig time (typically 24 hours at $300/hr) spent on the cementing operation, on waiting for the cement to harden, and on drilling through the cemented zone to reach new rock formation. Consequently, the costs of lost circulation in a typical geothermal well may range from several thousand to several hundred thousand dollars, depending on the severity and number of loss zones encountered.

Lost circulation costs represent an average of 10% of the total well costs in mature geothermal areas (Carson & Lin, 1982), and they often account for over 20% of the costs in exploratory wells and developing fields. Well costs, in turn, represent 35-50% of the total capital costs of a typical geothermal project (DOE, 1989). It can thus be concluded that lost circulation accounts for roughly 5-10% of the total costs of a typical geothermal project.

These direct costs and the unknown costs associated with possible contamination of freshwater aquifers provide strong incentives for a technology development program to address these problems. DOE sponsors the Lost Circulation Technology Development Program at Sandia National Laboratories for this purpose. The five-year goal of this program is to develop and transfer to industry new technology to reduce lost circulation costs by 30-50%. The Level III programmatic objective adopted by DOE is to reduce the costs associated with lost circulation by 30% by 1992 (DOE, 1989). This objective combines with others to produce a Level II objective of reducing the life-cycle cost of hydrothermal electricity by 10-13% through improvements in fluid production technology by 1992. Expectations for technology improvements in several areas combine to produce a Level I objective of reducing the life-cycle cost of hydrothermal-produced electricity to 3-7 cents/kWh by 1992. This compares with a cost of 4-15 cents/kWh in 1986.

LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROJECTS

There are currently twelve projects in the program at various stages of development. Table I lists these projects, which are grouped into three categories: technology to plug porous and minor-fracture loss zones; technology to plug major-fracture loss zones; and technology to characterize loss zones. A brief description of the work underway on each project and recent significant results are provided in the following subsections.

TABLE I

LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROJECTS

Porous and Minor-Fracture Fluid Loss Control:
1. Bridging Model Development
2. High-Temperature Lost Circulation Material (LCM) Development
3. Fabrication of LCM Pill Delivery System

Major-Fracture Fluid Loss Control:
4. Development of Cementitious Mud Formulations
5. Development of Cementitious Mud Flow Models
6. Downhole Injector Development
7. Porous Packer Development
8. Drillable Straddle Packer Development
9. Evaluation of Commercial Lost Circulation Treatments

Loss Zone Characterization:
10. Wellbore Hydraulics Model Development
11. Development of Wellbore Hydraulics Data Acquisition System
12. Borehole Televiewer Log-Formation Fracture Correlation Study

LCMs for Porous and Minor-Fracture Loss Zones

Porous and minor-fracture loss zones, where pore and fracture thicknesses are less than the diameter of the drill bit nozzle, may be plugged with particulate material added to the drilling fluid. Conventional lost circulation materials (LCMs) used in oil and gas drilling, however, do not survive the high-temperature, high-differential-pressure environment often associated with geothermal drilling. The objective of the first three projects listed in Table I is to identify or develop high-temperature LCMs and emplacement methods for plugging porous and minor-fracture loss zones encountered in geothermal drilling.

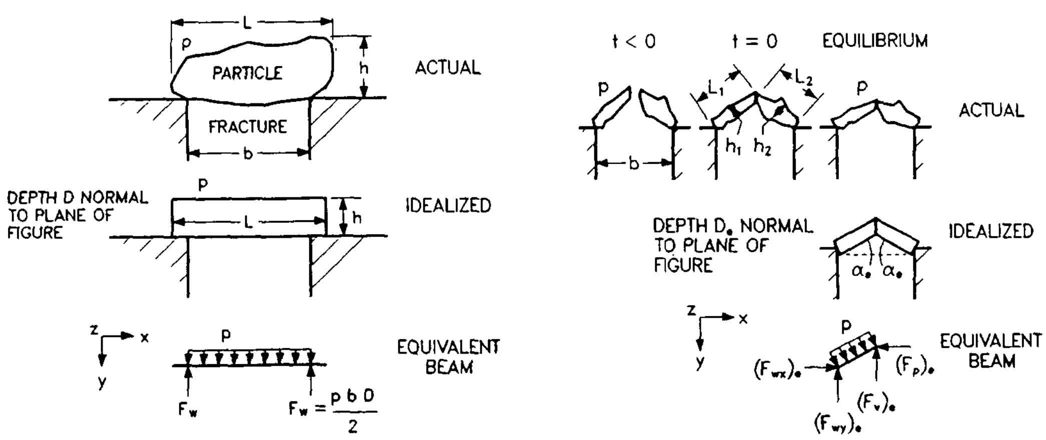
An analytical/experimental approach is being employed under the first two projects. Mathematical models of the particle bridging process have been developed that allow predictions of fracture plugging capabilities based on mechanical and physical properties of an LCM, such as compressive strength, elastic modulus, particle size, and particle shape (Loeppke et al., 1990). Both single- and two-particle bridging models, as seen in Fig. 1, have been developed for a variety of geometries. These models are used to guide the testing of LCMs in the laboratory.

Three laboratory test systems to evaluate LCMs have been developed under this program:

* the Particle Material Properties Tester (PMPT), which is a small compression tester with heated platens that allow particle stress-strain data to be obtained at elevated temperatures (to 300°C);

* the Modified API Tester, which is a bench-scale laboratory device for pressurizing room-temperature, LCM-laden drilling fluid against a slot that simulates a fracture in order to measure the pressure sealing capability of the LCM; and

* the Lost Circulation Test Facility (LCTF), which is a larger-scale version of the API tester that more accurately simulates downhole conditions,



ONE-PARTICLE BRIDGING MODEL

TWO-PARTICLE BRIDGING MODEL

Fig. 1 - Schematic of configurations assumed in one- and two-particle bridging models.

including elevated temperature capability (to 200°C) and an annular cross-flow geometry.

An LCM screening process using these test systems has been developed, and many LCMs have been tested (Loeppke et al., 1990; Hinkebein et al., 1983; Loeppke, 1986). Development of the laboratory test systems has also been previously described (Loeppke and Caskey, 1983; Caskey et al., 1985; Loeppke et al., 1990).

Typical results from the PMPT are shown in Fig. 2. Seen here are the compressive strength (S) and elastic modulus (E) of eastern black walnut shell particles over a temperature range of 72-440°F (22-227°C). The general tendency for materials to lose both strength and stiffness at elevated temperatures reduces the ability of most materials to withstand the pressure differential necessary to plug a fracture.

A typical comparison of theoretical and experimental plugging pressures is shown in Fig. 3. Shown here are the maximum room-temperature pressure capabilities of various one- and two-particle bridges formed by thermoset rubber particles as they span a slot or fracture of given thickness. The different curves represent different orientations of the particles as they approach the fracture and form a bridge. The data points represent results

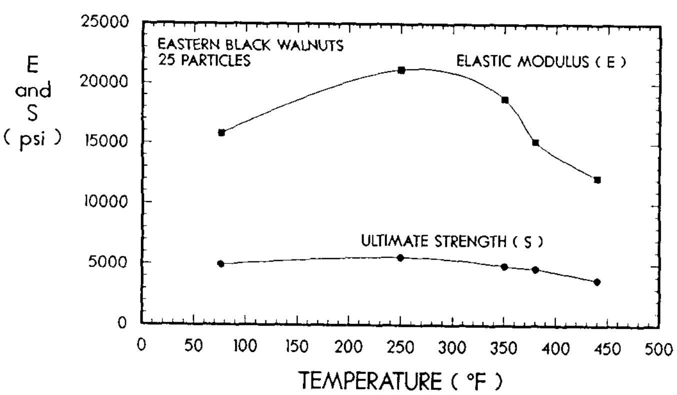


Fig. 2 - Measured mechanical properties of a potential high-temperature LCM.

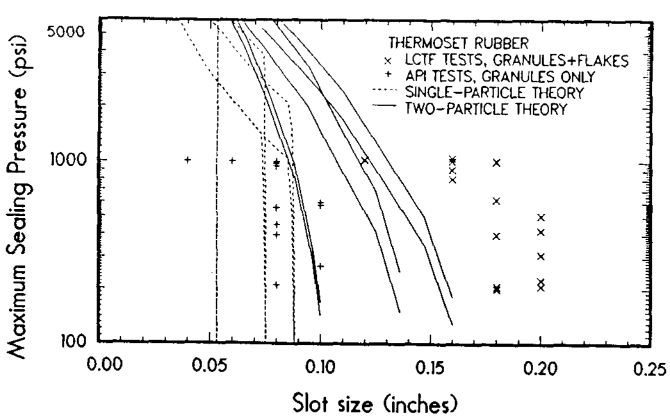


Fig. 3 - Comparison of experimental and theoretical plugging pressures for a typical LCM (maximum lab test capability = 1000 psi; from Loeppke et al., 1990).

measured with granular particles in the API tester and with granular and flake particles in the LCTF. The random particle orientation assumption accounts for most of the apparent scatter in the data. The single- and two-particle theory predictions agree well with the granular-particle data. The effects of adding flake material to the granular bridging material is to promote three-particle bridging, for which a theory is not yet available. The agreement of experiment with the existing one- and two-particle bridging theories is the basis for using these models as a tool to guide continuing evaluation and application of potential high-temperature bridging materials. Efforts to develop improved, more general bridging models are also underway.

Although ideal LCMs for high-temperature service have not yet been identified, a recent reconsideration and compilation of our previous slot-plugging test data has identified several materials with low to moderate temperature capabilities. Shown in Fig. 4 is a comparison of the slot-plugging capabilities of several materials that have been found capable of forming plugs that can withstand 1000-psi pressure differentials. The curves represent the LCM concentrations necessary to achieve 1000-psi plugs at room temperature with a given slot or fracture thickness. Listed for each material are the measured room-temperature compressive strength and elastic modulus as well as the softening temperature range, above which the material has practically no pressure capability. Note that as the particle compressive strength increases, the maximum pluggable slot or fracture thickness also increases. This chart is directly applicable to field use. The size fracture that can be plugged with each material as well as the drill bit nozzle size required to pass the material can be estimated to allow selection of an LCM for site-specific applications.

The third project listed in Table I is currently inactive. An LCM pill delivery system is needed for emplacement of large-diameter bridging particles, such as coarse-ground rubber tires, which are currently under evaluation as an LCM. Large particles cannot be pumped easily with the drill rig's mud system; thus a stand-alone system capable of mixing and pumping high-concentration LCM pills will be needed if the large-particle evaluations continue to show promise. Because such a system

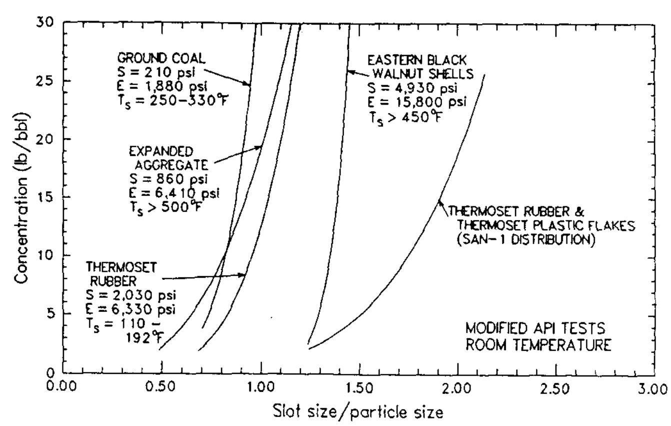


Fig. 4 - Plugging performance curves for various commercial LCMs (after Loeppke et al., 1990).

would consist of commercial hardware, no significant development is deemed necessary. Further design and construction of this equipment will await the need for its use in a specific field test.

Techniques for Major-Fracture Loss Zones

When the maximum thickness of the loss-zone fractures is greater than the diameter of the drill bit nozzles, it is not possible to plug the loss zone with drilling mud additives without also plugging the bit nozzles. In such cases, it is necessary to use a material that either solidifies after it flows through the bit or is emplaced downhole after first removing the bit. The objective of the projects listed in the major-fracture loss category in Table I is to develop alternative materials and emplacement techniques for more effectively and economically plugging loss zones dominated by large fractures, vugs, and caverns.

A joint study with Brookhaven National Laboratory is underway to develop cementitious mud formulations. Brookhaven has found that a rapid-setting, temperature-driven cement can be formulated by mixing conventional bentonite mud with ammonium polyphosphate, borax, and magnesium oxide (Sugama et al., 1986). Significant compressive strength is developed by such admixtures in less than two hours when sufficient concentrations of the magnesium oxide accelerator are used; and the setting time decreases with temperature. Furthermore, the material expands approximately 15% upon setting. These setting characteristics are ideal for plugging major-fracture loss zones, but more control over the setting process is necessary to ensure that the cement will not set up inside the drill pipe during field application.

To this end, we are pursuing a concept whereby the magnesium oxide accelerator is encapsulated with an inert material that is sheared off by fluid action at the bit nozzles. The cement would be mixed at the surface and pumped downhole; but with the accelerator shielded from the other cement constituents, the cement would not harden in the drill pipe, regardless of the time period required for pumping. As the cement flows through the nozzles, the encapsulant would be sheared off, exposing the accelerator and initiating the cement setting process. The chemical setting reaction would be further accelerated as the cementitious mud flows into the high-temperature formation. Sandia has designed, built, and delivered to Brookhaven a high-temperature, high-differential-pressure cement tester to simulate the downhole nozzle shear environment (Dunn, 1989). The tester is currently being used by Brookhaven to test the effects of nozzle shear on the setting characteristics of encapsulated cementitious mud formulations.

To develop an understanding of cementitious mud flow characteristics, a research contract has been placed with the University of Arizona. The scope of work includes development of the governing flow equations for a fast-setting, temperature-activated fluid and using the model in a parametric study to identify parametric constants that must be determined empirically in the laboratory. The governing equations include heat transfer from the rock formation and the effects of cement hydration kinetics on the time-dependent viscosity of the fluid. Several geometries are being investigated, including those of the drillpipe, wellbore annulus, and loss zone fractures.

The downhole injector concept was recently conceived as an alternative technique for emplacing cementitious mud downhole, in case the encapsulation technique proves to be unworkable. The concept, shown in Fig. 5, would use a coiled tubing unit or coiled hose to deliver a magnesium oxide slurry to a downhole tool (the injector), which contains a valve that opens to direct the slurry into the wellbore annulus above the bit. At the same time, a slurry of bentonite mud, ammonium polyphosphate, and borax is pumped through the drillstring and bit nozzles in the normal manner. If the bit is situated above the loss zone, the two slurry streams should enter the loss zone and mix, thereby initiating the chemical reaction that hardens the mud into cement. A feasibility study is currently underway on this concept. Detailed design of the injector has been completed, and it appears feasible. The practicability of the concept will depend on the type of required tubing or hose and its cost.

A second downhole tool currently under development is the porous packer, shown in Fig. 6. This is a wireline-deployed packer unit that inflates to seal the loss zone in order to prevent wellbore fluid from entering the zone. The porous fabric "leaks" at a controlled rate to allow a sealant material to seep into the loss zone, harden, and seal it off. After deployment of the sealant material, the service module would decouple from the packer and be retrieved with the wireline. The packer and hardened sealant material would be drilled through upon resumption of drilling operations.

Two-component polyurethane foam may be a good candidate for the sealant material, based on the results of a testing program recently completed (Glowka et al., 1989). These results indicate that

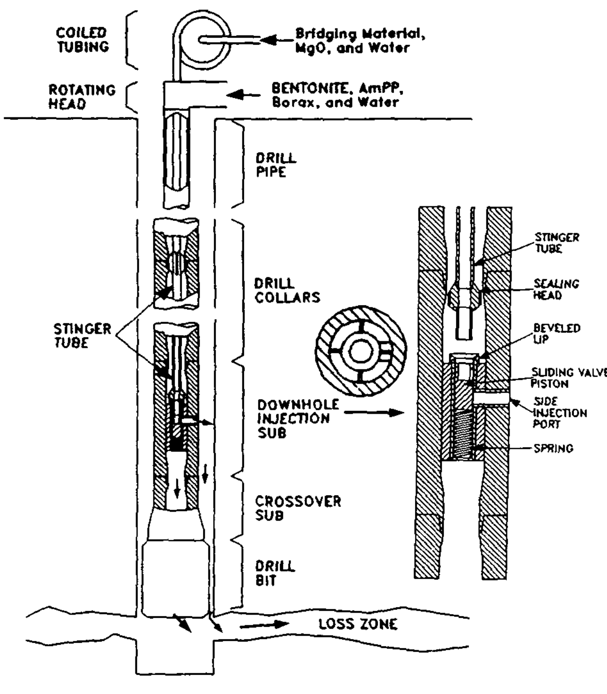


Fig. 5 - Schematic of downhole injector concept.

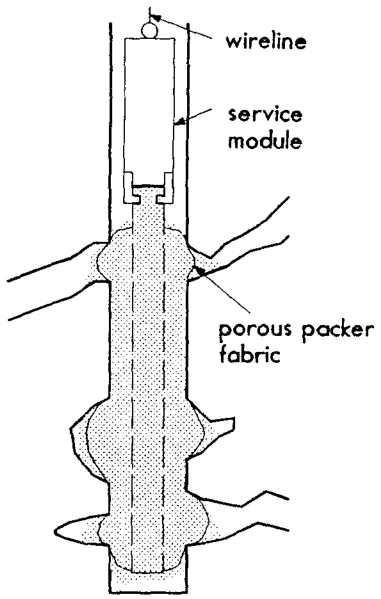


Fig. 6 - Schematic of porous packer concept.

if the polyurethane foam chemicals can be prevented from undergoing significant mixing with the ambient water downhole, the chemicals can be expected to expand in volume by a factor of 7-10 upon mixing the two components together. Emplacing the mixed chemicals into an expandable, porous bag such as that contemplated here may accomplish this function, and there is some laboratory data (obtained with canvas bags at ambient pressures to 900 psi) that supports this idea (Tschoepe, 1982).

Concepts for the packer design are still evolving, but the porous fabric has been identified as a critical component. Accordingly, a test facility has been designed and constructed to allow evaluation of potential fabrics and sealant materials. The facility allows fabric permeability and strength to be measured as a function of fluid viscosity and temperature. A search of commercial fabrics has identified a number of promising fabrics, such as woven fiberglass mat, coated with Teflon to control permeability. Samples of various types of fabrics have been obtained, and testing is scheduled to begin in June, 1990.

A third downhole tool under development is the drillable straddle packer, shown in Fig. 7. This tool employs two inflatable packer elements that straddle the loss zone and direct cement into the zone, rather than allowing it to fall to the bottom of the hole. As a result, more cement is available to plug and fill the loss zone, thereby minimizing both the volume of cement that must be pumped downhole and the volume of hardened cement that must be drilled through to reach new rock formation.

The drillable straddle packer concept currently under development uses lightweight, low-cost, drillable materials with the intent of leaving the assembly in the hole and drilling through it after the cement hardens. This packer concept differs from commercial straddle packer assemblies in that it simply uses differential pressure caused by the cement flow to inflate the packer elements, rather than downhole valving. It is thus very simple in design and construction and can be considered disposable. Detailed design of the mechanism for coupling the packer to the drillstring has been completed, and component testing will begin in June, 1990. Design of the packer assembly is currently underway.

The ninth project listed in Table I is currently inactive. Under this project, we plan to evaluate existing, commercial lost circulation treatments to provide the drilling industry with an independent evaluation of their attributes and limitations. Several candidate treatments using various types of thickening or setting fluids have been identified and will be tested as time permits. None of these commercial treatments have been promoted as having particularly promising high-temperature capabilities.

Lost Circulation Zone Characterization Techniques

Techniques are needed for evaluating lost circulation zones in order to determine the type of treatment most likely to be effective in a given case and to promptly evaluate the effectiveness of any treatment applied. The objective of the projects listed under this category in Table I is to develop loss-zone characterization techniques based on drilling fluid flow tests and to verify the accuracy of those techniques by correlation with physical loss-zone characteristics derived from borehole televiewer and temperature survey logs.

A thorough evaluation of steady-state wellbore hydraulics models was recently completed. A detailed mathematical model of a typical well was constructed and exercised to determine the sensitivity of calculated loss zone characteristics to measureable parameters (such as inflow rate, outflow rate, and standpipe pressure) and calculated frictional pressure drops. The results indicate that steady-state models are far too sensitive to the calculated frictional pressure drops to make them useful in determining the loss zone location, permeability, and effective pressure. Evaluation of transient wellbore hydraulics models is currently underway.

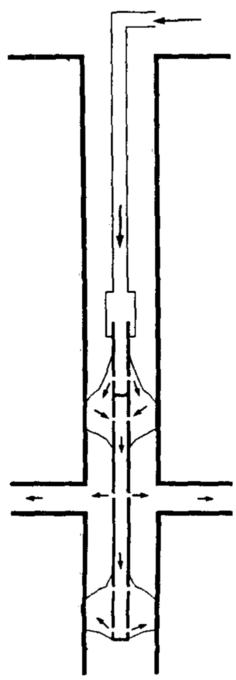


Fig. 7 - Schematic of drillable straddle packer concept.

Plans were recently initiated under the eleventh project to test commercial transducers and develop new transducers for measuring drilling fluid flow rates in the field. Because of the wide range in possible drilling mud properties and flow conditions and because of other special requirements imposed by the harsh drill rig environment, suitable trandsucers for measuring rig flow rates are not currently available. The basic technology may exist, however, and simply require repackaging. Design work has begun on a test flow loop to evaluate the technology base for this application. In addition, a new type of transducer was recently conceived for measuring the outflow rate by detecting both the fluid level and the velocity in the inclined return line and combining this data to indicate flow rate. A drawing of the concept is shown in Fig. 8. Detailed design of the first prototype of the velocity-level flow transducer is currently underway.

In addition to transducer development, the flow loop will also be used to develop software for monitoring flow rates, reliably detecting a fluid loss, and alerting the driller to the loss. Algorithms developed for this purpose could ultimately be used in an expert system for lost circulation control. Such a system could direct wellbore hydraulics flow tests, measure and analyze hydraulics data, and prescribe lost circulation treatments based on the calculated loss zone permeability, pore pressure, and location.

The final project listed in Table I is a study of the correlation between logs obtained with an acoustic borehole televiewer and the actual fracture characteristics that exist downhole. A laboratory scoping study on this subject has been recently completed (Glowka et al., 1990). In this study, a simulated wellbore was constructed of sandstone blocks stacked in a barrel of water. Planar, inclined saw cuts through the blocks were made to simulate fractures, and special rock fixtures were designed to allow the fracture thickness to be adjusted.

A commercial slim-hole borehole televiewer was used to develop a technique for measuring fracture thickness. This technique involves digitization and examination of the analog return amplitude signal to determine the proper signal amplification to apply through the downhole and uphole amplifiers. At the optimal amplifier gain, the width of the signal perturbation caused by the presence of the fracture is directly related to the fracture thickness. By applying a correction factor to the signal perturbation width, a reliable measure of fracture thickness has been obtained, as seen in Fig. 9. With the tool used in the study, fracture thicknesses greater than 0.15 inch (3.8 mm) can be measured within 15% accuracy in a 5.1-inch (13-cm) wellbore. Fractures as thin as 0.031 inch (0.79 mm) can be detected but not reliably and accurately measured. These minimum fracture detectability limits are directly proportional to the wellbore diameter and are televiewer system-dependent.

The scoping study indicates that the acoustic borehole televiewer, if properly applied in the field, could provide a reliable measurement of fracture thicknesses in lost circulation zones. Further work is required to refine the technique by incorporating the acoustic travel time data into the analysis.

TECHNOLOGY PERFORMANCE GOALS

The lost circulation technology development projects were examined to develop a list of ten alternative treatments that could result from the projects if they are successful. The time and costs required to perform each treatment in a typical 4,000-ft (1220-m) wellbore were estimated in detail and compared with the time and costs of a conventional one-plug cement treatment and a conventional two-plug cement treatment. The percentage cost savings estimated for each alternative treatment are shown in Fig. 10. The baseline estimates for the conventional cement treatments are $16,600 for a one-plug treatment and $23,400 if two cement plugs are required in the same loss zone. Two or more cement plugs are often required in severe loss zones. Note that estimated cost savings with the alternative treatments range from 9 to 69% (averaging ~30%) compared with the one-plug cement treatment, and from 35 to 78% (averaging ~50%) compared with the two-plug cement treatment.

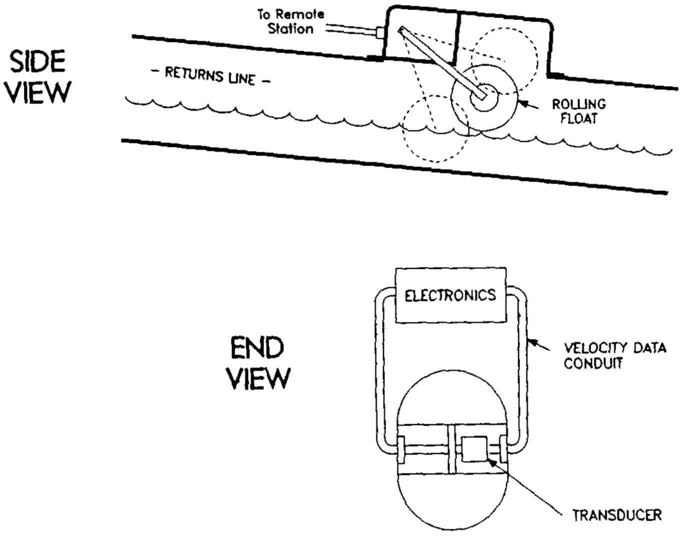


Fig. 8 - Schematic of velocity-level flow transducer concept.

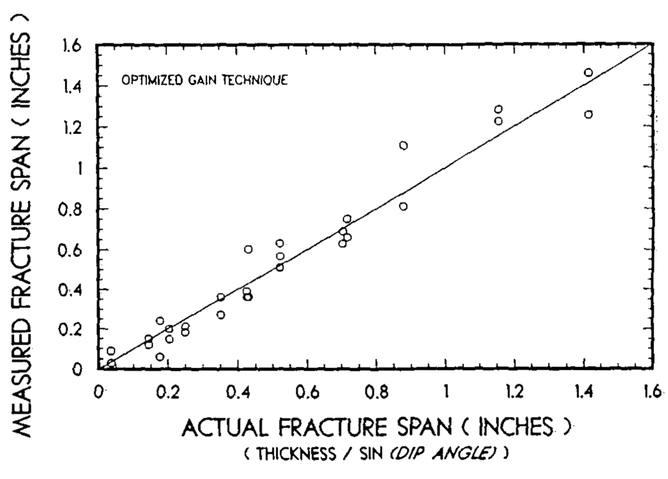


Fig. 9 - Comparison of actual fracture span with span measured with the borehole televiewer (after Glowka et al., 1990).

The actual cost savings that will occur as a result of this technology development program depend on the success of each of these alternative techniques and on their relative frequency of use. Any attempt to predict these factors at this stage of development would be subject to considerable uncertainty; thus equal weight is given to all ten alternative treatments in establishing a cost-savings goal for the program. As a result, the goal adopted for the Lost Circulation Technology Development Program is to develop and transfer to industry new technology that will reduce lost circulation costs by 30-50%. This goal is realistic because it is based on the average, detailed cost estimates for the alternative techniques currently under development.

SUMMARY

Significant progress has been made recently in restructuring and expanding the Lost Circulation Technology Development Program into a more comprehensive and more clearly defined program. Several new projects investigating different aspects of the lost circulation problem have recently been initiated. Ten projects are currently active. A surface flow transducer and three downhole tools are at various stages of development. Laboratory tests to identify suitable high-temperature LCM drilling mud additives are continuing, with the assistance of a recently developed and refined analytical/experimental screening process. Cooperative work with Brookhaven National Laboratory is continuing on cementitious mud development. Contract work on cementitious mud flow modeling is underway at the University of Arizona. Finally, recent progress in loss zone characterization has been made with the completion of a scoping study that indicates a good potential for using the acoustic borehole televiewer to provide reliable, quantitative measurement of fracture thicknesses downhole.

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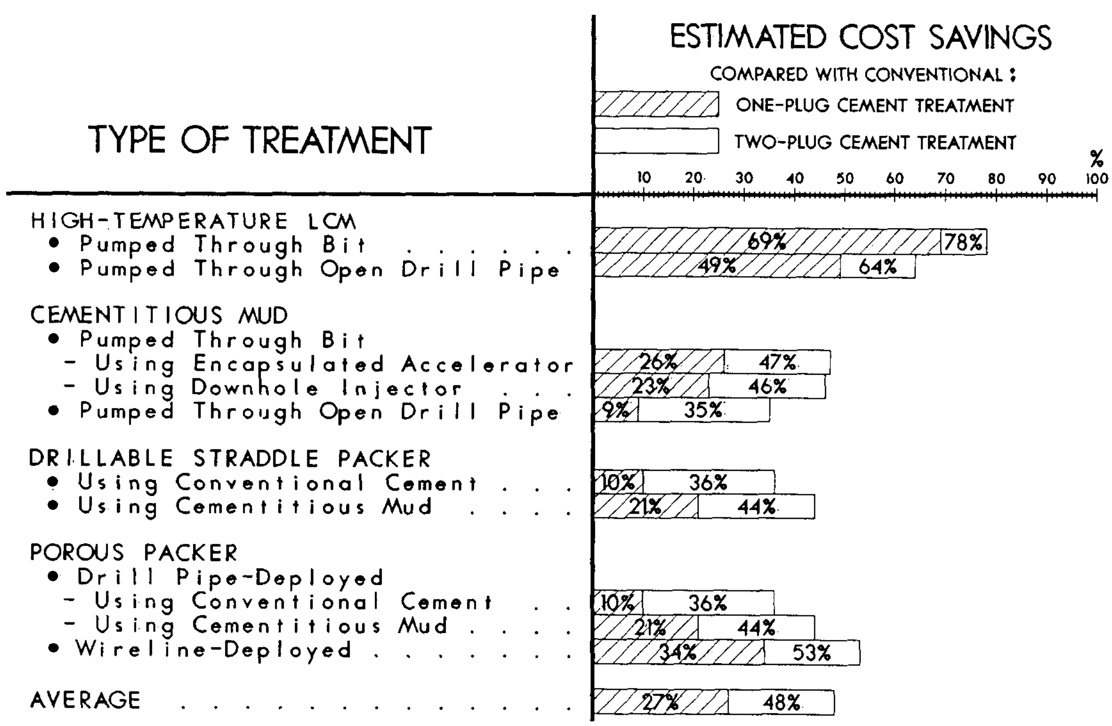

Fig. 10 - Estimated cost savings for alternative lost circulation treatments.

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HOT DRY ROCK TECHNOLOGY

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

Status of the Hot Dry Rock Geothermal Energy Development Program at Los Alamos

David Duchane
Earth and Environmental Sciences Division
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Introduction:

The geothermal power industry is built upon the use of hot water or steam sources occurring at a variety of locations around the world. The potential of hydrothermal sources to supply energy to a world demanding it in ever increasing quantities is large, but very geographically specific. It is restricted to those relatively unusual locations which contain natural sources of geothermal fluids.

The Hot Dry Rock (HDR) Geothermal Energy Development Program is an effort to utilize the inherent heat present in dry rock at depth as a source of energy. The HDR resource base is extremely large and is widespread. It has been estimated that HDR energy reserves are on the order of 10 billion quads in the United States alone (Armstead and Tester, 1987). As a point of comparison, world energy consumption in all forms is about 300 quads per year (Gray, Tester, and Wood, 1990). Thus HDR potentially could supply the energy requirements of the U..S., and indeed, the world, for many thousands of years, even if only a small fraction of the total HDR resource could be economically accessed.

HDR is an environmentally benign source of energy. When used in a binary closed-loop system, practically no pollutants are released to the atmosphere. Water consumption is low, and there is no effect on groundwater or surface waters. Plant siting can be small and unobtrusive. Since the energy is extracted from below the earth with minimal surface disturbance, there are no environmental effects related to obtaining the fuel, or disposing of spent ash or other residue. Hydrothermal power has been recognized as an environmentally desirable energy source. HDR brings all the benefits of hydrothermal energy and more, since plant siting and well placement decisions are not as closely tied to specific resource locations for HDR as they are for hydrothermal resources.

Methods being developed to access and extract energy from HDR are based on work done in the petroleum and hydrothermal industries. These include deep drilling, hydraulic stimulation, seismic analyses, reservoir modeling, tracer measurements, and related techniques. The nature of the HDR resource has required many modifications to the standard technologies that have been employed in petroleum and hydrothermal applications. Special drilling and coring bits have been developed in cooperation with private industry for use in hard, crystalline rock. A large number of downhole instruments have been specially designed to operate at the high temperatures (250-300°C) encountered in HDR environments (Dennis, Koczan, and Stephani, 1985).

Advanced modeling, seismic, and tracer techniques have been employed to analyze and explain HDR reservoir creation, characteristics, and operation. Many of the unique contributions of HDR research have been reported earlier (Smith, 1983; Dash, Murphy, and Cremer, 1981; Brown, Potter, and Tester, 1989). A brief historical synopsis, the most recent work done at Los Alamos, future plans, and advanced concepts in HDR technology are discussed in this paper .

Earlier Work:

The first HDR system was completed by Los Alamos at Fenton Hill, New Mexico, in 1977. An injection well was drilled to a depth of about 3000 m and hydraulic fracturing was used to create a reservoir in granitic rock at a temperature of approximately 185°C. A second well was drilled to intercept the reservoir at a distance of about 100 m from the injection wellbore.

The system was operated for more than a year in several runs, the longest of which lasted 280 days. Over 26 million kilowatt-hours of thermal energy were produced during this time at power levels of 2.5-5 MW, and a 60 KW electric generator was powered by the system for part of the time to supply electricity for some operations at the site. This Phase I system provided a scientific basis for further work on energy production from HDR.

Work began on a larger, Phase II, reservoir in 1979. The Phase II program involved drilling deeper, to hotter rock, and the creation of a larger reservoir in order to demonstrate the technical feasability of HDR as a practical energy source for commercial power production. Two wells were drilled to depths of 4000 m and 4400 m, respectively. The final 1000 m of each well was drilled at an angle of 35 degrees to the vertical, and in a direction parallel to the least principal stress direction in the rock, as determined in the shallower Phase I system.

Extensive fracturing operations were conducted in the lower well (designated EE-2) at a depth of 3500 m in an attempt to connect the two wellbores, but no connection was achieved even after employing pressures as high as 48 MPa (7,000 psi) at water injection rates of 108 l/s (1700 gpm). Microseismic analyses indicated that a large reservoir had been created, but that it was inclined approximately 25 degrees to the vertical in a direction almost parallel to the injection wellbore. The reservoir fractures did not intersect the upper well (designated EE-3). In order to connect the two wells, the lower part of the upper well was redrilled to penetrate into a fracture zone of the reservoir. The redrilled well was designated EE-3A. Further fracturing was then employed to create a highly connected HDR system.

A 30-day flow test of the reservoir was conducted in 1986. Results of this test were uniformly encouraging (Dash, 1989). The impedance and the water loss rate decreased over the span of the test, while the flow rate, wellhead fluid temperature and power production increased. After this test, sidetracking and redrilling was carried out in wellbore EE-2 to bypass damaged casing. The modified wellbore was designated EE-2A upon its completion in June, 1988.

The Phase II HDR system as it exists today is shown in Figure 1. The reservoir is centered at a depth of approximately 3600 m in rock at a temperature of about 240°C. The separation between the two wellbores over the reservoir interval is in the range of 110 m. Seismic

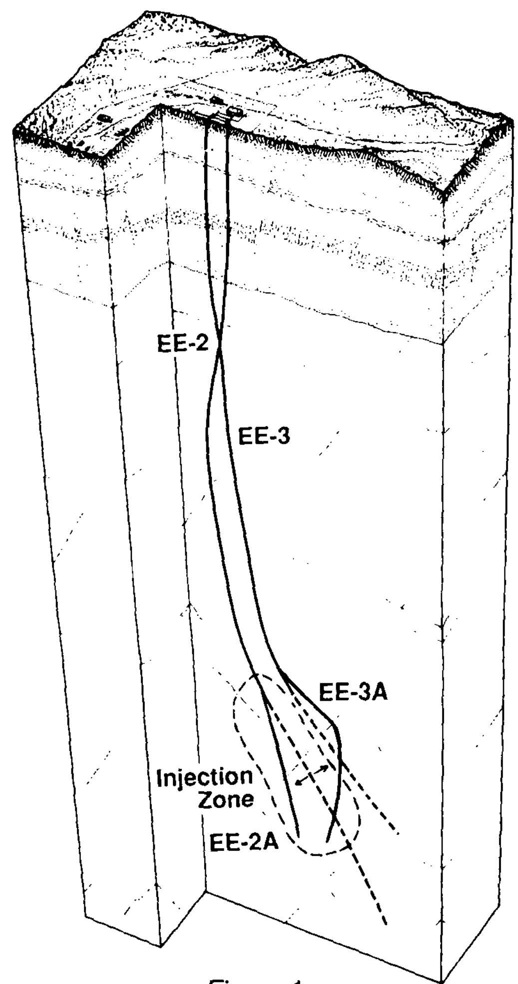


Figure 1
The phase II HDR well and reservoir system

analyses indicate that the reservoir is nominally 800 m high, 800 m long in the N-S direction, and 150 m wide in the E-W direction. Only a small portion of the reservoir appears to be accessed by the EE-2A/EE-3A well pair.

Current Efforts:

Sustained Pressure Testing

A sustained pressure test of the Phase II reservoir was initiated in May of 1989. In this test, water is being pumped into the reservoir at a rate sufficient to maintain a predetermined reservoir pressure. Water consumption is measured to gain information on the rate of fluid loss from the reservoir. Previous studies have indicated that growth of the reservoir will not occur at pressures of less than 27 MPa (3900 psi), but inflation of the current reservoir will occur as the pressure is increased up to this value (Brown and Fehler, 1988). In the first part of this test, the pressure was maintained at 7.5 MPa (1100 psi). Over a period of 19 days, water losses declined from an initial level of 0.8 l/s (12.5 gpm) to only about 0.3 l/s (5 gpm). In June, 1989, the pressure on the reservoir was raised to 15 MPa (2200 psi). Water loss rates, which initially were very high as the reservoir inflated at the higher pressure, dropped to about 0.6 l/s (10 gpm) within two weeks. Even more significantly, they have continued to decline until now, approximately 10 months into the 15 MPa pressure plateau, they are averaging less than 0.25 l/s (4 gpm).

Figure 2 is a graph of the water loss rate as a function of the natural logarithm of time during this phase of the test. The linear relationship indicates that the reservoir behaves as expected

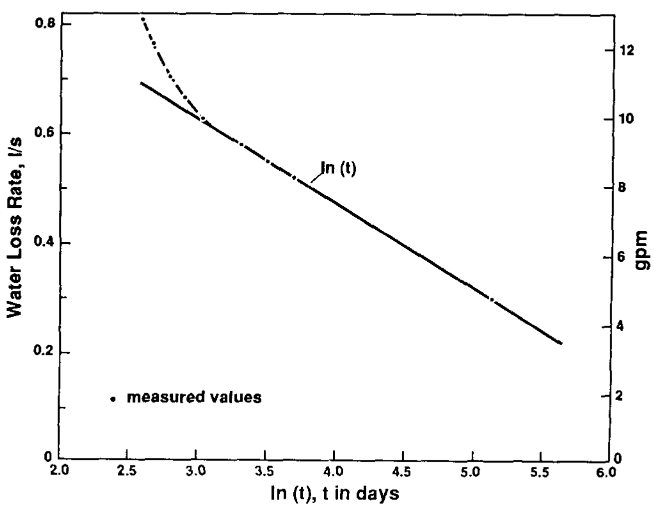


Figure 2
Water loss rate from the Phase 2 HDR reservoir at a constant injection pressure of 15 MPa.

for transient diffusion from a nonplanar body. The data also suggest that water loss rates in HDR reservoirs can be expected to be very low during extended operations. The sustained pressure test is providing important information regarding water needs for the long-term flow test of this reservoir which is now in the planning stages and is discussed below.

Seismic Results

A massive amount of seismic information was collected during creation and initial testing of the Phase II HDR reservoir. Analysis of this data is continuing to increase our understanding of the characteristics of HDR reservoirs. Over the past several years, research has centered on application of a technique termed "the three-point method" in an attempt to define planes of seismic activity which, by implication, may be shear planes created during reservoir formation (Dreesen, Malzahn, and Fehler, 1987; Fehler, 1990).

Application of this analytical technique to data from four separate stimulation experiments in the Phase II HDR reservoir showed only one plane of seismic activity common to all. Based on the best estimates of stress states in the reservoir, this plane can be shown to have the highest ratio of shear stress to normal stress acting on it. Thus, there is an implication that microearthquakes associated with fracturing operations occur when pre-existing jointed planes slip as the existing stress is reduced by the fluid pressure of hydraulic injection.

Figure 3 depicts a series of planes of seismicity identified in the Phase II HDR reservoir using

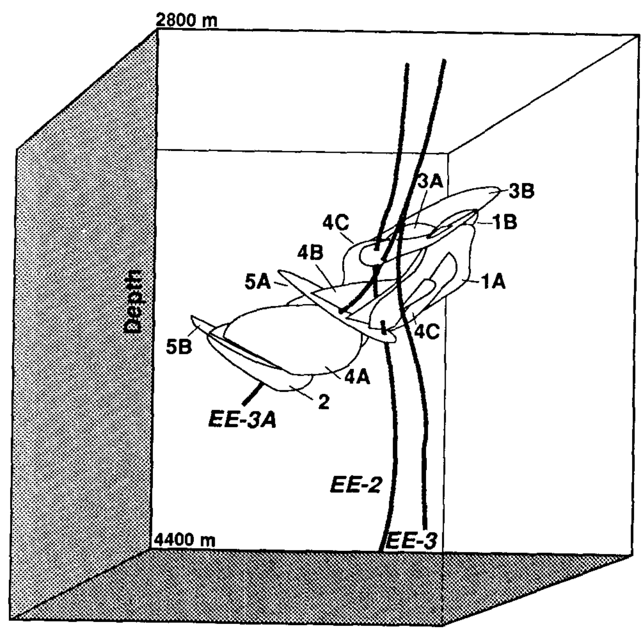


Figure 3
Hypothetical planes identified in the Phase II HDR reservoir by applying the three point method to microseismic data.

the three-point method, and the trajectories of the EE-2, EE-3, and EE-3A wellbores with respect to these planes. The figure shows that EE-3 does not intersect any of the planes penetrated by EE-2, but that there are at least two planes penetrated by both EE-2 and EE-3A (planes 3B and 5A). In fact, as discussed above, the system EE-2/EE-3 is poorly connected, but redrilling in the EE-3 wellbore has produced the well-connected EE-2/EE-3A HDR system. These results indicate that the three point method may be useful in engineering future HDR reservoirs by providing a good basis for determining the location of the production wellbore after creation of the reservoir from the injection well.

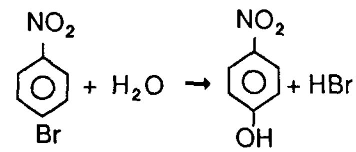
Work is now underway on the development of methods to more accurately determine the locations of microearthquakes induced during the creation and growth of the Phase II HDR reservoir. The new techniques will apply corrections to the data to account for velocity variations that occur as the seismic signals travel through regions of different densities in the fractured rock. Application of the three-point method to velocity-corrected data should enable more accurate mapping of HDR reservoirs.

Recent studies have indicated that the seismic energy release in hydraulic fracturing operations such as those used to create the Phase II HDR reservoir, is dominated by a large number of small events (Fehler, personal comm.). These results suggest that numerous microearthquakes of a magnitude too small to be detected by techniques employed at Fenton Hill may account for the release of significant amounts of energy. Thus, seismic dissipation may account for a greater portion of the expected energy release during creation of the Phase II reservoir than had previously been calculated.

Reactive Tracer Development

The use of tracers to measure fluid flow parameters in the HDR Phase II reservoir has provided a basis for modeling the fracture network and reservoir performance (Robinson and Jones, 1987). Radioactive bromine-82, in the form of the soluble salt, ammonium bromide, is in many respects an ideal tracer. It is rapidly and unambiguously detectable at low concentrations, as well as compatible and inert in HDR fluids. Since the isotope has a relatively short half-life, problems of background accumulation of the tracer in the system with repeated use are avoided as are any potential problems with radioactive residues.

While tracer work with radioactive bromine has provided much useful information, reactive tracers can bring an added element of sophistication to tracer studies. After extensive investigation of a wide range of organic compounds, p-bromonitrobenzene has been selected for development as a reactive tracer in the Phase II HDR system. This compound is rapidly hydrolized at the temperature of the HDR reservoir,



but reacts much more slowly with water at the lower temperatures characteristic of the injection fluid. The reaction product is p-nitrophenol.

Analytical techniques have been developed to detect both the reactant and the product at the temperature of the Phase II HDR reservoir, 240°C, the half life of the reaction is ten hours, but it increases logarithimically so that it is over 100 hours at 220°C and well over 1000 hours at 200°C (Robinson and Birdsell, 1987). Laboratory studies have shown that contaminants such as diesel fuel and drilling mud residues will not interfere with this tracer, and that neither the reactant nor the product is significantly adsorbed on any surfaces in the circulation system.

Analysis of the concentration of the product, p-nitrophenol, after circulation of the tracer through the HDR reservoir, will give a good indication of the fraction of the time spent by the fluid in the hot portion of the reservoir. Analysis of the reactant, p-bromonitrobenzene, will provide mass balance information and help to confirm the data. When used as one component of a long term flow testing protocol, reactive tracer analysis can yield information about growth in the volume of cooled rock over time, and provide a scientific basis for predicting reservoir lifetime. It may be possible to extrapolate the data obtained in one or two years of reactive tracer measurements to predictions of reservoir characteristics over five- ten- or even twenty-year time spans.

Reservoir Modeling - High Back Pressure Operation

Impedance to fluid flow within an HDR reservoir may be an important parameter in determining whether or not the system can be operated efficiently. If the impedance is too high, excessive pumping pressures will be required to produce the flow required for economical power production. High pressure operation increases the cost of the pumping, and leads to conditions of reservoir growth and high water loss rates. These factors increase the costs of operating the system and, consequently, negate the very efficiency that is being sought.

Recent modeling studies have indicated that by operating a closed-loop HDR circulation system at high internal pressures, it may be possible to significantly reduce pumping energy and thus costs while still maintaining high flow rates (Robinson and Birdsell, 1990). Figure 4 shows the calculated pressure isobars in the Phase II HDR reservoir when operated at an injection pressure of about 30 MPa (4,300 psi). It is obvious that the production well acts as a pressure sink. The greatest impedance to flow is in the relatively low pressure region immediately adjacent to the production well. If the production wellhead pressure, the effective system backpressure, were increased, pressure in the surrounding region of the reservoir would also be increased, and the aperture of fractures in the affected region would increase, leading to decreased impedance.

Table 1 shows results of calculations of flow rates based on a 27 MPa (3,900 psi) injection pressure and a variety of back pressures at the production wellhead. The data indicate that intrasystem differential pressures can be reduced from a level of 27 MPa to 13 MPa (1,900 psi) without a significant effect on fluid flow, if the system is kept at elevated pressure with respect to the external world. This reduces the energy needed to pump fluid around the system

Production-Well Pressure (psi)	Pressure Drop (psi)	Flow Rate (gpm)
350	3550	125
1000	2900	125
1500	2400	124
2000	1900	114
2500	1400	98
3000	900	73

Table 1
Calculated flow rate of the Phase II HDR reservoir at a constant injection pressure of 27 MPa and various backpressures.

by about 50%, thus increasing the net power production.

Reservoir Engineering - The Guard Well Concept

While high back pressure operation addresses the issue of reservoir impedance in an economical manner, the problem of reservoir growth at high pressures remains. Referring again to Figure 4, it is obvious that the high pressure region in the reservoir is on the opposite side of the injection well from the production well. Reservoir growth and water loss would be expected to occur in this high pressure region. That is, in fact, what seismic studies indicate occurs.

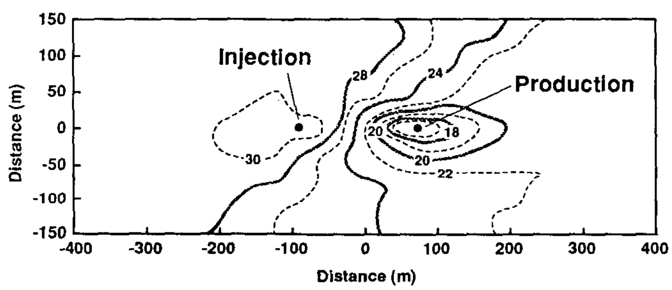


Figure 4
Calculated pressure isobars in the Phase II HDR reservoir.

Figure 5 is a map of seismic events associated with two operations in the Phase II HDR reservoir. The open circles indicate the sources of seismic signals associated with the massive hydraulic fracturing operation carried out in well EE-2 during the creation on the reservoir. These events are more or less symmetrically distributed around the wellbore. The shaded circles represent the locations of seismic events associated with a later flow test of the

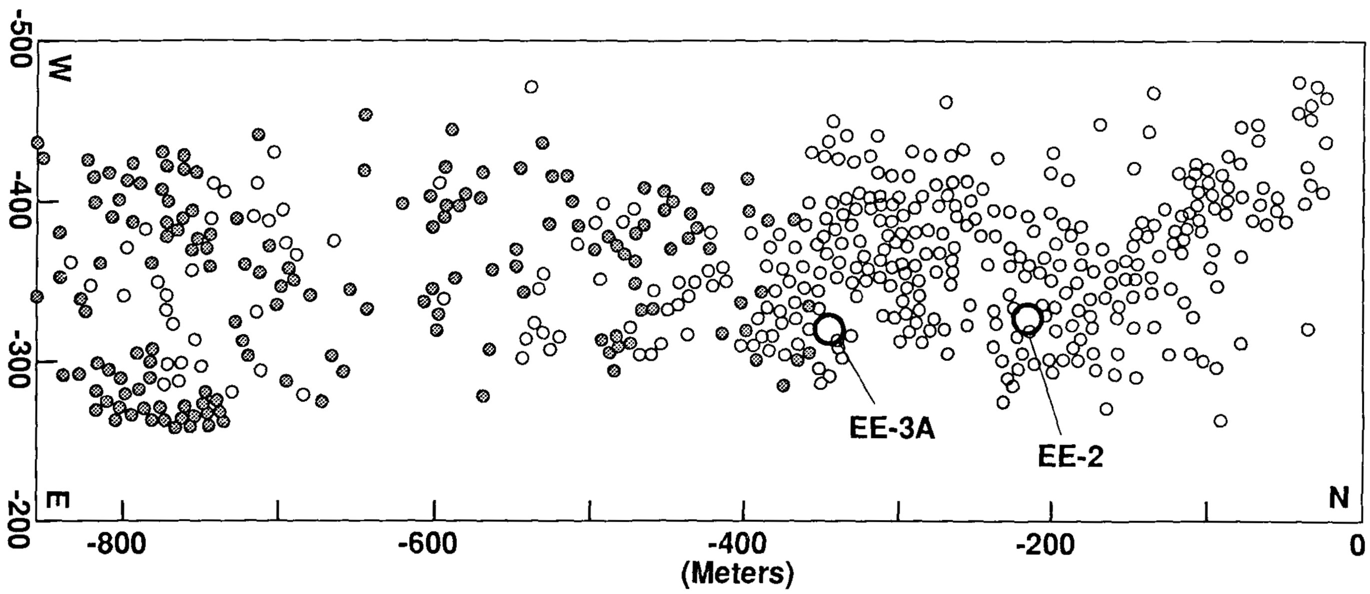


Figure 5
Distribution of seismic events in the Phase II HDR reservoir during massive hydraulic fracturing in wellbore EE-2 (open circles), and high pressure flow test with injection at EE-3A and production at EE-2 (shaded circles).

system, in which fluid was *injected* at well EE-3A and withdrawn through well EE-2. Virtually all of the seismic events during the flow test occurred on the opposite side of the injection well from the production well. The production well is thus seen to act as a guard well, providing a region of low pressure and checking further reservoir expansion in the region where it is located.

A HDR system engineered for maximum operating efficiency would have guard wells at each end. The system could then be operated at high injection pressure and high back pressure without reservoir growth. In fact, calculations have shown that a three well HDR system with one injection well and two production wells would produce about three times as much energy as a two well system. Thus for a 50% increase in drilling costs, a tripling of output could be achieved.

The Long-Term Flow Test (LTFT)

A long-term flow test (LTFT) of the Phase II HDR reservoir is scheduled to begin in fiscal year 1992. Work is now underway to design and construct the surface portion of the circulation loop for the LTFT. Safety, maximum reliability, and flexibility of operation are all important considerations in the design of the surface loop. The design presents unique challenges in the areas of materials of construction, fluid handling and treatment, and equipment specification. Safety and equipment reliability in particular must be considered in light of the extremely cold winter weather encountered at Fenton Hill.

A simplified schematic of the surface loop is shown in Figure 6. The hot geothermal fluid

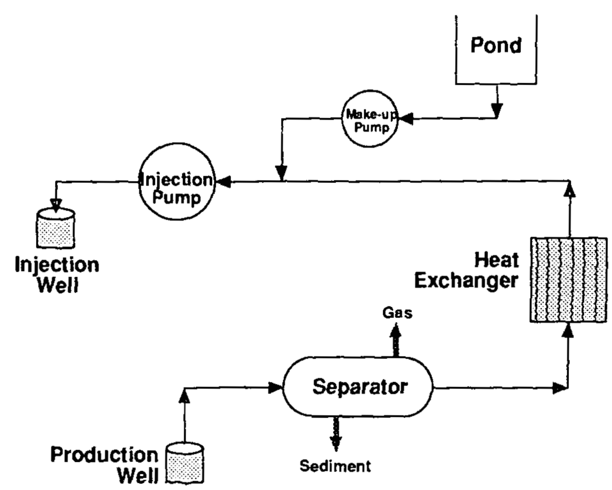


Figure 6
The surface loop for the long term flow test of the Phase II HDR reservoir.

from the production well will be passed through a separator to remove sediment and noncondensable gases, and fed to a heat exchanger where the temperature will be reduced to about 35°C or less. The cooled fluid will then flow to the injection pumps for repressurization and return to the reservoir. A makeup water line will be incorporated in the surface loop to replace any fluid lost during circulation.

The surface loop is being designed to operate at injection pressures of up to 31 MPa (4,500 psi), using two diesel driven, five cylinder, reciprocating pumps. The production side of the loop will be capable of running at 7 MPa (1,000 psi) pressure to allow for high backpressure operations.

The LTFT will be used to evaluate reservoir lifetime, flow impedance, water loss rates, production fluid temperatures, and energy production on an extended basis. Long-term operational and maintenance conditions will be established, environmental effects will be thoroughly assessed, and predictive models will be tested adjusted and confirmed. Reactive tracers such as those described above, will be used to predict the ultimate useful lifetime of the reservoir on the basis of one to two years worth of data.

Upon completion of the LTFT, much of the data needed to validate the commercial viability of HDR should be in hand. Analysis and understanding of this information will provide the basis for future decisions regarding the exploitation of HDR resources at other locations throughout the world.

Summary:

During the past two decades, the extraction of energy from HDR has been scientifically demonstrated and a large HDR reservoir has been created at Fenton Hill, New Mexico. Developments in drilling and logging hardware, reservoir engineering, seismic science, tracer analysis, and modeling have all contributed to the advance of HDR technology. The long term flow test planned for the early 1990's will provide a basis for future commercial exploitation of HDR resources worldwide. Given an adequate commitment of developmental resources, HDR may begin to supply environmentally sound and economically attractive energy to the world within a period of five to ten years.

Acknowledgements:

As an overview document, this paper describes the work of many individuals involved in HDR research and development at Los Alamos. The specific contributions of D. Brown, B. Robinson, L. House, M. Fehler, and R. Ponden to this report are gratefully acknowledged.

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USING HDR TECHNOLOGY TO RECHARGE THE GEYSERS

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ABSTRACT

The main reason for the productivity decline at The Geysers geothermal field is obvious: more fluid is being withdrawn from the reservoir than is being returned by reinjection and natural recharge. However, there is another factor that may be contributing to this decline -- the method of reinjection. By reinjecting cold condensate directly into the steam dome as is the current practice, the very large pressure difference between the injected condensate and the underpressured reservoir guarantees that the reinjected fluid will fall rapidly to the bottom of the reservoir, with very little residence time for heat transfer. This point is very important since the vast majority of the heat contained in The Geysers geothermal field is stored in the hot rock comprising the reservoir.

A more thermally effective method of reinjection is here proposed, using stimulation techniques developed in the Hot Dry Rock (HDR) Program. The objective would be to limit -- or possibly even reverse -- the observed productivity decline at The Geysers. The injection of fluid, either into boundary regions just outside the productive reservoir or below the boiling interface, would be obvious approaches. These regions are under much higher earth stresses than the main body of the reservoir, providing a large inward flow potential. However, no matter how thermally effective this method of artificial recharge might be, the amelioration of the productivity decline at The Geysers still will be directly related to the amount of fluid available for reinjection relative to the overall mass rate of steam production.

Assuming that a fracture zone similar to the Fenton Hill reservoir could be created adjacent to the steam field, preliminary modeling results indicate that over two-thirds of the injected fluid will be flowing into the reservoir after only 20 days of pumping. This fluid will start to flash as it approaches the underpressured reservoir through the network of stimulated joints, providing a hot recharge with a significant steam fraction. To evaluate this concept, a series of tests should be conducted in several nonproductive regions of The Geysers, in cooperation with one or more of the major steam producers.

INTRODUCTION

By aggressively applying HDR-developed reservoir stimulation technology, the natural recharge of The Geysers could be significantly augmented in the near term, with the potential for greatly increasing the ultimate thermal recovery from this presently fully developed steam field. Hot fluid, generated in the nonproductive margins of the reservoir, would flow preferentially into the underpressured steam dome, providing an additional artificial recharge. If successful, this method of augmenting natural recharge could be applied to other commercial hydrothermal reservoirs, significantly increasing the nation's proven reserves of geothermal energy.

In this context, it should be noted that the Japanese, primarily with funding from the New Energy Development Organization (NEDO), have started a significant program to investigate methods of applying HDR stimulation techniques to the broad geothermal resource intermediate between hydrothermal and HDR (Sato, 1990). The initial thrust of their program will be to apply HDR technology to improve production in presently poorly producing hydrothermal reservoirs.

STRUCTURE OF THE GEYSERS

Because of the very subhydrostatic pressure within The Geysers geothermal field, it appears that the reservoir stresses have been effectively decoupled from the overburden -- probably due to a bridging of the cap rock just above the reservoir. As discussed in Nielson and Brown (1990), the cooling and associated subsidence of the underlying concordant felsite intrusion (Thompson, 1989) may account for the arching of the overlying rock strata, and the relief of the overburden stresses within the steam dome. The presence of conductive, near horizontal fractures within the reservoir (Thompson and Gunderson, 1989) supports this conclusion.

The arching and associated subsidence of the overlying rock strata would result in additional horizontal compression in the region immediately above the developing steam dome, effectively closing preexisting near-vertical joints that may have provided recharge early in the formation of The Geysers. This decoupling of the stresses within the reservoir is shown schematically in Fig. 1, a highly simplified structural view of the evolution of The Geysers.

Both the steam reservoir and the underlying felsite body have an axial orientation of about N55W, which is coincident with the direction of regional strike-slip faulting as shown in Fig. 2 (from Nielson and Brown, 1990). In our view, venting of fluid upward through one or more of the intersecting fault systems ultimately allowed a steam dome to form by the boiling off of some of the contained hot water as the vertical stresses were slowly relaxed.

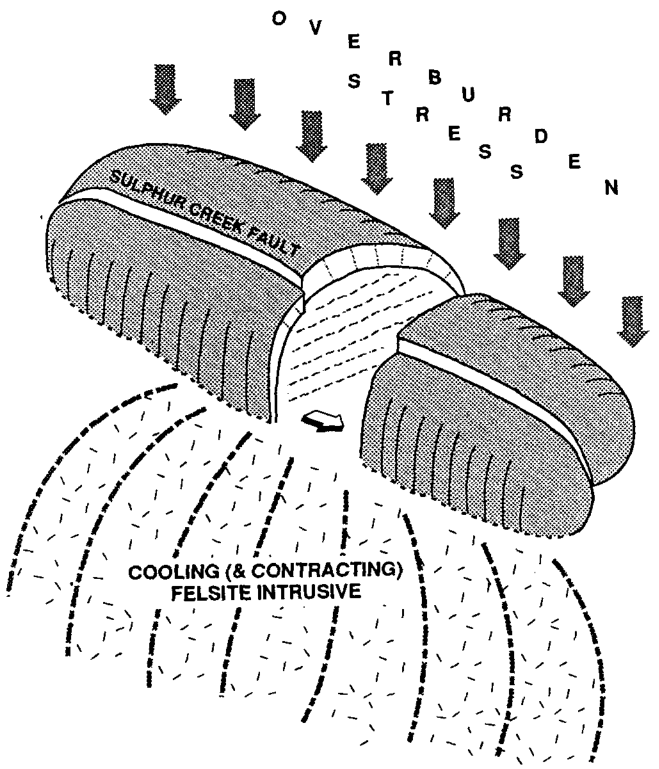

Figure 1. Schematic of The Geysers Geothermal Field.

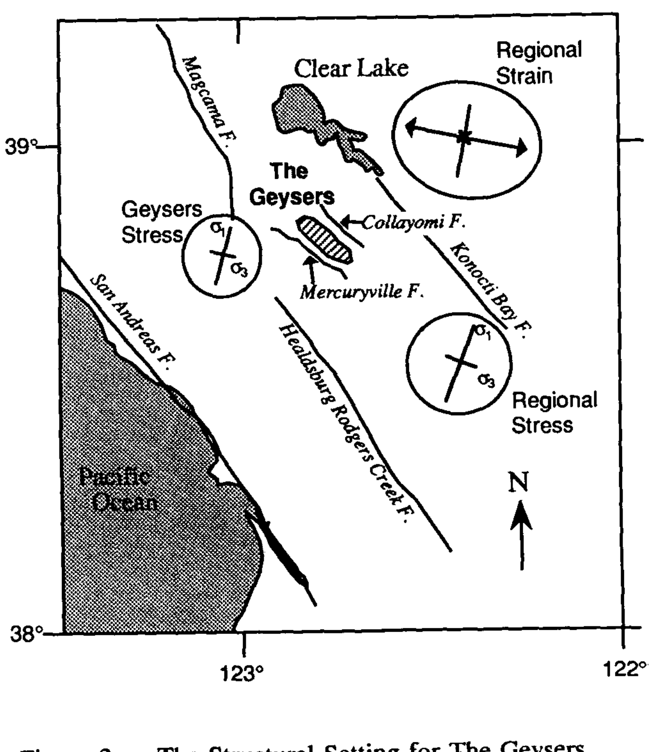

Figure 2. The Structural Setting for The Geysers Geothermal Field.

METHOD OF ARTIFICIAL RECHARGE

We submit that The Geysers geothermal field can be regenerated by artificial recharge from the margins of the productive reservoir using proven HDR-based techniques. From our extensive experience at Fenton Hill, the Laboratory has developed a number of pressure-stimulation and associated microseismic mapping techniques that could be used in creating fractured reservoirs in other deep regions of competent rock (Brown, 1990). Our experience has shown that the most favorably oriented sets of preexisting joints would be hydraulically stimulated, forming a network of multiply interconnected flow paths with an overall large heat transfer surface, allowing for very efficient heat extraction from the adjacent hot rock.

Most deformed regions of competent rock, presumably including the deeper regions surrounding The Geysers geothermal field, contain one or more sets of intersecting joints. In fact, it is well known (e.g., Jaeger and Cook, 1979) that joints represent by far the most pervasive structural features found in deformed rock masses. Therefore, if one were to pressurize an isolated zone in a deep borehole at the periphery of The Geysers geothermal field, one would expect to open a number of joints within a significant volume of hot rock. This pressure-dilated region, based on our Fenton Hill experience, would extend outward in all directions from the pressurized borehole interval until it ultimately intersected the much lower pressure steam reservoir. At this point, the well would be completed for use as an injection well -- albeit at injection pressures somewhat lower than those used to initially stimulate and extend the jointed region.

The injected fluid would be heated as it flowed preferentially down-gradient through the network of open joints, and would partially or completely flash as it approached the underpressured reservoir. This method of artificially recharging The Geysers, depending on the degree of implementation, has the potential for both restoring lost productivity and also greatly extending the lifetime of this major commercial geothermal resource.

In this context, it is significant to note that a peaking operation at The Geysers is now planned for later this year (Egan, 1990). In this mode of operation, large portions of the reservoir would be shut-in during off-peak hours to conserve steam, which would allow natural recharge to better stabilize production. HDR-augmented recharge, if successful, could provide an expanded range of possibilities for the efficient utilization of The Geysers resource.

PRELIMINARY ANALYSES

An analysis of the flow field that develops during the pressurized injection of cold fluid into a fractured region at the periphery of The Geysers geothermal field has been performed using a transient two-dimensional finite-difference representation for a network of intersecting joints in an anisotropic stress field. (Details of the computer code FRACNET are reported in Robinson, 1990.) The fluid flow and storage terms in this model are nonlinear. This is due to the inherent nonlinear deformation of joints with increasing internal pressure (e.g., Sun et al., 1985). The pressure-dependent fracture permeability model of Gangi, and the fracture porosity equivalent, as used in the numerical modeling, are presented in Brown and Robinson, 1990.

For our preliminary analysis of the flow distribution in a pressure-stimulated recharge region adjacent to The Geysers geothermal field, we have assumed the joint orientations and geometry of our Fenton Hill HDR reservoir, since the joint structure adjacent to the main Geysers steam field is not known in any detail. The fracture network used in the analysis is shown in Fig. 3. The

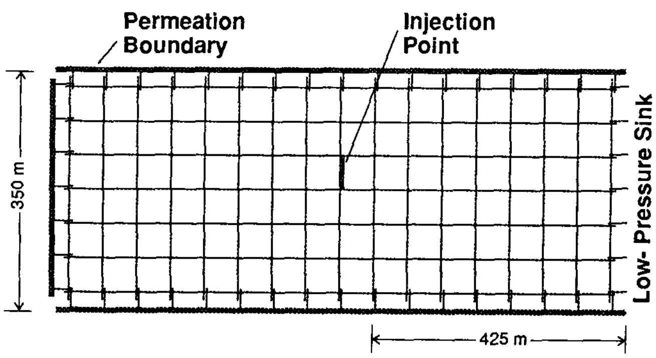

Figure 3. Fracture Network Model Used to Analyze the Artificial Recharge of The Geysers from a Jointed, Pressure-stimulated Peripheral Region.

pressure-stimulated region has a length of 850 m and a width of 300 m, with nonlinear permeation boundary conditions on the three sides which are not adjacent to the steam reservoir. The assumed principal effective confining stresses are 10 MPa and 35 MPa above hydrostatic, with the lower stress acting normal to the long axis of the stimulated region. The injection point is as shown, approximately in the center of the stimulated region.

The results of our analysis are given in Fig. 4. At early times, most of the injected fluid is being stored in the fracture system, or leaking off at the boundaries. However, after only 20 days of injection at 840 gpm (53 kg/s), over two-thirds of the injected water is reaching the hydrothermal reservoir. After 100 days, the recharge efficiency is almost 90 percent.

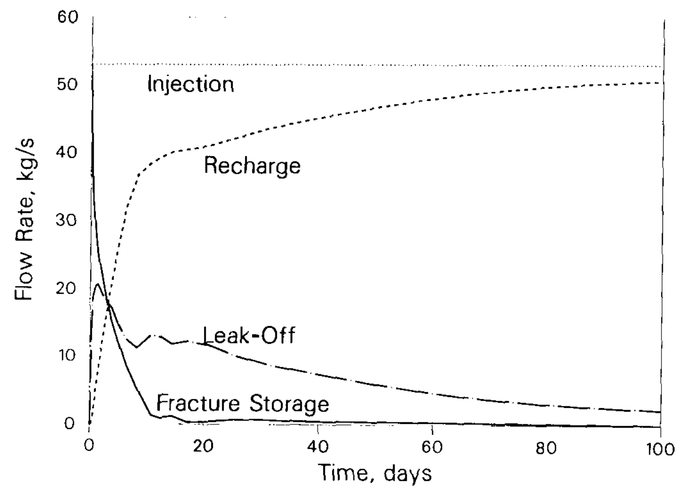

Figure 4. Flow Simulation of the Lateral Recharge of The Geysers.

CONCLUSIONS

Many of the current problems associated with steam production at The Geysers geothermal field would be ameliorated with artificial recharge from the nonproductive marginal regions using HDR-developed stimulation techniques. Depending on the degree of implementation and the availability of water, this augmented recharge could prevent a continued decline in productivity, or even possibly restore a measure of lost productivity. Further, with restored productivity, one would anticipate a reversal in the reservoir pressure decline.

ACKNOWLEDGMENT

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HDR Technology Transfer Activities in the Clear Lake area, California

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Abstract

A large Hot Dry Rock resource has been recognized in northern California. It underlies the region extending NE of The Geysers to N of the City of Clearlake. The long-range productive potential is thousands of megawatts.

The geothermal resource is heterogeneous. There are two mechanisms of heat flow occurring together. One is fluid transport, up natural zones of permeability, to outflows as surface springs. The other is conductive heat flow through impermeable rock. The temperature isotherms are thought to be nearly level surfaces, for example, the 300°C isotherm is at about 8000 ft depth, with "spikes" or "ridges" occurring around narrow zones of fluid flow. While there is accessible heat at shallow depth in the naturally permeable rocks, the really substantial resource is in the impermeable rock. This is the HDR resource.

The potential reservoir rocks are Franciscan greywackes and greenstones. Recorded drilling problems appear to be mainly due to intersection with serpentinites or to the effects of stimulation, so are potentially avoidable. Greywacke is favoured as a reservoir rock, and is expected to fail by brittle fracture.

The water shortages in Northern California appear to be surmountable. Leakoff rates are expected to be low. Sewerage water may be available for fill and makeup. There is a possibility of combining HDR heat power production with sewerage disposal.

To establish the first HDR producer in Northern California offers challenges in technology transfer. Two significant challenges will be creation of dispersed permeability in a greywacke reservoir, and pressure management in the vicinity of naturally permeable zones. A successful demonstration of HDR production technology will improve the long-term prospects for the geothermal power industry in California.

1. Heat Resources of the Western US

1.1 Introduction: In the late 1970's, the DOE commissioned studies of Hot Dry Rock (HDR) geothermal resources of the United States. Goff & Decker (1983) listed four prime areas, which were Fenton Hill NM, Geysers-Clearlake CA, Roosevelt Hot Springs UT, and White Mountain NH. Heiken et al (1982) made a wide-area resource evaluation which was based, in the western US, largely upon volcanology. It was a search for young volcanics. They identified five high-grade areas in the western US, which were Long Valley, Clear Lake, Salton Trough alluvium, Salton Trough granite, and Roosevelt Hot Springs. Using criteria of size of the thermal resource, material properties of the reservoir rock, and temperature gradient, they selected Roosevelt Hot Springs as their prime target. An engineering and economic evaluation of the Roosevelt Hot Spring site was made by Bechtel National Inc (1987, Cochrane et al, 1988).

Work at Clearlake has continued, however. We consider the Geysers - Clearlake region to be a most promising site for a commercial demonstration of HDR energy production technology, because of the high temperature gradient, size of the resource, and nearby industrial markets. In addition, the proximity to an established geothermal industry ensures the availability of technical resources and financial expertize in commercial geothermal energy production and consumption.

1.2 The Geysers - Clearlake Geothermal Anomaly: The heat resources of the western United States occur in several different regional settings. One pattern is random clustering of volcanism and high heat flow, related to crustal extension, in the high desert areas of Nevada, Arizona and New Mexico. A second pattern is linear belts associated with continental rifting in the Rio Grande of New Mexico, and Imperial and Owens Valleys of California. A third pattern is linear magmatic trails associated with hot-spot volcanism, such as along the Snake River plain, Yellowstone, and Jemez Mountains. A fourth pattern is alignments of island-arc volcanoes, such as the Cascades Range of Oregon, Washington and north-eastern California.

The Geysers - Clearlake geothermal anomaly is situated within the Coast Ranges north of San Francisco ("G" in Figure 1). It is not clear whether it belongs to any of the thermal tectonic trends described above or is a different feature entirely. Tectonic models include the severed limb of a subduction zone (Isherwood, 1981) and a leaky transform (Zandt & Furlong, 1980). Other possibilities are a subcrustal incipient spreading ridge and a migrating hot spot.

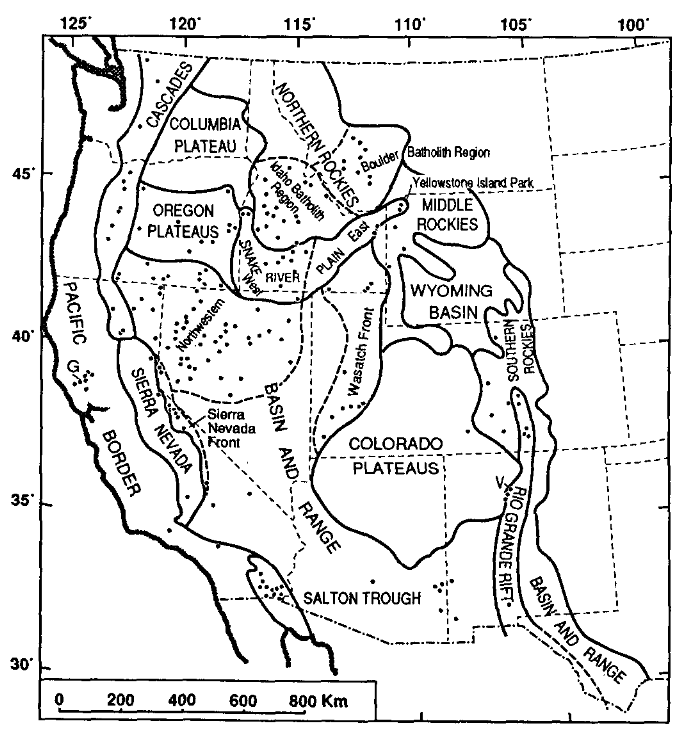

Figure 1: Geologic Provinces of the Western United States showing locations of hydrothermal systems with reservoir temperatures >= 90°C. From Brook et al, 1979, Figure 12 p.32.

The source of heat may be latent heat of crystallization from magmas freezing at a depth of about 6 km. Hyndman (1988) suggested that the source for the fluids may be connate water, generated by dehydration reactions of oceanic material in the crust at temperatures above 300-400ºC.

1.3 Size of the Geothermal Anomaly

The size and extent of the anomaly is inferred, from hot springs and young volcanism, to be as shown in figure 2.

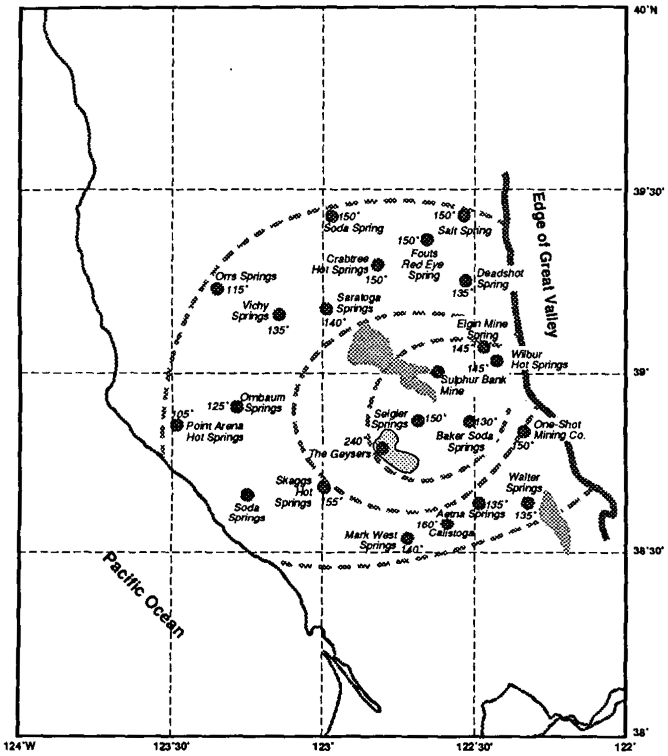

Figure 2: Location of The Geysers steamfield, nearby hot springs, associated with The Geysers - Clearlake geothermal anomaly, and contours indicating relative grade of heat resource. The contours are approximately 70, 100, and 150ºC/km. Map by R. Potter, based on Brook et al (1979).

The Geysers steamfield occurs near the center of the anomaly, with steam temperature of about 250ºC. Surrounding this is a region of hot spring activity. The recoverable energy from some of the hydrothermal systems within the field were estimated by Renner et al (1975), as shown in Table 1. The largest system is the vapor field at The Geysers, followed by hot water systems in the Clearlake Volcanic field and nearby areas.

The Hot Dry Rock resource lies around and between the areas of hydrothermal activity. The geothermometry of the springs and temperature measurements in exploration holes suggests a central core region with geothermal gradient of about 120ºC/km, and an outer core region at 100ºC/km. These would be Class A and Class B geothermal resources, respectively, on Japanese criteria, which means they both have commercial potential.

Heiken et al (1982, Table II) estimated the HDR potential of the Clearlake Volcanic Field at 3600 quads. In practice, only a small part of that energy would be recoverable. Assuming that only 1% of the resource can be reached, and only 50% recovered, from only that part between depths of 2.5 and 3.5 km, the recoverable HDR resource is substantially larger than the recoverable steam resource at The Geysers.

Regime	Name	Mean Reservoir Temp. °C	Reservoir Volume km^3	Thermal Energy 10^{18}J	Wellhead Thermal Energy 10^{18}J	Wellhead Available Work 10^{18}J	Electrical Energy (MWe for 30 Years)
Vapor Dominated	The Geysers	237	1167	100	9.3	3.1	1610
Hot Water >150°	Clearlake Volcanic Field	191	83	39	9.8	2.1	900
	Sulphur Bank Mine	194	6.7	3.2	0.8	0.2	75
Hot Water 90-150°C	Wilbur Hot Springs	144	12.5	4.4	1.09	0.26	
	Calistoga Hot Springs	144	6.9	2.4	0.60	0.145	
	Skaggs Hot Springs	113	3.3	0.88	0.22	0.053	

Table 1: Thermal energy being vented or recovered from hydrothermal systems in The Geysers - Clearlake region. From Renner et al, 1975.

2. Geothermal Regimes

2.1 Introduction: Knowledge of the mechanism of transport of heat from the base of the crust, and fluids from their subsurface sources, is important in evaluating the productive potential of the resource and deciding on the most appropriate production method. The phase of the fluids, liquid or vapor, has a big influence on heat transport. In this section, we review what is currently known about the Clear Lake area, and how we propose to use numerical modelling to find out more.

2.2 Geology and Geophysics: The bedrock is Franciscan greywacke, chert and greenstone of Jurassic age overlain unconformably by greywackes of the Eocene Great Valley sequence. The basement is folded on N-S trends and dissected by NW-trending right-lateral strike-slip faulting of the San Andreas system. The cover rocks are Plio-Pleistocene volcanics of the Clear Lake volcanic field. They occupy a graben SW of Clear Lake with the volcanic edifice of Mt. Konocti above.

The gravity and magnetic data show linear ridges with an azimuth of 300 degrees, interrupted by transverse faults with an azimuth of 035 degrees. The subsurface is interpreted as broad belts defined by density and magnetic susceptibility, basically greenstone and greywacke alternating on the NW-SE Coast Range trend. The gravity and magnetic anomalies indicate lithological variations, and do not seem to be affected by geothermal processes.

Radiometric dating of the volcanics at Clear Lake shows that the ages get younger northwards, suggesting northward migration of a magma chamber. The youngest deposits, with radiometric ages in the range 0.1 to 0.01 m.y., occur in the north. This indicates a northward migration, and suggests that the underlying magma chamber is currently NE of Borax Lake.

2.3 Heat and Fluid flow: The heat flow and resistivity yield patterns that are indicative of the geothermal process.

There are a number of deep exploration wells, at locations shown in Figure 3. The variation of temperature with depth in some of the wells is shown in Figure 4. Some of these indicate conductive heat flow with a gradient of about 100ºC/km. Combining data from deep and shallow wells, and using regression on a linear part of the temperature log, gives the temperate gradient shown in light contours in Figure 5. Using temperature data from only the deep wells, and using drilling logs to identify transient effects, we arrive at the revised estimates shown by the heavy contours in Figure 5. The revision indicates a NE-trending belt of high gradient, reaching about

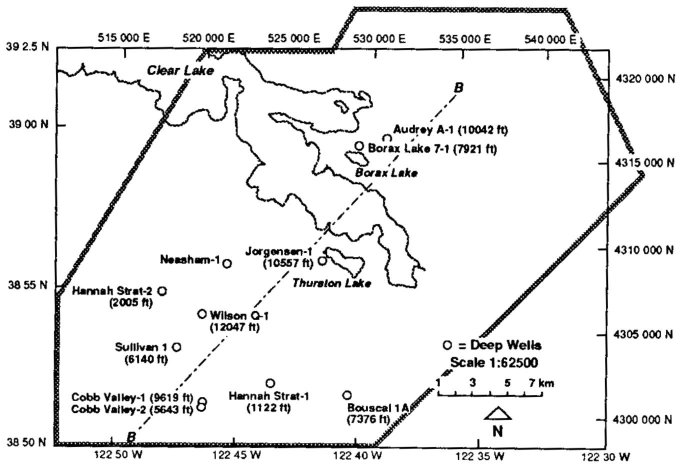

Figure 3: Map of deep exploration wellbores in The Geysers - Clear Lake region. The heavy line shows the region to be studied for geothermal regimes. The center line, BB, is the location of the FEHM model.

150oC/km at two central highs, and about 100oC/km elsewhere. The result is supported by the distribution of young plugs (Figure 6). A depth section along the axis of the anomaly is shown in Figure 7. South of Clear Lake, the 300oC isotherm dips gently NE, then rises sharply near the Audrey A well, NE of Borax Lake.

This result is supported by the resistivity (Figure 8). The resistivity lows coincide with the temperature gradient highs, and the resistivity shows an inflection at the SE boundary of the high temperature belt. The high thermal gradients correspond to fluid

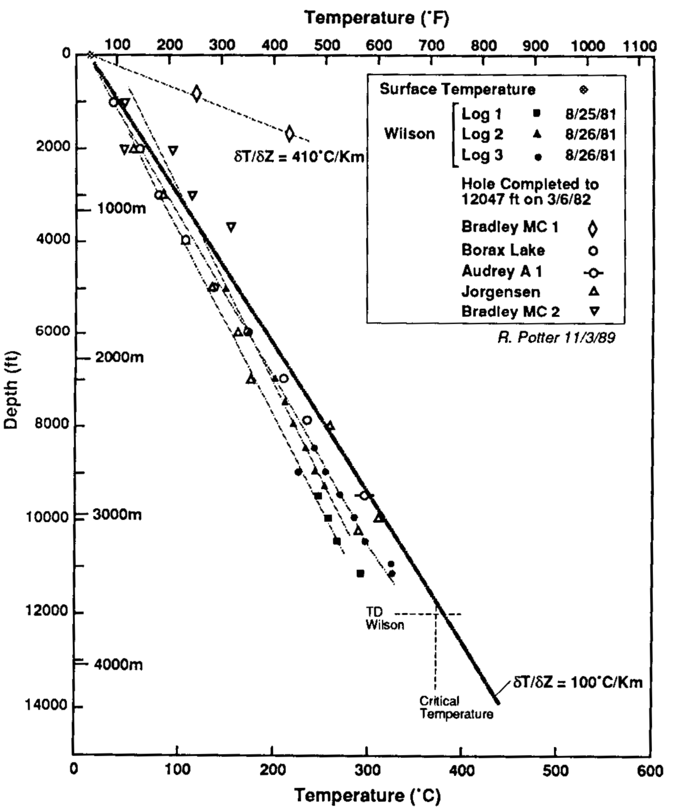

Figure 4: Graphs of temperature versus depth for five deep wells in a conductive heat flow regime. The gradient is close to 100oC/km.

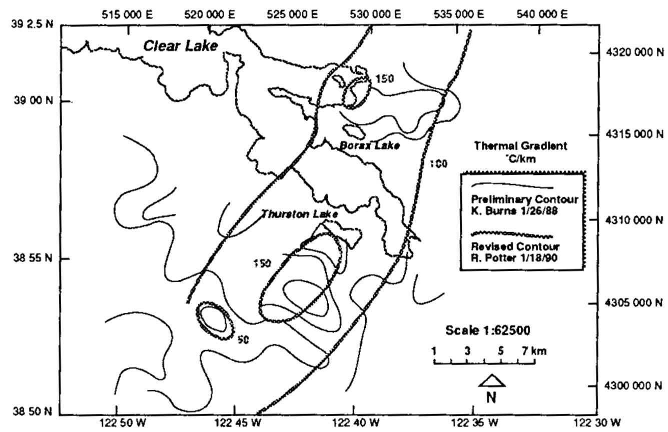

Figure 5: Contours of temperature gradient by two different methods. The geothermal anomaly appears to trend NE and is higher than 100oC/km with hot spots at 150oC/km.

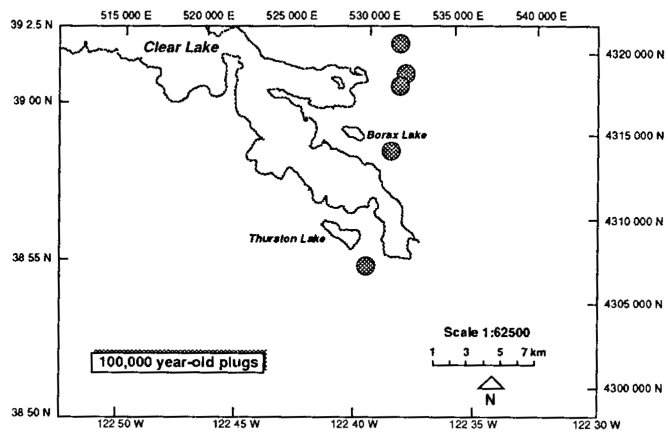

Figure 6: Location of young plugs in The Geysers - Clearlake region. This alignment agrees with the revised geothermal gradient of Figure 5.

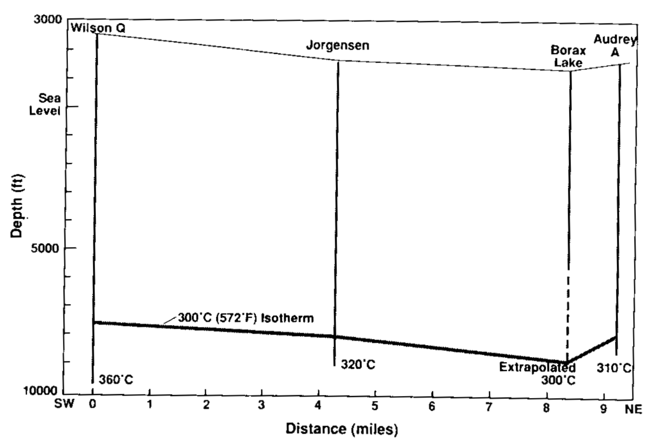

Figure 7: Section along the axis of the geothermal anomaly, (line BB of Figure 3) showing the 300oC isotherm. South of the lake, the isotherm is tilted north towards the lake. North of the lake it rises sharply near Audrey A well.

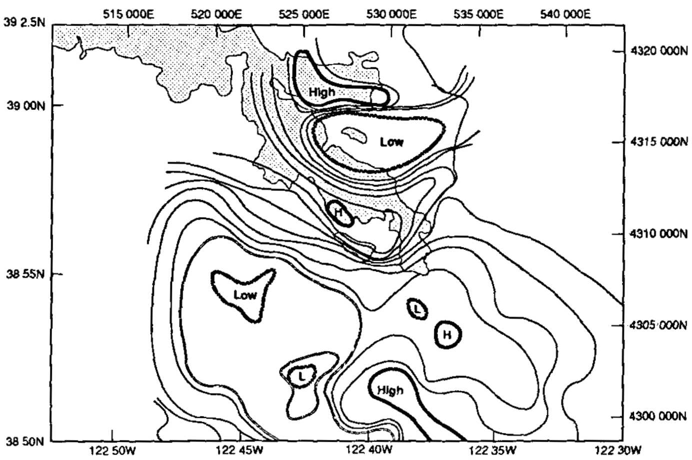

Figure 8: Resistivity contours. The high is 70 ohm-m. There are two lows at 4 ohm-m, which approximately coincide with high temperatures.

flows, suggesting that movement of connate fluid is contributing to the heat flow.

This behavior is consistent with a heat source at a depth of the base of the crust, moving towards the NE. On the south side of Clear Lake, heat is being transferred through the crust by conduction. The combination of moving source and slow conductive transfer may explain the slope on the isotherms. On the north side of Clear Lake, heat is being conveyed to the surface by convection, giving the high gradients near Sulphur Bank Hot Spring.

2.4 FEHM Model: These preliminary results are consistent with a moving magmatic source at a depth of about 6km. The latent heat of crystallization is being conducted upwards through the crust, down a gradient of about 100^{o}C/km, so that the 300^{o}C isotherm is at a depth of about 3 km. Where fluids are available, magmatic or connate, heat transfer is by convection, leading to highs in the isotherms. The fluid condenses at shallow depth, giving a resistivity signature.

The geothermal anomaly is therefore expected to have a mixture of wet and dry rocks. The fluids in different places may have different sources. The heat may be transported by conduction in places, convection in others. The convecting fluid may be liquid, or vapour, or both at various depths. To understand the resource and estimate its potential with confidence, requires that these source and transport factors be evaluated.

In the next stage of investigations, geological and geophysical methods will be used to determine the crustal structure, and in particular, to locate potential source rocks for fluids, and permeable pathways through the crust. The springs and groundwaters will be sampled and the isotopes analyzed, to determine their provenance, geothermometry and transport phases. These two data sets will be combined with temperature data as constraints on a Finite Element Heat and Mass-flow model (FEHM model) of the transport of heat and fluids within the crust. The modelling work will simulate the heat and fluid flow until agreement is reached with field observations. It is expected that this will distinguish between convective and conductive regimes, and enable an accurate determination of the geothermal resource. The form of the model is illustrated in Figure 9. The front slice shows a SW-NE section across the Geysers-Clearlake volcanic field at the present time. The model has two dimensions in space, along a longitudinal section through the geothermal anomaly, and a third dimension in time. This is a novel approach to resource evaluation, and if it succeeds as expected, should be useful in other geothermal regions.

3. Technology Transfer Policy

3.1 Introduction: Technology transfer is a matter of matching technology push to market pull. The HDR technology exists, but unless there is a pull from a demonstrated need, it has no present value.

3.2 Technology Push: The DOE resource studies have established several areas which are potential areas for HDR energy production. During the 1980's, the DOE commissioned a number of economic feasibility studies. These were compiled and recalculated to a common datum by Tester & Herzog (1989). The studies were a mixture of site-specific and generic studies. The two site-specific studies were Roosevelt Hot Springs and Fenton Hill. The break-even power cost, in 1986 cents/kWhe, were found to be 4.18 for Fenton Hill and 5.27 for Roosevelt Hot Springs. All generic studies give higher results (see Table 2), and the studies give a mixed message. When Tester & Herzog calculated the economic models by grade of resource, they obtained a much clearer picture (see Table 3). It is concluded that the thermal temperature gradient is a major factor in HDR economics. High grade resources (>80^{o}C/km) resources are economically competitive for electric power production at today's energy prices.

Numerous economic feasibility studies have been made of Hot Dry Rock, both generic studies, and at particular sites. In 1989 Tester and Herzog used two economic models, Levelized Life Cycle and Fixed Cost methods, to recalculate the previous results in 1989 dollars ($1989). Table 2 shows the results for particular regions. Table 3 shows the results when the resources are graded according to temperature gradient. Tester and Herzog (1989) conclude that high grade (80^{o}C/km) HDR resources are competitive at today's energy prices, mid grade (50^{o}C/km) HDR resources are only marginally competitive at today's energy prices, while low grade (30^{o}C/km) HDR resources would not be competitive for electricity production until significantly higher energy prices exist.

This means that the high grade region near Clear Lake is potentially economic for Hot Dry Rock methods of power production. The thermal gradient is well above Tester and Herzog's high-grade threshold of 80^{o}C/km, and in places reaches the Japanese Grade A level of 120^{o}C/km.

3.3 Market Pull:

Decline at The Geysers - The State of California is interested in environmentally-benign electric power production. The major geothermal resource west of the Sierra Nevada is in The Geysers - Clearlake area. However the current production method (dry steam at The Geysers) is declining.

According to Thomas (1989), a typical well in The Geysers declines 9.2% annually during the early years of the life of the well. The production rate falls to 50% of the initial rate in a little over 7 years, in a typical decline curve. However accelerated rates were noted in 1985 and 1986. Robinson (1989) said that the reservoir pressure dropped dramatically from early 1983. Von Hoene (1989) found a high decline rate in late 1986 and 1987, and attributed it to excessive production. He estimated that only 70 percent of the current Southern Geysers installed capacity should be utilized if we are to expect acceptable decline rates, reducing production to 50% of current levels by about the turn of the century.

The staff of the CEC reported (Warne & Blanton, 1989b),

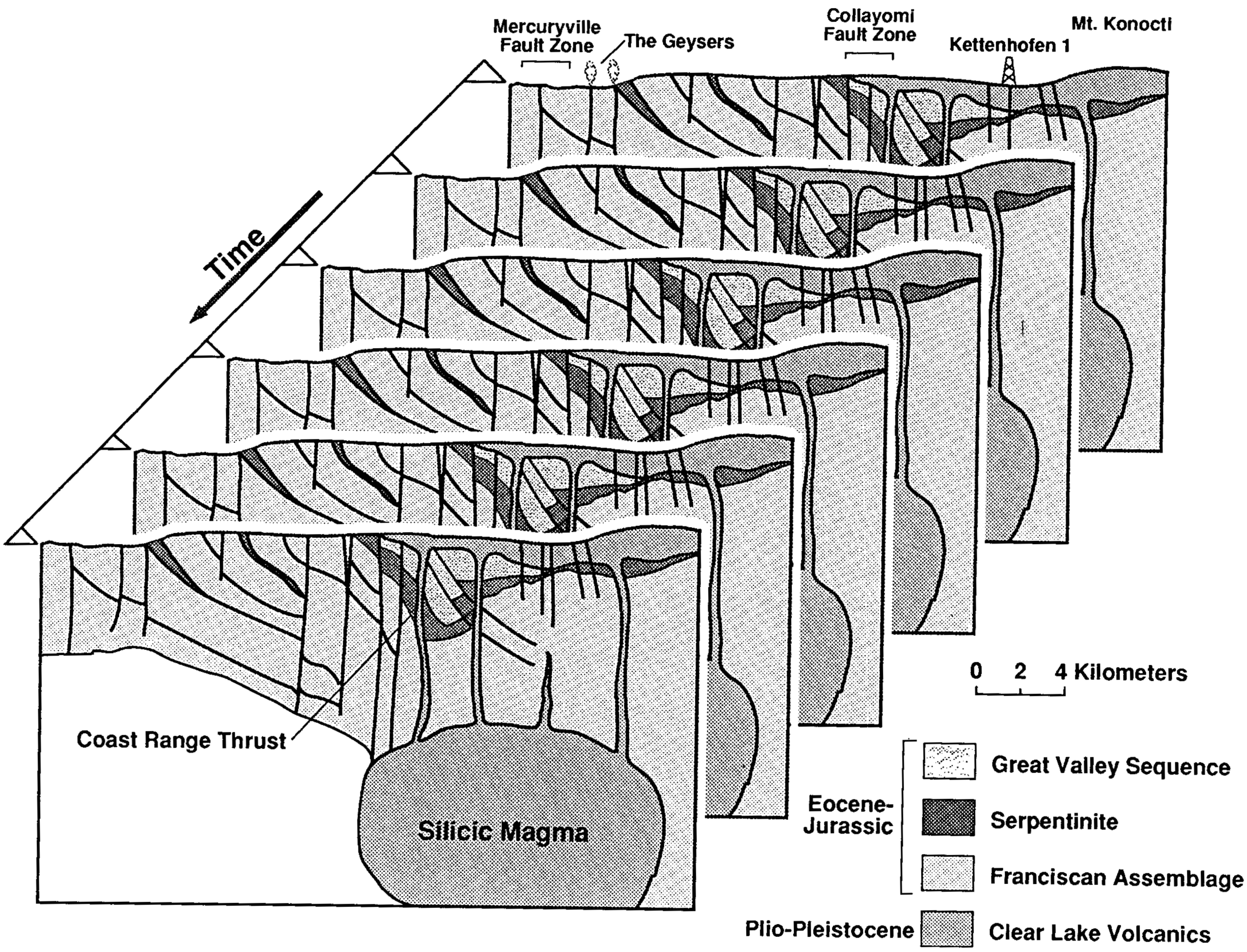

Figure 9: Design of the three-dimensional FEHM model. The section is along the line BB in Figure 5. Based on Heiken et al, Figure 8, p.20. The time ranges from 1 m.y. ago to the present.

HDR Economic Studies
By Region

Model	Date	Applicability	Locality	Breakeven Cents/kWh $1986
EPRI	1979	generic	US	5.98
LANL	1982	specific	Fenton Hill, NM	4.18
Japan	1986	generic	Japan	10.33
UK TWVC	1986	generic	UK	6.17
Meridian iii	1987	generic	US	7.81
Bechtel	1988	specific	Roosevelt Hot Springs, UT	5.27

Tester & Herzog, 1989

Table 2: HDR economic studies, by region. From Tester & Herzog, 1989, Table 9 p.58. Costs are in 1986$.

HDR Economic Studies
By Grade of Resource

Resource	Average Gradient °C/km	Electricity Breakeven Cost (Cents/kWh, $1989)	
		Levelized Life Cycle Cost Analysis	Fixed Charge Rate Cost Analysis
High-Grade	80	5.6	6.3
Mid-Grade	50	8.8	10.0
Low-Grade	30	16.5	18.9

Tester & Herzog, 1989

Table 3: HDR economic studies, by grade of resource. From Tester & Herzog, 1989, Table 12 p.71. Costs are in 1989$. Estimates are based upon a capacity of 50 MWe.

that up to the time of the CEC Informational Hearing of Sept.21,1989, The Geysers geothermal field was estimated to contain initial reserves to produce about 120,000 MWe years of electrical energy. Staff projected that development in The Geysers could reach a maximum capacity of 2,700 to 3,000 MWe. This is enough power to supply 3 million people. These estimates are no longer valid. Because of the accelerated development during the early 1980's, steam pressure in much of the reservoir has dropped to 200 psi from the initial pressure of 500 psi in 1960. The problem could significantly alter the expected production and lifetime of the resource. Of the approximately 2,000 MWe of installed capacity, 400 MWe may be idle due to insufficient steam, enough to serve 400,000 people. This is 60% to 75% of capacity (Heimoff, 1989).

Development of an HDR producer in The Geysers - Clear Lake region would support the geothermal industry by providing nearby experience of a new production method, which may become important in prolonging the life of The Geysers known geothermal resource area (KGRA). It provides a means for the industry to extract heat in hot, impermeable ground beyond the borders of the present steamfield. Hot Dry Rock technology is of interest as a possible supplement or replacement, at the boundaries of the steamfield or below it.

Growth in Direct Use - The high-grade hydrothermal resource at The Geysers steamfield and in hot springs in the surrounding area have made the population conscious of the resource, and there is widespread interest in the distributed commercial possibilities.

In recent years numerous small communities have investigated their local geothermal resources for horticultural, co-generation and space heating purposes. For example, the County of Lake recently brought an Agricultural Park into production. An indication of the level and variety of activity is provided by the California Energy Commission's Geothermal Resources Development Account. Warne & Blanton reported (1989a) that proposed expenditures in FY 1989-90 included space and water heating, horticultural irrigation, and district heating. The interested authorities included the Counties of Lake, Mono, and Sonoma; the Cities of Clearlake and Colton; the South Lake County Fire Protection District, the North Sonoma County Air Pollution Control District, and the Kelseyville Unified School District.

However the hydrothermal resources are finite. There is interest in Hot Dry Rock technology as a means of expanding the opportunities for direct use. Tester & Herzog (1989) said that (p.16) "... HDR resources provide a degree of flexibility which is inherently absent from natural hydrothermal systems. Namely, ... HDR reservoir temperatures may be selected by drilling to a specified depth determined by the geothermal temperature gradient." HDR provides " ... a framework for exploring the economic tradeoffs of drilling deeper, hotter, more costly wells versus drilling shallower, cooler, less expensive wells balanced against the value of the product; that is, electricity or heat or both". They also said that low-grade HDR resources would compete favourably in non-electric, space or process heating applications, because the second law efficiencies, which penalize the conversion of low-grade thermal energy into electricity, are not restrictive in this application.

3.4 Potential Use of HDR Energy at Clearlake:

Electric Power Production - From the standpoint of research-push, the high-grade option restricts the site to a few select locations in the western US. The Clear Lake region is a leading contender because of the high temperatures at shallow depth, and proximity to established geothermal industry. The accelerated decline at The Geysers is expected to raise industrial interest in modified production methods. The technical environment should be more receptive to new research and technical results than on any of the immature geothermal fields in Southern California.

From the standpoint of market-pull, HDR has the potential to make up some of the shortfall in planned hydrothermal power production at The Geysers. From a State-wide viewpoint, geothermal energy has environmental advantages over coal, oil, and nuclear. There should be a demand from PG&E for replacement of Geysers production, and from the state, for some of that production to be from geothermal sources.

The decline of a steam producer is a fact of life. However the decline to below projections means a shortfall in the State's expected production of environmentally-acceptable power. It has been reported (Rose, 1990) that Pacific Gas & Electric Co. forecasts potential new demand of 3,300 MWe over the next decade. This presumably includes the 400 MWe anticipated decline. PG&E plans to meet 2,500 MWe by customer efficiencies, leaving 800 MWe to be found by new or increased production. Most of the new production will come from gas and oil-fired stations, but there will be a market for power from environmentally-acceptable new producers such as HDR. Steps are in hand for the proposed HDR demonstration producer to compete for part of that load.

Water Conservation - The urban growth of Clearlake City forces the issue of sewerage disposal. It has been found that there is a synergism between HDR energy production and sewerage refinement which means a combined plant is more valuable than either alone.

Energy production from HDR means requires fill and makeup water (Brown, 1989 and Figure 10A). Water is a scarce commodity in Northern California. The water could be provided by treated sewage.

Waste water disposal has become a major environmental issue (Mapes, 1990). For example, Santa Rosa has to dispose of

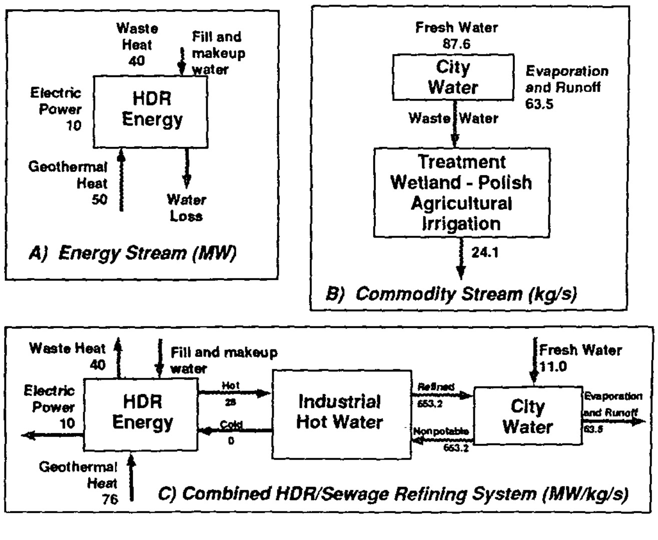

Figure 10: Diagrams illustrating combined electric power production and direct-use heat for sewage refining. A and B show the systems separately. C shows the combined system. The combination enables more efficient recovery of energy and a substantial reduction in the volume of waste water for disposal.

29 million gallons a day. One proposal is secondary treatment and disposal to the Russian River (cost: $97 million). Another is to follow the example of Arcata (Stewart, 1990), and "polish" the effluent by residence in wetlands prior to disposal to San Francisco Bay (cost: $172 million). A third proposal is to irrigate about 12,000 acres of cow pastures. All these proposals have opponents, by abalone fishermen, the Bay water board, and dairy farmers, respectively. Their common weakness is that the water is passed through the system without recycling (Figure 10B).

Sewerage can be "refined" by heat from an HDR source. The water could be heated to 250oC or distilled, to make re-use acceptable. This leads to the notion of an integrated facility, incorporating power production, direct-use for agriculture and urban uses, and sewerage refinement (Figure 10C). For the City of Clearlake, such a facility would supply every household with fresh drinking water (potable water) as at present, generate 10MWe of electricity, provide about 28MWt of thermal energy for direct uses, and provide recycled, distilled water (non-potable water) for toilets and garden hoses. The direct application would be cascaded community, tourist, agricultural or industrial uses.

The water use of the community is about 10 kg/s of potable water, and 50 kg/s of non-potable water. The availability of the non-potable supply would reduce the city's fresh-water intake from about 60 kg/s to about 10 kg/s, which is a substantial economy. Water could be taken from the non-potable pond and distilled at the rate of about 90 kg/s, with the effect of continuously clarifying the non-potable pond.

This integrated facility would be about three times as efficient an energy producer as a pure power producer. This is because the heat usually lost in the cooling towers of an electricity producer would be put to use, and also because conversion and transmission losses would be minimal. It is concluded that the greatest return on HDR might not be from pure power production, but from mixed power production and direct use. This agrees with Tester & Herzog (1989, p.16) who states that HDR resources offer a degree of flexibility that is inherently absent from hydrothermal systems. The system can be balanced against the value of the product, that is, electricity or heat or both.

Whether or not sewerage refining becomes a reality, it is concluded that there is a great demand for direct use geothermal energy for a variety of local purposes, and HDR has potential in that context.

3.5 Conclusions: In conclusion, HDR energy production has been considered, up till now, simply as a means of power production, in competition with hydro-electric, hydrothermal, coal, oil, and nuclear, and solely in terms of baseload supply to an industrial grid. Direct utilization of geothermal energy has been considered, but only in relation to hydrothermal sources (Anderson & Lund, 1979).

In Northern California, an integrated facility, producing electric power, thermal energy and refining sewerage, is potentially viable. There is a clear community demand for water conservation and thermal energy. An integrated facility would combine the functions of power production, energy production for direct use and water conservation. This is a new concept of the role of HDR in the US industrial economy.

4. Economics of an HDR Power Plant at Clearlake

4.1 Introduction: The Net Present Value (NPV) method provides a simple way to examine the economic feasibility of an HDR producer near the city of Clearlake.

4.2 Return on Production: We take as a basis a long-term rate of 5 cents per kWhe in 1989, which is $438.3 per MWe. Assuming that prices escalate at 3% per annum, and the plant life is 20 years, the gross return for the years 1994 to 2014 is $14.6m per MWe. Discounting to 1994 at 15% per annum, the return in $1994 is about $3.8m per MWe.

4.3 Power Plant Efficiency: Assuming a geothermal fluid temperature of 300oC and a condensation temperature of 37.5oC, the conversion efficiency is 20%, from the nomogram of Armstead and Tester, 1987, Figure 14.2, p.403. A power output of 1 MWe requires a thermal input of 5 MWt.

4.4 Power Plant Costs: The estimated cost in 1984 was $600 per installed kWe, from the nomogram of Armstead & Tester, 1987, Figure 14.8, p.410. Escalating costs to 1992 at 7%, this is $0.735m per MWe.

4.5 Drilling Costs: Northern California is a wrench tectonic regime, so that the size and shape of the reservoir is taken from the Cornwall experience. Armstead and Tester (1987, Figure 14.6, p.407), developed a method of optimizing the reservoir depth, by setting the increase in drilling costs with depth against the improved conversion efficiency with temperature. In this case, the depth is limited by the temperature-resistant properties of materials. We suppose the reservoir is centered at 3.1 km depth, with injection well at 4.1 km, and production well at 2.8 km.

Armstead & Tester (1987, figure 14.9, p.413) give a range of drilling costs for HDR. A recent study by Dreesen et al (1989) was aimed at determining realistic drilling costs. The operation was conducted in a hot, fractured reservoir from 2896-3767 m depth. The cost of rotary drilling for 602 m was $531 per m. Tester et al (1989) estimated the cost of developing a two-well reservoir at a depth of 4.5 km at $10.38m per well-pair.

The construction costs of a two-well system at Clearlake are estimated at Armstead and Tester's unburdened rate as $7.4m.

4.6 Required Performance: The net receipts of the system are then Earnings - Surface costs - Subsurface costs. If the system is operated at P MWe, the result is [P*$3.8m - P*$0.735m - $7.4m]. The break-even point is at 2.4 MWe, or 12 MWt.

The Fenton Hill reservoir has produced 10 MWt on a sustained basis during experimental work and this break-even rate should be readily attained at Clearlake. Profitability depends upon obtaining a higher production rate. Table 4 illustrates the possibilities.

Production Rate MW (t)	Production Rate MW (e)	Expenditure $m (1992)	Net Return $m (1992)	Receipts/ Expenditures
10	2	8.87	-1.23	0.86
20	4	10.34	+4.86	1.47
30	6	11.81	+10.99	1.93
40	8	13.28	+17.12	2.29
50	10	14.75	+23.25	2.58

Table 4: Simple economic model applied to the site at Borax Lake.

4.7 Conclusion: This simple NPV model indicates that an HDR power producer would break-even at Clearlake if the power could be sold on a long-term contract at 0.05 $1992 per kWhe and a sustained production rate of 12 MWt could be achieved. Since production rates of 30-50 MWt are envisaged, the potential exists for a commercially viable operation.

5. Engineering Problems

The Clear Lake hydrothermal field is a heterogeneous geothermal resource. There are three different geothermal systems in the region, steamfields, hot springs, and hot dry rocks. Each needs to be managed differently for optimum production. If different systems intersect in the subsurface they will interfere with each other. This is a potential problem in construction and in managing production from an HDR plant.

There are various solutions available, which include avoidance, pressure management, and grouting of connections. Experience with similar problems at Fenton Hill indicates that these problems will be soluble.

6. Conclusions

6.1. The Geysers - Clear Lake geothermal anomaly is a distinctive heat resource in the Coast Ranges of northern California. It is a major geothermal resource of great economic significance to California. The Geysers steamfield is only a small part of the total energy content.

6.2 The heat probably originates from latent heat of crystallization of magma at a depth of 6 km under Clear Lake. It is transported to the surface by both conduction in impermeable rock, and convection up permeable fault zones. The transporting fluid is probably connate water from the Great Valley sequence. The differing rates of transport and possibly, movement of the source, result in a complex pattern of heat flow. Isotope geochemistry and numerical modelling of transport processes will be used to evaluate the commercial potential of the resource.

6.3 Technology push from the DOE research indicates that an HDR producer can built at Clearlake and given fair trading conditions, could be an economic supplier of electric power to the California grid.

6.4 Market pull from the CEC is influenced by the decline of production at The Geysers. New heat mining methods are needed, to prolong the life of hydrothermal resources, and to extract heat that cannot be reached by orthodox techniques. A second market pull comes from urban communities interested in direct use energy. A plant in a populated area that can combine power production with direct use, is more energy efficient than plants in remote areas that have no use for low-grade heat.

6.5 A potential obstacle is the shortage of water for fill and make-up water in the HDR plant. However the problem of disposing of sewerage water in northern California, offers the prospect of cooperative water management, to the mutual benefit of both the HDR energy producer, and the nearby county sewerage treatment plant.

6.6 Various economic studies put the cost of production of HDR energy at a level which is economically feasible for electric power on the Californian grid. The sustainable production rate, utilizing high back pressure or cyclic operation, may be higher than the previous studies suppose. This would increase the rate of return. At Clearlake the investment costs are below the model assumptions because of higher temperatures at shallow depth, and might be reduced still further by refurbishing abandoned exploration wells. The return on production of geothermal fluid could be enhanced by direct-use in the adjacent city. These are all favorable possibilities.

6.7 The geothermal resource at Clear Lake turns out to be heterogeneous. There are three types of resources, namely steamfields, hot springs and dry rock, occurring in proximity. Hot Dry Rock production methods are characteristically high-pressure, which does not sit well with the other resources. However a mixed resource should be manageable.

6.8 Clearlake has the potential to become the world's first commercial Hot Dry Rock energy producer.

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GEOPRESSURED-GEOTHERMAL TECHNOLOGY

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GEOPRESSURED ENERGY - AN ENVIRONMENTALLY SAFE ALTERNATIVE

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ABSTRACT

As a response to the America's need for alternate energy sources, the United States Department of Energy has a Geothermal Program. Within this program is a category to study Geopressured Energy. Today many activities are taking place under the Geopressured Program. These activities for the most part fall under one of the following categories: Well Operations, Geoscience & Engineering Support, Energy Conversion and Technical Transfer. To date this program has had many successes. However, there is still more information needed concerning the Geopressured Resource. It is thought that continued research will give the developer a better understanding of the Geopressured resource and in turn increase the likelihood of it's development.

INTRODUCTION

Today, America is continuing the search for alternative energy sources. As part of this effort, the United States Department of Energy (DOE) has numerous programs exploring various energy alternatives, one of which is Geothermal Energy. The Geopressured Program is one of the many activities in the Geothermal Program. This paper gives an overview of the program.

The geopressured energy resource is made up of large reservoirs containing high temperature - high pressure brines saturated with various amounts of hydrocarbons. These properties often result in large amounts of thermal, mechanical and chemical energy. The goal for the Geopressured Program is to improve the technology to the point where this energy can be converted to electricity in a cost range of 6 to 10 cents per kWh. Several questions must be answered before this goal can be obtained. These questions range from reservoir reliability to energy conversion technology.

The USDOE's Geopressured Program is actively pursuing answers to the questions that are limiting the development of the Geopressured resource. The program management is provided by the DOE-Headquarters' Geothermal Technology Division located in Washington D.C. The project management is provided by the DOE's Idaho Operations Office with assistance from EG&G, Idaho, Inc.

The program is broken down into three tasks: Well Operations, Geoscience and Engineering Support, and Energy Conversion. Each of these tasks are made up of several projects that are carried out by various contractors and universities.

The Funding for the program in fiscal year 1990 is $5,800,000. This has resulted in a large amount of activity in the Geopressured Program tasks. A description of this activity follows.

WELL OPERATIONS

The Well Operations Task is a major part of the Geopressured Program. This task consists of flow testing DOE geopressured wells and then re-injecting the produced brine. DOE-ID currently has a contract with the Eaton Operating Company located in Houston, TX, to operate and maintain the wells. The goals for the Well Operation task are: 1) to obtain production data that can be used by the program researchers to address the Geoscience and Engineering Support goals, and 2) to obtain experience to address the specific well operations goals. The specific goals for the well operations task are summarized below.

Prove long-term injectibility of large volumes of spent brine,

Minimize fluid production expenses,

Develop technology for automated operation of geopressured production system,

Develop modified scale inhibitor treatment procedures, and

Reservoir Analysis

The testing ground for the well operations task currently consists of three geopressured wells located in the Gulf Coast Area. They are the Pleasant Bayou Well, the Gladys McCall Well and the Hulin Well.

Pleasant Bayou Well - The Pleasant Bayou Well is located in Brazoria County, TX. The well has a total depth of 16,500 feet. The temperature of the brine at the surface is 291 F. The brine has a total dissolved solids count of 131,320 ppm and a gas/water ratio of 29 scf/bbl. The site also has an injection well, where brine is being injected at a depth of 6,400 feet.

In May 1988 the well was brought on line. It is currently being flow tested at approximately 16,000 barrels per day. The Eaton Operating Company has a subcontract with the Institute of Gas Technology to operate the surface handling equipment. Program plans call for well testing to continue through FY-1990. A 1 MWe Hybrid Power System (which will be discussed in the Energy Conversion Section) was installed at this site in the spring of 1989.

Gladys McCall Well - The Gladys McCall Well is located in Cameron Parish, LA. The well has a total depth of 15,831 feet. The temperature of the brine at the surface has been recorded at 288 F. The brine has a total dissolved solids value of 92,800 ppm and a gas/water ratio of 31.8 scf/bbl. This site also has an injection well where brine is injected at a depth of 3,514 feet.

Flow testing of the Gladys McCall Well was initiated December 1982. The well was tested off and on through October 1987 when it was shut in to monitor reservoir pressure recovery. During the 4 1/2 year production period 27 million barrels of hot brine were produced with 676 million scf of natural gas. The production period was considered very successful both because of the large amount of brine produced and injected, and because an effective scale inhibitor was developed. The wellhead pressures before and after flow-testing were 5,935 psia and 3,580 psia respectively. Currently, the well has been shut in for 29 months and the wellhead pressure is 5,145 psia. Future plans for the well include side-tracking and coring of the production reservoir to determine the effects of long-term production and the scale inhibitor.

Hulin Well - The Hulin Well is located in Erath, LA. This well has a total depth of 20,700 feet. The temperature of the well at 20,700 feet is 366 F. The brine chemistry for the well is not yet available but preliminary analysis suggests total dissolved salts of 194,000 ppm. An injection well has been drilled to a depth of 6,700 feet.

On October 31, 1988, rework of the Hulin Well began. The intent of the rework was to clean out the well, replace old mud with new, and prepare the well for low rate short term flow testing in October 1989. The flow rates were limited to 6,000 barrels/day by the small tubing diameter. The flow test results indicated that the permeability of the reservoir may be high enough to support flow rates of 14,000 to 17,000 barrels per day. The gas/water ratio was measured as high as 34 standard cubic feet of gas per 1 barrel of brine. Currently, the data generated during the test is being analyzed. If the early indications that the well is capable of long term production hold true, larger diameter tubing will be placed in the well to permit higher rate brine production. In addition, a permanent production facility will be installed at the well site. Future plans may also include the construction and operation of a power plant and/or the implementation of some direct use operations.

GEOSCIENCE AND ENGINEERING SUPPORT

The Geoscience and Engineering Support Task is intended to accomplish two objectives: 1) to evaluate well operation data and 2) to examine factors which effect geopressured energy production. The task is broken into four projects: rock mechanics, reservoir engineering, liquid hydrocarbons, and environmental assessment.

Rock Mechanics - The effect of compaction and creep on geopressured-geothermal reservoir rocks is not well defined. Rock Mechanics are very important because they effect the wellbore stability and production from the reservoir. To better understand the rock mechanics, stress - strain relationships of reservoir rocks need to be defined so that basic rock properties at in-situ conditions can be determined.

Researchers at the University of Texas at Austin are conducting strength and mechanical property tests on Pleasant Bayou cores and completing work on compaction of Gladys McCall reservoir sandstone. This work is resulting in improved knowledge of the behavior of geopressured-geothermal reservoir rocks during production.

Additionally, the University of Texas researchers are making tensile measurements on core samples. The tensile behavior of geopressured-geothermal sandstone, the rock strength, well depth, fluid flow rate, temperature, and formation properties are all variables that effect wellbore stability during fluid production. This work is providing basic data for future well development programs.

Reservoir Engineering - The objective for the Reservoir Engineering project is to develop techniques to increase confidence in the ability to locate and evaluate geopressured resources. The project is taking two approaches to accomplish this objective: 1) data from the program's geopressured wells are being evaluated and modeled, and 2) improved logging techniques and interpretation methods are being developed.

Researchers at the University of Texas at Austin (including subcontractor S-Cubed in California), Louisiana State University, and Lawrence Berkeley Laboratory are utilizing geopressured well data to develop reservoir models. These models are intended to predict the reservoir size and behavior. Pressure drawdown and buildup data along with site specific geology is used to predict reservoir size. Brine chemistry, pressure, temperature and site specific geology are used to predict reservoir behavior.

The University of Texas at Austin is developing improved logging techniques intended to assist in evaluating the geopressured resource. The current efforts include evaluating logs from geopressured wells, conducting research on log resistivity resulting from rock wettability and shale content, and determining the effect boron and other trace elements have on the porosity log.

Liquid Hydrocarbons - The objective of this project is to determine the nature of hydrocarbons, their source and flow mechanisms in geopressured reservoirs.

Currently, the University of Southwestern Louisiana is conducting research on cryocondensates in geopressured wells. Brine from the test wells is sampled and analyzed to determine the solubility of aromatics. The geochemistry of the cryocondensates reflects the conditions in the geopressured reservoir. A spin-off of this work is the development of an in-line benzene monitor. This monitor has the capability to achieve a sensitivity level that could make it suitable for use by the EPA in their environmental monitoring. Additionally, the University of Southwestern Louisiana is developing an in-line pH monitor for use in the harsh environments present in a geopressured - geothermal well.

Environmental Assessment - There are environmental concerns related to producing and reinjecting geopressured brines. These concerns primarily deal with land subsidence, growth fault activation and water quality. The objective for this project is to determine if geopressured fluids can be produced and disposed of in an environmentally safe manner.

Researchers at Louisiana State University are conducting an environmental monitoring project at the DOE test wells. Subsidence and seismicity are monitored by instrument networks located at the well sites. Water quality is monitored by routine sampling of the ground water. To date, no adverse environmental effects have been observed. However, further monitoring must be done before a conclusion can be made.

ENERGY CONVERSION

The ultimate goal for the geopressured program is to find a way to economically utilize the energy from a geopressured resource. To accomplish this, a utilization system is needed which takes advantage of the three forms of energy available (chemical, thermal and mechanical). The current project taking place in the Energy Conversion category is the development, construction and operation of the Pleasant Bayou Hybrid Power System.

Pleasant Bayou Hybrid Power System, (HPS) - The DOE and EPRI have a contractual agreement to collaboratively design, build and operate a small 1 Megawatt power plant to be located at the DOE's Pleasant Bayou Well. The Eaton Operating Company is DOE's contractor for this project. They, in turn, have a subcontract with the Ben Holt Company to construct and operate the system. The HPS utilizes the geothermal brine as a heat source for a binary cycle and uses the methane separated from the brine to power a gas engine. The exhaust from the gas engine is used as an additional heat source to the binary cycle.

The HPS has been constructed and is operating. The nine month operational period of the plant will be completed July 1, 1990. Preliminary results have been good. At the completion of the operating period, the project results will be summarized in a final report.

CONCLUSION

There is a lot of activity taking place in the Geopressured Program. All efforts are being made to insure that these activities result in success. These efforts include a closer working relationship with Industry. Currently, a Geopressured Utilization Industrial Consortium is being developed. While this is not a DOE consortium, DOE strongly supports the development of such a group. This group will provide an ideal arena for technical transfer between the DOE and industry. It is the DOE's intension to make the geopressured wells that are currently being operated in the program, available for selected consortium projects. It is thought that by making the wells available for utilization experiments, consortium members will be able to gain valuable experience and potentially revenue from their respective projects with limited expense. This relationship between the DOE and the consortium will allow DOE to gain a better understanding of the challenges preventing industry from developing the geopressured resource. The next consortium meeting will be held at the University of Texas at Austin's Balcones Research Center, on September 11, 1990. Individuals interested in attending the meeting and/or joining this consortium should contact: Dr. Jane Negus-de Wys, Idaho National Engineering Laboratory or Dr. Myron Dorfman, University of Texas at Austin.

By continuing down the path developed by program researchers, it is hoped that the program goal of economically producing electricity can be realized. This would represent a very positive step in our nation's search for alternative energy sources.

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THE GEOPRESSURED-GEOTHERMAL RESOURCE, RESEARCH, AND USE

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ABSTRACT

The Geopressured-Geothermal Resource has an estimated accessible resource base of 5,700 quads of gas and 11,000 quads of thermal energy in the onshore Texas and Louisiana Gulf Coast area alone (Wallace et al., 1978). After 15 years the program is now beginning a transition to commercialization. The program presently has three geopressured-geothermal wells in Texas and Louisiana. The Pleasant Bayou Well has a 1 MWe hybrid power system converting some gas and the thermal energy to electricity. The Gladys McCall Well produced over 27 MM bbls brine with 23 scf per bbl over 4 1/2 years. It is now shut-in building up pressure. The deep Hulin Well has been cleaned out and short-term flow tested. It is on standby awaiting funds for long-term flow testing.

Supporting research in the Geopressured Program includes research at the University of Texas at Austin on rock mechanics, logging, geologic studies, reservoir modeling, and co-location of brine and heavy oil in Texas and California; at the Louisiana State University on environmental monitoring and geologic studies; and at the University of Southwestern Louisiana on hydrocarbons associated with the geopressured brines and development of a pH monitor for harsh environments. Recently, Lawrence Berkeley Laboratory has been added to the research support in prediction of reservoir behavior. EG&G Idaho, Inc. is developing feasibility studies in FY-1990 on four use areas: 1) Thermal Enhanced Oil Recovery, 2) Direct Use, 3) Hydraulic and Thermal Conversion, and 4) Use of Supercritical Processes and Pyrolysis in Detoxification. This on-going research and well operations are preparing the way to commercialization of the Geopressured-Geothermal Resource.

In January 1990 an Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource was convened at Rice University, Houston, TX. Sixty-five participants heard industry cost-shared proposals for using the hot geopressured brine. Proposals ranged from thermal enhanced oil recovery to aquaculture, energy conversion, and environmental clean up processes. By the September meeting at UTA-Balcones Research Center, industry approved charters will have been received, an Advisory Board will be appointed, and election of officers from industry will be held. The 2-volume proceedings of the January meeting have been completed and are available to interested parties.

INTRODUCTION

Geological formations located in the northern Gulf of Mexico contain large reservoirs of hot, saline brine under abnormally high pressure and temperatures. Estimates of the energy potential of this undeveloped resource range as high as 160,000 quadrillion BTUs (quads) (DOE, 1989). The U. S. Geological Survey has estimated that there are 5,700 quads of accessible gas and 11,000 quads of thermal energy in the onshore Gulf Coast reservoirs without regard to economics (Wallace, 1978). Because the energy consumption of the United States is presently 80 quads per year (DOE/EIA, Energy Monthly, August, 1989), this resource could conservatively provide a portion of the domestic energy supply for many centuries. Geopressured-geothermal resources have been developed slowly because of the relative price advantage of other energy resources and the technical limitations on exploitation of this resource.

A goal of the DOE is to provide energy research, development, and utilization of stable, long-term, domestic energy. One area of research is the development of the geopressured-geothermal energy resource. In recent years, the DOE has been sponsoring the Geopressured-Geothermal Research Program and three DOE well operations with the assistance of the Idaho National Engineering Laboratory (INEL) to assess and evaluate the technical and production characteristics of this undeveloped resource. Current direction of the Geopressured-Geothermal Program is to develop new technologies to profitably produce electricity for \$0.07 to \$0.11/kWh (in 1990 dollars) by 1995 (DOE, 1989), plus investigating various process heat applications of the resource. A consortium for the utilization of geopressured resource was initiated January 10, 1990, at Rice University with sixty-five participants. This activity heralds the transition to commercialization for this undeveloped resource.

THE RESOURCE

A geopressured reservoir has a pressure gradient exceeding the normal hydrostatic gradient of 0.465 psi/ft in the Gulf Coast area. Pressures may approach lithostatic pressure and gradients have actually been measured up to 1.05 psi/ft in the Gulf Coast area (Figure 1.). Geopressured reservoirs are a normal phase of basin evolution. Present geopressured basins occur in many locations throughout the world and in many states in the U. S. (Figures 2. and 3.). Data shown are from Strongin (1981), and Meyer, (private communication, U.S.G.S., 1989), and Fertl et al.(1976).

Geopressured-geothermal resources have three energy forms: thermal, hydraulic, and methane gas. These three energy forms can also be converted to higher value forms of energy using available technologies. Thermal energy can be converted to electricity using a geothermal turbine. Hydraulic energy can be converted to electricity using a hydraulic turbine. Dissolved methane gas can be separated and sold, burned, compressed, liquefied, converted to methanol, or converted to electricity by fueling a turbine (Plum et al., 1989).

DOE GEOPRESSURED PROGRAM STATUS

The present program includes three geopressured wells: Gladys McCall Well in Cameron Parish, Louisiana; Pleasant Bayou Well in Brazoria County, Texas; and the Hulin Well in Vermilion Parish, Louisiana. The Gladys McCall is shut-in, being monitored for pressure buildup which is approaching the original pressure after extensive flowtesting. At the Pleasant Bayou Well a 1 MWe hybrid power system was constructed and is in operation. Power sales to Houston Power and Light passed the one-million kWh mark on January 8, 1990. The Hulin Well was reworked and short term flow-tested. It is presently shut-in, until additional funding for testing is available (Eaton et al., 1988).

Data concerning the wells, brine, and reservoir characteristics are provided in Table 1. Data sources include Eaton Operating Company Reports, DOE Program Reports, Geothermal Reviews, University of Texas at Austin, Louisiana State University, and Idaho National Engineering Laboratory.

The DOE also supports continuing research at the University of Texas at Austin (UTA), Louisiana State University (LSU), and the University of Southwestern Louisiana (USL). Research emphasis at this present time is on rock mechanics, well logging, geology, reservoir engineering, environmental monitoring, hydrocarbons content, and co-location of geopressured brine with medium to heavy oil in Texas, Louisiana, and Kern County, California.

A discussion of the Geopressured wells follows:

Gladys McCall

Data from the Gladys McCall reservoir testing and analyses represent the most comprehensive information available on long-term production and depletion of a geopressured-geothermal reservoir. This design well was drilled in 1981 to 16,510 ft, plugged back to 15,831 ft, and completed with 5-in. production tubing. After initial testing of a deeper sand zone, the well was perforated from 15,160 to 15,470 ft in Sand Zone No. 8. Testing of this zone was initiated in October 1983, and the well was shut-in October 1987. Initial static reservoir conditions were 12,784 psia and 298°F. Brine temperatures at the surface remained relatively constant at 268°F during most of the testing. Gas content in the brine ranged from 22.9 to 29.7 scf/bbl, depending on the separator pressure. Average salinity of the brine was 57,000 mg/L and total dissolved solids (TDS) content was 95,000 mg/L (IGT, private communication, 1988). During the testing period, production rates ranged from about 10,000 to 30,000 bpd, with an average production rate of about 17,000 bpd. A total of over 27 MM bbls brine and 23 scf/bbl natural gas were produced during this period; water was reinjected in a shallow saline aquifer without difficulty.

Based on the performance during testing, the UTA estimated the reservoir volume to be 4 billion barrels; UTA performed geological and rock mechanics studies to estimate the reservoir parameters of permeability, compressibility, etc. Reservoir calculations using these parameters indicated that the well could produce 40,000 bpd for 5 y with a final wellhead pressure of 1300 psi.

This projection may be optimistic, however, in view of the actual performance of the well during the testing period. During 1986, for example, the production rate declined from 31,000 to 25,000 bpd while maintaining the first-stage separator at 1000 psia. Projections of reservoir performance made by S-Cubed indicate that the well could sustain a production rate of 25,000 bpd for about 7 y with a wellhead pressure of 1000 psia at the end of that time. Anticipating that the well could sustain this production rate for 10 y is considered optimistic; anticipating 20 y is considered unrealistic. Similar projections for a production rate of 30,000 bpd indicate that the well could sustain this flow for 4 to 5 y before the wellhead pressure dropped below 500 psia.

However, it is important to note that analyses of pressure buildup data obtained since the well was shut-in indicate that the recovery is better than would have been anticipated from simulations based on drawdown data alone. This type of performance could affect long-term development alternatives.

Pleasant Bayou

The first design well drilled at the Pleasant Bayou prospect encountered completion problems that precluded its use as a production test well. Pleasant Bayou #2 was drilled to a depth of 16,465 ft, perforated in the Frio sand at 14,644 to 14,704 ft, and completed with 5-1/2 in. O.D. production tubing. Structural failures in the production tubing occurred on two separate occasions after the well was drilled in 1979, necessitating expensive rework operations. Initial static reservoir conditions were 11,168 psi and 302°F. The brine temperature at the surface under production is about 292°F. The brine's salinity averages 127,000 ppm and the gas produced at a separator pressure of 800 psi is 24 scf/bbl (Eaton Operating Company, 1989). Analyses of the gas indicate that about 85% of the gas is methane, another 6% is ethane and higher components, and the remainder is CO_2.

Early estimates of reservoir volume based on initial testing of the well were on the order of 2 billion barrels. Initial projections of brine production rate suggest the well could produce 20,000 bpd for 6 to 7 y and 30,000 bpd for 3 to 4 y. More recent projections (Riney, private communication, 1989) indicate the flowing wellhead pressure would decline to about 1200 psia after 5 y of production at 20,000 bpd. Since June 1988, the flow rate has been 18,000 to 20,000 bpd. Reservoir size based on UTA geological studies and reservoir modeling has been revised upward to 8 billion barrels (Riney, private communication, 1989) and may provide better estimates of reservoir performance.

It should be noted that production from the well is limited to 20,000 bpd because of sand production that occurred at brine production rates above 22,000 bpd. Sand production could be a short- or long-term problem and is currently one of the primary considerations in controlling well operations.

Hulin

The Hulin Well was drilled and completed to a depth of 21,546 ft by Superior Oil Company in 1978. After 19 months of gas production, the wellhead pressure had declined to 1000 psi. Subsequent efforts to restore production resulted in a packer or tubing failure and the well was abandoned. It was subsequently transferred to DOE to test geopressured-geothermal zones above the gas production zone.

Well log interpretations indicate that the well penetrated a massive geopressured zone from 20,010 to 21,120 ft. The first test zone was perforated after well rework in late 1988. The DOE Program initiated short-term flow testing in December 1989. These tests resulted in preliminary estimates of 34 scf/bbl and 7,200 psia shut-in wellhead pressure. These data are from the first three perforation zones, two at the base and one at the top of the 500 ft thick sand that is the major production target.

Estimates of resource parameters based on well logs and data obtained during rework indicated a reservoir temperature of 350 to 375°F, a brine salinity of 195,000 mg/L and a gas content of about 50 scf/bbl (Meahl, private communication, 1989). Occurrence of free gas has been suggested from well log interpretations (Dunlap, private communication, 1989). However, thus far the limited testing has not shown evidence of free gas.

Reservoir volume estimates as high as 14 billion bbls have been calculated based on probable fault block size and expected porosity (geological studies at UTA and Riney, private communication, 1989). These calculations are preliminary and may require more definition based on well performance.

The Hulin Well provides an example of using a reworked oil or gas well, rather than drilling a geopressured well. The production will be limited from 15,000 to 18,000 bpd by the well depth and tubing size restrictions. This wellbore limitation would be typical for depleted wells that are recompleted for geopressured-geothermal production. Thus, it is not reasonable to assume 40,000 bpd production from an existing reworked well even with excellent reservoir conditions.

South Texas

Higher temperature geopressured-geothermal resources, based on available data from the Wilcox Formation in the Mirando trend in south Texas, have reported temperatures of from 350 to 500°F (C. Kimmell, private communication, 1989). Typical geopressured conditions are found below 12,000 ft in the onshore Gulf Coast area but are encountered at 6,000 ft or less in the Mirando trend. The zones of interest in the Wilcox Formation are located at 16,000 to 18,000 ft with reported porosities of 26 to 30%. Gas content in the brine is reported to be high; 62 scf/bbl and 100 scf/bbl are estimated based on temperature, pressure, and total dissolved solids of 3,600 mg/L (INEL analysis, 1989; Negus-de Wys 1989; Kimmell, private communication, 1989).

There is no available information on the productivity of these zones. It is expected that, like Hulin, the production may be wellbore limited; thus, production rates of 20,000 bpd are reasonable. Little excess pressure at the surface is expected because of the depth of the resource and wellbore losses; therefore, utilization of hydraulic energy may not be realistic for these cases.

However, the Wilcox may contain some of the more promising geopressured-geothermal reservoirs due to the higher temperatures and pressures, low total dissolved solids, and potentially high gas contents. The south Texas Wilcox Formation should be tested with dedicated geopressured-geothermal wells.

RESEARCH

Supporting research for the Geopressured-Geothermal Program is performed at Louisiana State University (LSU). The University of Texas at Austin (UTA), and the University of Southwestern Louisiana (USL). Research at LSU in Environmental Monitoring, Geological Studies, and Co-location of brine and heavy oil will be reviewed by Dr. Charles Groat. Lawrence Berkeley Laboratory has been added to the research team this year and will be working on modeling prediction of reservoir behavior. Additionally, the INEL is developing four feasibility reports on utilization of the geopressured resource. These reports include thermal enhanced oil recovery, direct use, energy conversion to electricity, and supercritical fluid processes.

The UTA research includes work in rock mechanics, logging, geological studies, co-location of brine and heavy oil, and reservoir modeling carried on by S-Cubed under a subcontract to UTA. These areas of research are coordinated by Dr. Myron Dorfman.

Dr. Henry Dunlap's Logging Research this past year has focused on the effect of boron concentrations on the porosity log, and interpretations of the Hulin Well logs. Numberous publications have resulted from this research, and the UTA Logging Consortium has received support through this work.

Dr. Ken Gray has reported the following accomplishments in rock mechanics research:

1. Published a paper at the Energy Sources Technology Conference on a finite element wellbore stability model.

2. Obtained cyclic uniaxial compaction, triaxial compaction, and pore-pressure drawdown compaction data for use in reservoir-mechanics modeling.

3. Developed apparatus and procedures for determining tensile strength of geopressured-geothermal sandstones at elevated pressures.

4. Designed, built, and implemented a pore pressure loading system for use in apparatus to determine strength and deformation moduli of geopressured-geothermal cores under in-situ conditions of three-dimensional stresses.

Dr. Jay Raney, P.I. for Geological Studies at UTA Bureau of Economic Geology, has reported data on the following:

1. Bottomhole pressure versus cumulative brine production at the Pleasant Bayou Test Well.

2. Bottomhole pressure versus cumulative gas production at Pleasant Bayou Test Well.

3. The relationship of reservoir pressure (p) to gas compressibility (z), for depletion type, aquifer support, and linear extrapolation curves. This represents a decline curve used commonly to estimate recovery factor and the reservoir drive mechanism.

4. Upper Wilcox Geothermal Fairways and Heavy Oil Reservoirs.

Descriptions of this work were prepared by Mr. Scott Hamlin (UTA):

"The decline in flowing bottomhole and static reservoir pressures at the test well was plotted as a function of cumulative brine and gas production. The pressures have declined by about 300 psi from their original levels during a cumulative brine production of 7 million barrels and a cumulative gas production of 162.2 million cubic feet. Straight line extrapolation of the flowing pressure decline trend to 7,000 psi (below which economic gas production rate may not be sustainable) indicates that 38 million stb (stock tank barrels) of brine and 1.1 billion scf (standard cubic feet) of gas will be recovered by that time.

Approximatly 6 billion barrels of brine in-place has been estimated at Pleasant Bayou in the C-Zone (Hamlin and Tyler, 1988). With a gas-brine ratio of about 24 scf/stb (standard cubic feet/stock tank barrel) this translates into a gas volume of 144 billion cubic feet. Therefore, when the pressure has declined to 7,000 psi the cumulative brine and gas recovery would be less than 1% of the original estimated volume in-place. However, additional factors will influence ultimate recovery. These factors include: the effects of aquifer recharge, changes in formation and fluid compressibility with pressure depletion, free-gas movement and shale dewatering. Interplay of these factors has not been fully determined in the early depletion history of the Pleasant Bayou reservoir."

"The plot of p/z (reservoir pressure/gas compressibility factor) versus cumulative gas production represents a decline curve used commonly to estimate recovery factor and reservoir drive mechanism. Most geopressured reservoirs do not exhibit ideal linear depletion characteristics. Aquifer recharge, shale dewatering and compressibility changes introduce non-linearity in the decline curve. Evaluation of production history from other geopressured gas reservoirs in the vicinity of Pleasant Bayou reflect some common factors: (1) deliverability is high in early life due to gas and brine expansion, then drops off sharply as reservoir pressures decline, (2) after depletion to hydrostatic pressure, the decline is often flat with increased co-production of water, due to water drive from a communicating aquifer. The decline at Pleasant Bayou is still at an early stage and its final character will be determined by a combination of factors outlined above."

"In South Texas heavy oil reservoirs in the Jackson and Yegua Formations (Eocene) overlie Wilcox Group (Paleocene to lower Eocene) geopressured-geothermal sandstones. The reservoir characteristics of various parts of the deep upper Wilcox geopressured-geothermal zone have been summarized using data from previous University of Texas at Austin Bureau of Economic Geology Studies (Gregory and others, 1980; Bebout and others, 1982). Areas with the highest temperatures and pressures occur downdip (southeast) and in the northeast. These downdip areas have low salinities, but porosities are also low. Higher porosities and thicker sandstones generally coincide with lower temperatures and pressures. However, in general, the entire region outlined has fair to good geopressured-geothermal potential."

The earlier described characteristics of the geopressured resource in the Mirando Trend (hotter, more gas, lower TDS) are from unpublished data made available to the author.

The S-Cubed reservoir modeling work was reported by Dr. David Riney (Riney, private communication, 1990).

During FY 1989 S-Cubed developed a three-dimensional heterogeneous reservoir simulation model for the Pleasant Bayou geopressured resource. The model employs a reservoir configuration, based on geologic studies by the UTA Bureau of Economic Geology, consisting of a main high-porosity sandstone layer sandwiched between low-porosity layers which represent thinner, more isolated sandstones that are considered to comprise the "remote volume" of the reservoir. BEG estimates the total C-Zone reservoir volume to be about 8.0 billion barrels and concludes that most of the sandstone in the remote volume is interconnected by circuitous flow paths around shale interbeds and internal faults with the main reservoir sandstone in which the well has been perforated. The effective pore volume of the C-zone is estimated to be between 6.2 and 6.6 billion barrels.

S-Cubed synthesized information from various researchers to develop the input parameters required to construct a reservoir simulation model within the BEG configuration. The model employs rock properties measured on core samples by the UTA rock mechanics group, fluid properties measured at various laboratories, data from the current production testing of Pleasant Bayou Well No. 1 by IGT/EOC, and S-Cubed's interpretation of pressure transient tests at the well during 1980 and 1988-89. The hydrologic boundaries detected by the pressure data were correlated with the geologic faults mapped by BEG.

Recently, the S-Cubed Pleasant Bayou reservoir simulation was extended in time using the test well production history from May 26, 1988 (test day 0) through January 31, 1990 (test day 584). The model continues to match the reservoir response over the full 584-day production history. The data points include the bottomhole measurements during May 26-June 1, 1988 multi-rate drawdown/buildup test and values estimated from wellhead recordings during 1988-1990 production testing using a calibrated wellbore flow model.

The reservoir model will be used as a tool for synthesizing and integrating new data from measurements being made under the continuing test program being conducted by DOE at the Pleasant Bayou site.

During 1989-1990 the total available data sets from the Gladys McCall test well have been re-evaluated. Analysis of the pressure transient data from the four separate downhole tests has shown that both the drawdown and buildup portions of the Reservoir Limits Test infer a near-well transmissivity of kh = 44,090 md-ft, whereas all three subsequent tests infer a transmissivity of kh = 28,340 md-ft for Sand Zone 8. Analysis of the change in the wellhead pressure, just prior to and just after shut-in following periods of stable flow, infer values of the skin factor that are related to the effective stress on the formation adjacent to the wellbore. It is reconfirmed that when scale inhibitor pills were injected the skin factor also abruptly increased and that the most plausible explanation for the change in near-well kh value is plugging of Sand Zone 8 below the shale stringer present near the center of the zone (since November 1984). Re-calibration of the wellbore flow model using all available profile data has allowed better estimates of bottomhole pressure values from wellhead recordings.

The depositional model for Gladys McCall provides a geological basis for much larger reservoir lateral dimensions than were assumed in earlier simulation calculations. The lack of information for the actual reservoir properties away from the test well require that the simulated production history be repeated in a series of calculations in which the assumed values were varied and the final choices represent "effective reservoir parameters" that provide the best history match. The enlarged reservoir with heterogeneous properties has permitted a good match to the complete data available.

The connected pore volume for the enlarged reservoir model is 7.8 billion barrels. This value may be compared with the estimate of 2.5 billion barrels made in August 1985 and used in earlier simulations. In contrast to the Pleasant Bayou case, the geological information at Gladys McCall was too limited to allow the construction of a reservoir model configuration with a pre-test estimate for the connected pore volume.

Drs. Dean Keeley, John Meriwether, and Mr. William Koon of the University of Southwestern Louisiana are conducting geochemical research on the fluids produced from geopressured wells. Specifically, they are studying the dynamics of the production of dissolved aromatic hydrocarbons from the various wells and the physical and chemical characteristics of the nearly 100 compounds that make up the dissolved aromatics.

In addition to this basic work, the research team has recently developed two devices which have the potential to be applied in other research and industrial endeavors.

The first of these devices is the gas scrubbing system installed at the Pleasant Bayou Well. The inlet gas is dispersed through fritted metal into a high molecular weight oil. The compounds of interest from the gas are partitioned in the oil and vapor until they reach equilibrium. After collection, the samples are sealed and returned to the laboratory where head space/gas chromatographic analyses are used to determine the collected compounds. The vapor pressure of the collected compounds can be increased by raising the temperature of the oil during analysis to detect compounds which had very low concentrations in the original gas. This system can be used to collect and detect compounds in the air or other gaseous media. The system should find application in environmental analyses.

One of the chemical parameters that is required for the study and operation of geopressured wells is the pH of the flowing brine (it changes rapidly when a sample is removed to atmospheric pressure). The research team including Chen Jie, a graduate student from China, is testing a new pH probe based on ISFET technology (Ion Sensitive Field Effect Transistors). These probes are rapidly coming into general laboratory use, but have not been tested under the harsh environment found in geopressured brines. A high pressure test cell with a heater will be used to simulate well conditions. The research group has already tested probes at various temperatures (at low pressures) in the experimental setup. The probes have so far performed very well.

The ISFET probes should also find application in many industrial environments where the pH must be measured in harsh process streams.

INDUSTRIAL CONSORTIUM FOR THE UTILIZATION OF THE GEOPRESSURED-GEOTHERMAL RESOURCE

An industrial consortium planning meeting was held in September, 1989, at Eaton Operating Company, Houston, TX. This planning meeting was attended by 35 participants, fifteen of whom were from industry. On January 10, 1990, the first consortium meeting was held to present industry cost-shared proposals for utilization of the resource. Sixty-five participants convened at Rice University, Houston, TX, two-thirds of whom represented industry. Cost-shared proposals included: (1) thermal enhanced oil recovery, (2) integrated systems (agriculture/aquaculture), (3) conversion of thermal and hydraulic energy, and (4) use of supercritical water for detoxification of pollutants. Areas for resource utilization and cost-shared proposals are shown in Figure 4. The proceedings from this consortium have been compiled into two volumes that are available to interested parties. Direct use projects are covered in the paper by Mr. Ben Lunis; Use of Supercritical Fluids by Ms. C. Rofer; Thermal Enhanced Oil Recovery by C. Kimmell, and Modular Conversion by Mr. K. V. Nichols.

A proposed consortium charter was reviewed and made available for comments and discussion. Comments are due to Dr. J. Negus-de Wys at INEL by April 30, 1990, after which a final draft will be sent out for approval and signatures. Consortium funds will be escrowed with the Geothermal Resource Council in an interest bearing account with a moderate fee to GRC.

Interest and response to the January consortium meeting have been excellent, with an average of two new calls per week. The mailing list is approaching 200. Dr. David Goldstein of the Naval Surface Warfare Center (NSWC) has submitted a topic to the Naval SBIR to develop a Nitinol (shape memory alloy) heat engine to be tested on a geopressured-geothermal well. The Western Resources Technology Company has obtained a geopressured well in Calcasieu Parish near Hayes, LA. They have obtained the funds to work over the well and plan to develop the gas, install a heat transfer system, and try secondary hydrocarbon recovery. This is a direct spinoff from the Industrial Consortium activities. DOE will make technology available through the Oregon Institute of Technology, Eaton Operating Company, the Ben Holt Company, and the Institute of Gas Technology.

FUTURE PLANS

The next meeting of the consortium is Tuesday, September 11, 1990, at the University of Texas. The organization sequence for the Consortium is shown in Figure 5. Interested industries or individuals may contact Dr. J. Negus-de Wys at the Idaho National Engineering Laboratory (208/526-1744) or Dr. Myron Dorfman at University of Texas at Austin (512/471-7265).

Maps showing the location of known geopressured-geothermal reservoirs in Texas and Louisiana Gulf Coast are shown in Figures 6 and 7. Theoretical locations of geopressured basins in California are shown in Figure 8 (Berry, 1977). Geopressured-Geothermal wells in the present program will be made available to industry for utilization projects in the next two years.

An estimate of the percentage of wells producing from geopressured reservoirs along the Texas Gulf Coast was made in 1987 by Timothy Jackson and Malcolm Light then at the UTA Bureau of Economic Geology. They concluded from 1983 data that 2% of the producing wells were producing from geopressured reservoirs; however, some of those reservoirs would not be considered viable. The data base included 50,938 actively producing wells, of which 989 gas wells and 35 oil wells were producing from geopressured reservoirs. By Texas State law, inactive wells must be plugged and abandoned. Thus, to obtain wells for utilization in the geopressured program it would be necessary to negotiate during the latter term of production or prior to plugging and abandoning. These numbers would suggest that at the 1983 drilling level an estimated 2,000 wells might be among candidates for utilization in the Texas and Louisiana Gulf Coast on-shore area with 1989 total drilling effort about 10% of that in the 1983 study, this estimate is reduced to 200 wells for 1989 alone.

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Table 1. Wells, Brine, and Reservoir Characteristics for the Three Department of Energy Wells[1]

	Gladys McCall	Pleasant Bayou	Hulin[2]
Depth of Reservoir (ft)	15,831	16,465	21,546
Maximum Flow Rate (bbd)	40,000	25,000	15,000
Bottomhole Pressure (psia)	12,784	9,800	18,500
Flowing Wellhead Pressure (psia)	2,000	3,000	3,500[3]
Bottomhole Temperature (°F)	298	302	360
Flowing Wellhead Temperature (°F)	268	292	330
Gas/Water Ratio (scf/bbl)	27	24	34
Methane (% of gas)	85	85	93
CO_2(% of gas)	9.7	10	4
Estimated Reservoir Size (billion bbls)	4	8	14
Total Dissolved Solids (mg/L)	95,000	127,000	195,000
Chlorides (mg/L)	57,000	70,000	115,000

[1] Resource Estimates

[2] Short Term Testing Only

[3] 7,500 psia Shut-in WHP

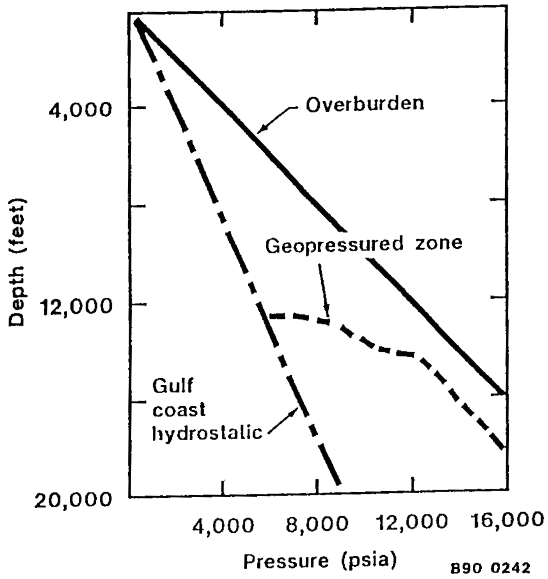

Figure 1. Geopressured-Geothermal Zone Characteristics

Figure 2. Location of Geopressured Basins, Heavy Oil Fields, and Major Tar Sands in the U.S.

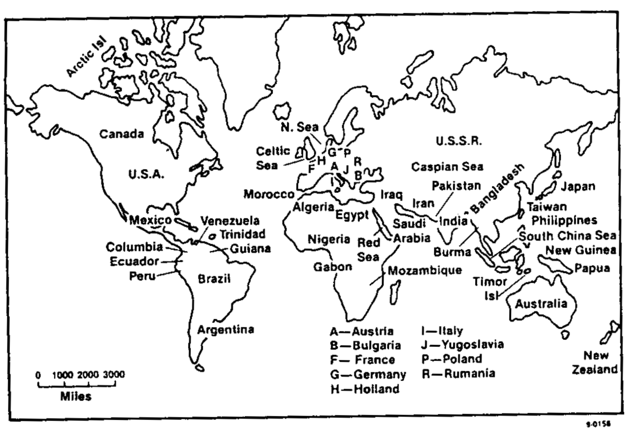

Figure 3. Worldwide Occurrence of Abnormal Formation Pressures (after Fertl, 1976).

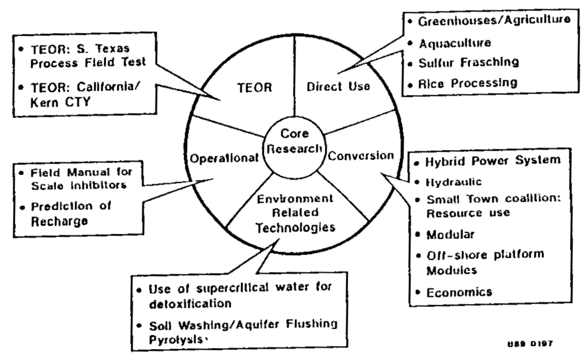

Figure 4. Utilization of the Geopressured-Geothermal Resource

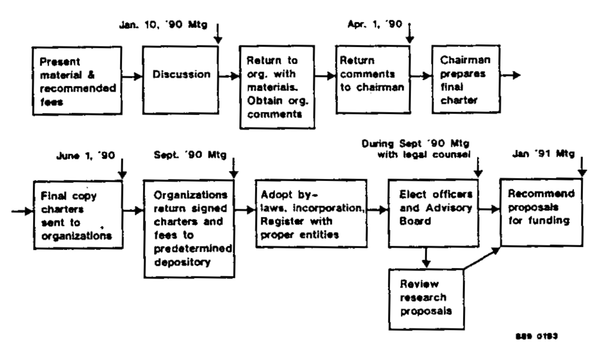

Figure 5. Sequence of Organization for the Industrial Consortium

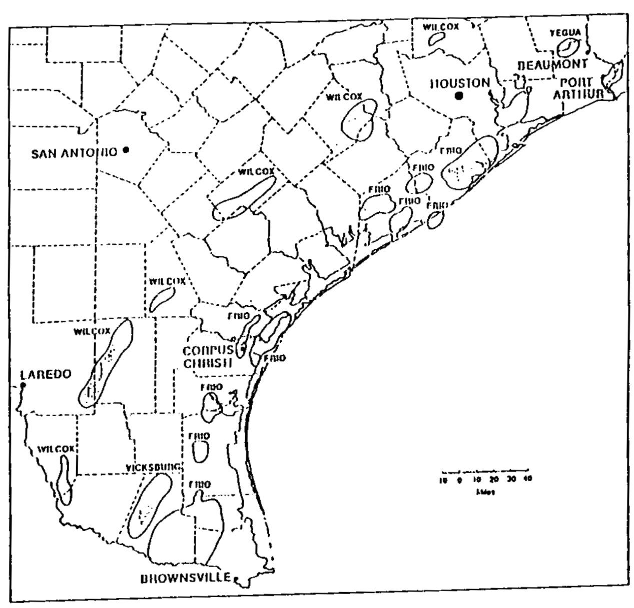

Figure 6. Geopressure Aquifers in Texas (UTA-BEG, 1990, personnel communication).

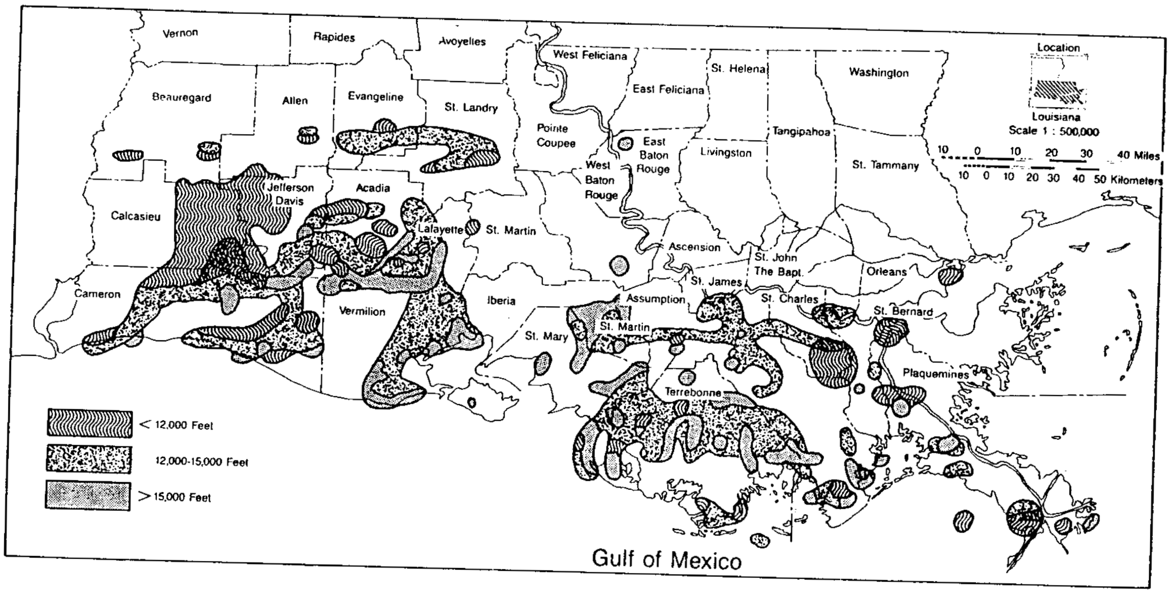

Figure 7. Geopressured Reservoirs in Louisiana Shown in Three Depth Ranges (LSG, 1990, private communication).

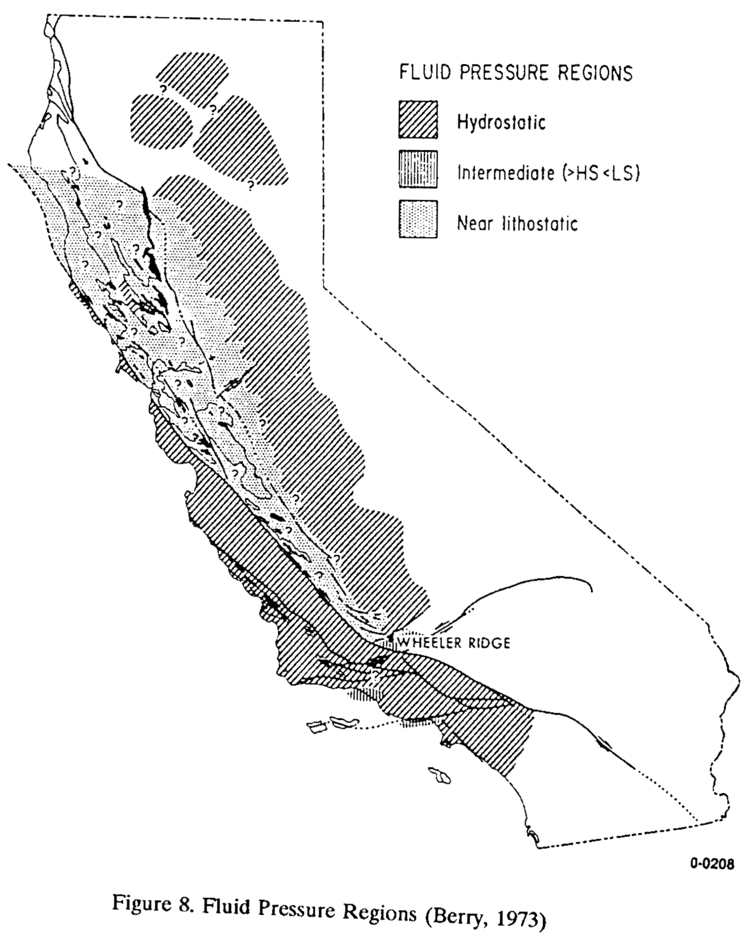

Figure 8. Fluid Pressure Regions (Berry, 1973)

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Assessment of Geopressured-Geothermal Resources for Near-Term Utilization

by

C. G. Groat, Chacko J. John, Donald A. Stevenson
Louisiana Geological Survey

ABSTRACT

There have been several assessments of the geopressured-geothermal resource base ranging from grandiose estimates of an almost boundless source of energy to very conservative forecasts tied to a very limited capability to produce only the methane component. Geologic studies and the test well programs supported by the Department of Energy have provided a better defined geologic framework for determining the true production potential of the thermal, kinetic, and dissolved methane components of the resource. New geophysical data are making it possible to complete the geologic analysis of the reservoirs at two of the designed test well sites which will aid in refining reservoir performance models. This should facilitate a more quantitative and accurate extrapolation of designed well test results to other reservoirs in the Gulf Coast area, thereby fostering realistic near-term resource utilization projections.

Production of geopressured brines at the Gladys McCall test well in coastal southwestern Louisiana had reached 27 million barrels when flow testing was discontinued in October, 1987. Reservoir modeling has been somewhat hampered by a lack of detailed geologic data on reservoir extent, geometry, and textural variations. Only limited production has occurred at the Hulin site near Erath, Louisiana where the deepest, hottest, and potentially largest geopressured reservoir system has been penetrated. The geologic understanding of this reservoir is also limited by the lack of other wells reaching to or beyond the depth of the reservoir of interest. Proprietary modern geophysical data from both areas are being used to more accurately portray the extent of the tested reservoirs and their relationship to other sand bodies.

Interest in the dissolved methane component has varied considerably during the period of DOE-supported investigations; during the period of highest natural gas prices in the early 1980's it far outreached interest in the geothermal energy. Given the increased emphasis being placed on natural gas in the development of energy strategies for the future, the estimated 5700 Tcf of speculative geopressured dissolved gas resources should be reassessed and data bases consolidated. This is necessary to bring our understanding of the geopressured gas resource onto a par with tight gas and unconventional gas resources that have received more attention in recent years.

Environmental monitoring at test well sites continues to demonstrate a lack of contemporaneous adverse subsidence, fault activation, and water quality impacts related to brine production and disposal. This good news should add to the appeal of the resource in a time of decreasing tolerance of energy-related adverse environmental impacts by the public.

INTRODUCTION

Assessments of the magnitude of the geopressured-geothermal resource have ranged from a seemingly infinite source of energy to one of limited scope tied to small single-well systems. Interest has varied from very high during the energy "crisis" that followed the imported oil supply disruptions of the seventies when both the thermal and dissolved methane components were sought after, to very low during the oil and natural gas glut of the mid to late eighties. Current interest is high and growing as a variety of applications of the energy is becoming appealing to a diverse group of users.

The geologic and engineering parameters of the resource and the reservoirs (aquifers) that contain it must be understood if there is to be any realistic evaluation of the general resource potential or the producability of any single reservoir system. While assessments conducted over the past several years have improved our understanding of the magnitude of the resource, we are still somewhat limited in our definition of the extent and physical properties of the most prospective geopressured-geothermal reservoir systems. This is largely due to their great depth, lack of enough penetrations to allow well-to-well correlations, and inability of geologists studying the reservoirs to buy seismic data. This latter situation has improved as DOE funding has allowed the purchase of seismic information for two deep designed test wells in Louisiana. These data are currently being interpreted and combined with existing information to improve our understanding of deep, thick geopressured sands at the Gladys McCall and Hulin sites (Figure 1).

Gladys McCall Prospect

The Technadril-Fenix and Scisson-Department of Energy (TF&S-DOE) Gladys McCall #1 well is located in Section 27, T. 15 S., R. 5 W., east of the town of Grand Chenier in a marsh area about 2.5 miles south of Louisiana 82 (Cameron Parish, Louisiana). It was drilled in 1981 to a depth of 16,510 ft and plugged back to 15,831 ft. The well location was based on preliminary regional and local geologic studies of this area done by the Louisiana Geological Survey (Bebout, 1982) and by Magma Gulf Company. These studies showed that this area had some of the thickest geopressured sand sections in South Louisiana. The occurrence of fluvio-deltaic clastic regression across the shelf break was postulated by Brunhild (1984) as a possible reason for the greater thickness of sandstones in this area. The Gladys McCall test well, drilled in the Miocene geopressured trend, penetrated the Miocene section from 4,000 ft to total depth and is geopressured below 14,400 ft. Approximately 1,150 ft of net sand was observed in this well from 14,412 ft to 16,320 ft.

The log correlations are relatively straightforward up to 15,000 ft, after which they become more complex. Two key microfossils, Cristellaria A (11,100 ft) and Siphonina davisi (16,440 ft), mark the upper and lower boundaries of the target section in this well and are characteristic of the

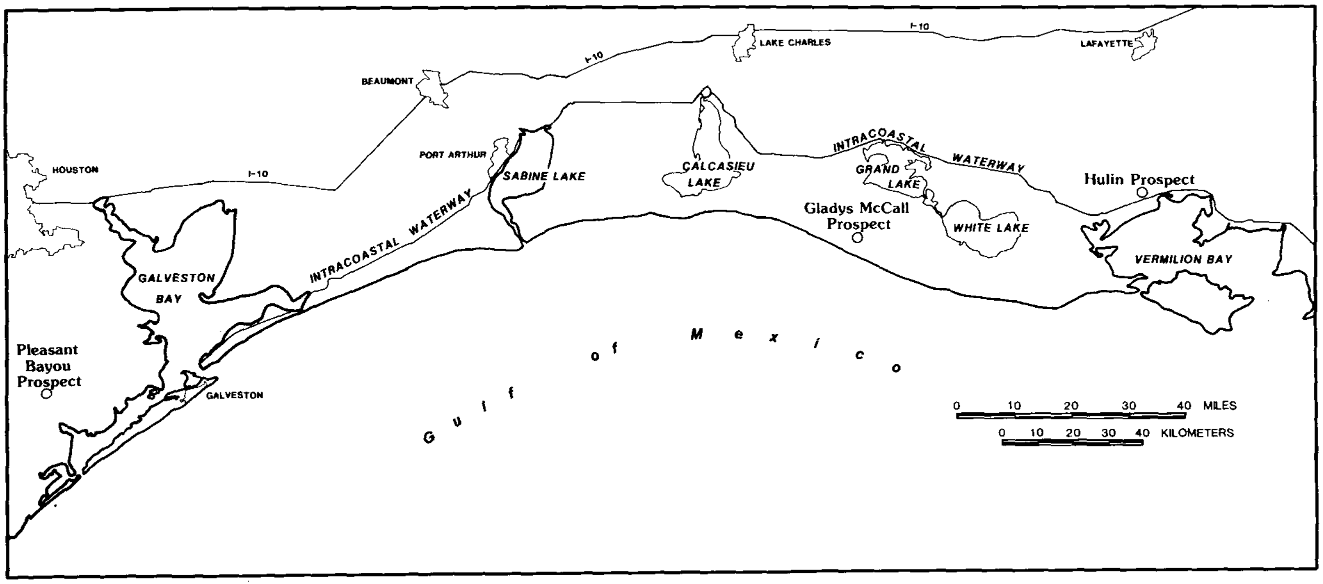

Figure 1. Map showing location of the three current geopressured-geothermal prospects: Gladys McCall and Hulin wells (Louisiana) and Pleasant Bayou well (Texas).

A structure map of the prospect area is shown in Figure 2 (Technadril-Fenix and Scisson, 1982). The geopressured reservoir system is fault controlled to the north and south, but because of a lack of deep-well ontrol, the reservoir's east-west dimensions are poorly defined. Because the test well is located in the Rockefeller Wildlife Refuge area, available seismic data are limited. Interpretation of seismic data will enhance the understanding of the areal extent of the reservoir and provide more accurate representation of faults on the structure map. A dip cross section of the area passing through the Gladys McCall test well is shown in Figure 3.

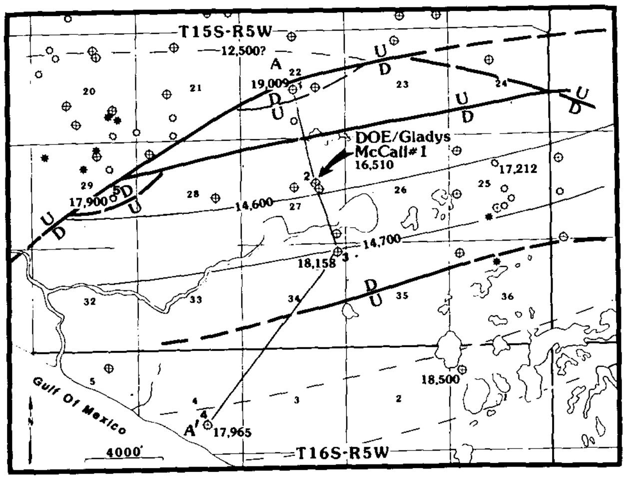

Figure 2. Structure map of the Gladys McCall prospect area (adapted from Technadril-Fenix and Scisson, 1982). A-A' is the line of cross sectior for Figure 3.

outer shelf and upper slope environments, respectively. These findings indicate that the sediments were deposited in a shelf environment by distributary channel systems. Details of the log correlations are provided in Bebout (1982) and John (1988).

The target section extending from 15,160 ft to 15,860 ft is made up of interconnected channel and point-bar sandstones which originated within the same channel system and which represent a genetic unit of sandstones. Hence, though on the electric log they may appear as possibly different sandstones, they may behave as a single interconnected body allowing fluid communication during high-volume brine production. For purposes of reservoir modeling, using the thickness of genetic units of sandstones rather than what appear to be separate reservoir sandstones on the logs may provide a more accurate estimate of reservoir production and longevity (John, 1988). At the time of being shut in, the well had produced over 27 million barrels of brine and 676 million scf of gas from the brine. The gas-separated brine was disposed of by subsurface injection through a brine disposal well in proximity to the test well. The brine disposal well was drilled in 1965 to test for hydrocarbons to a depth of 15,598 ft and was later re-entered and completed at 3,514 ft for use as a brine disposal well. During the test period the well was flowed at various rates ranging from 36,500 to 5,000 bbls/day for different lengths of time. The average rate of production was 20,000 bbls/day. Scaling problems encountered during initial production were successfully overcome on two occasions by injection of phosphonate pills. Long-term, high-volume brine production can cause fractures and subsurface faults related to volume depletion and stresses that may be

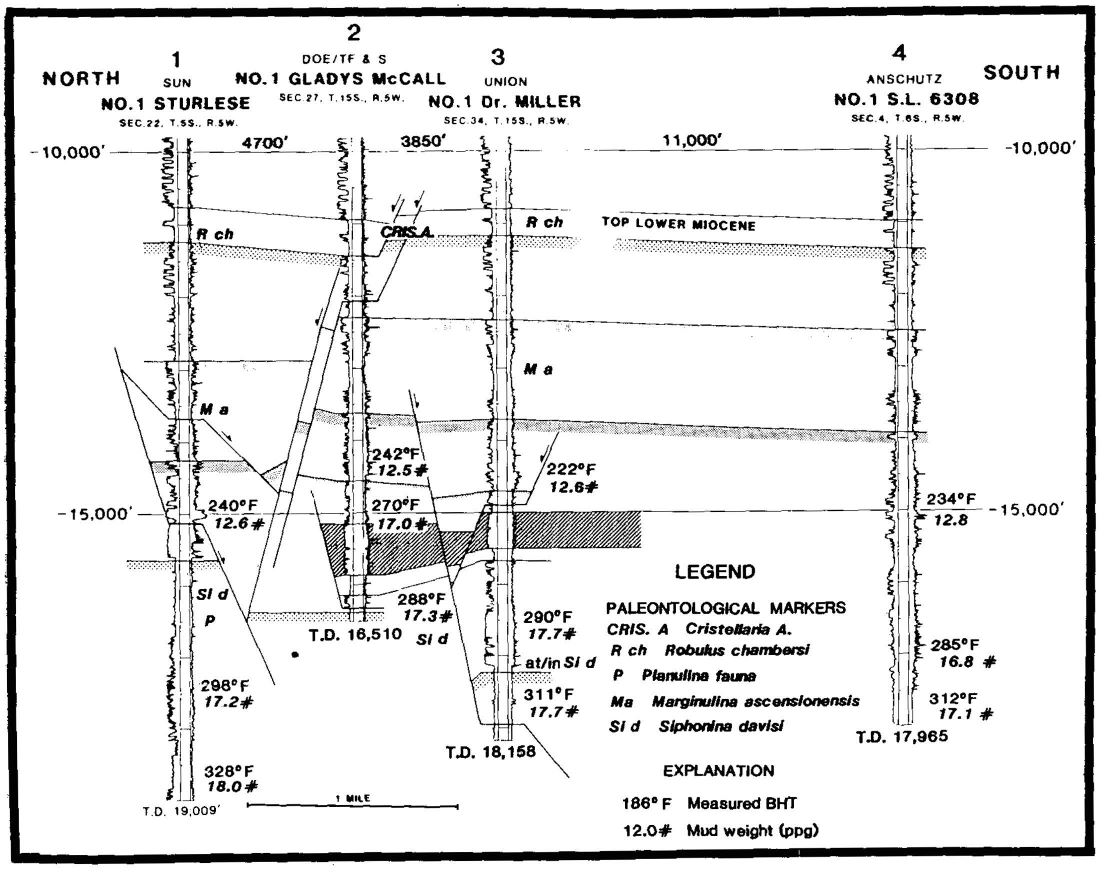

Figure 3. Dip cross section (north-south) of the prospect area. The line of cross section is shown in Figure 2 (adapted from Bebout et al., 1983).

associated with production. This could further facilitate fluid flow between reservoirs that may have been originally separate and hence could enhance the producing reservoirs longevity.

Hulin Prospect

The Superior Hulin #1 well is located in Section 2, T. 14 S., R. 4 E., approximately seven miles south of the town of Erath in Vermilion Parish, Louisiana. This exploration well was drilled by Superior Oil Company in 1978 to a depth of 21,549 ft. The maximum recorded temperature was 338°F. The well produced 0.3 BCF gas during a period of 19 months from perforations between 21,059 ft and 21,094 ft. Because of production problems and an apparent packer or tubing/casing failure, Superior Oil Company abandoned the well and it was later transferred to DOE for testing under its geopressured-geothermal program. In November 1988, Eaton Operating Company, Inc., Houston, Texas, under contract to DOE, began operations to clean and recomplete the well, to correct problems that were causing a pressure build up, for use as a geopressured-geothermal test well. The well was completed in February 1989 and plugged back to 20,725 ft, just below the geopressured sand section of interest. Long-term testing of this well is scheduled to begin late in 1990.

Figure 4 shows a structure map of the Hulin prospect area contoured at the top of the lower Planulina section (approximately 15,400 ft in the Hulin well). As seen on the map, the Erath field is situated to the north of the Hulin well, the Boston Bayou field is located to the south, and the Tigre Lagoon field lies to the northeast. All these fields are separated from the Hulin prospect by major down-to-the-basin growth faults. The western limit of the reservoir is presently undefined. Figure 5 is a dip cross

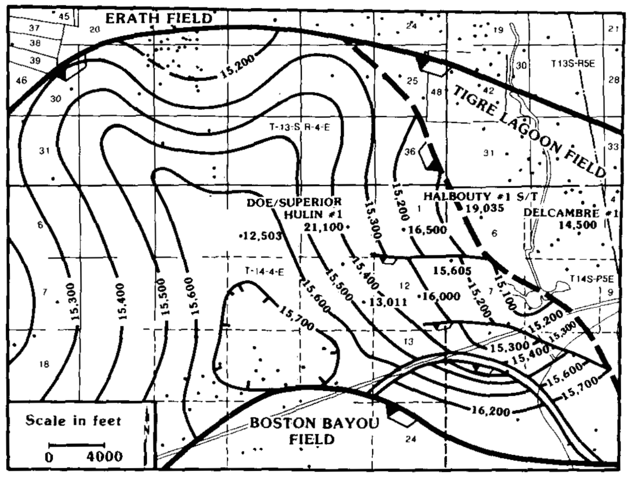

Figure 4. Structure map of the Hulin prospect area (Vermilion Parish, Louisiana) contoured at the top of the lower Planulina section in the Hulin well (adapted from U.S. Department of Energy, 1986).

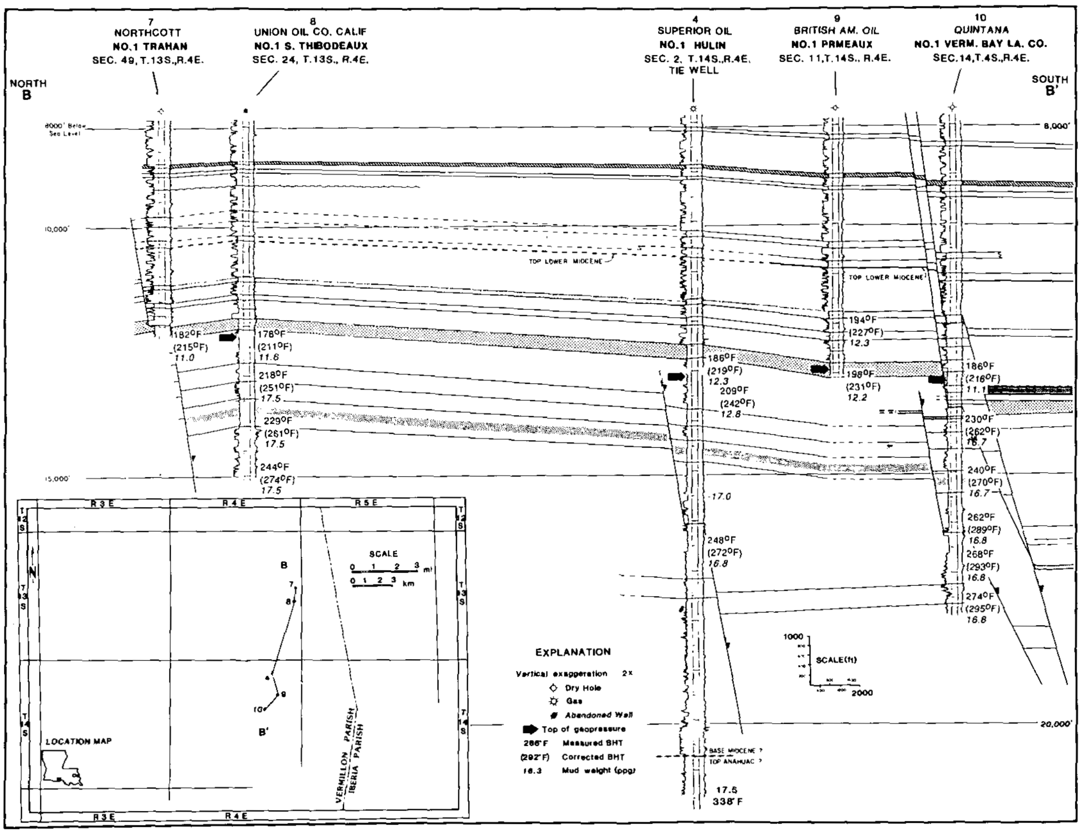

Figure 5. Dip cross section B-B' through the DOE/Superior Hulin #1 well (adapted from McCulloh and Pino, 1983).

section through the Hulin prospect area. The Hulin well is the deepest well in the area, and sections correlatable to the target section in the Hulin well have not been penetrated by any other wells in the vicinity. It is therefore difficult to determine details about the depositional environment and stratigraphic-structural relationship of the geopressured target section. Recently purchased seismic data over the Hulin prospect area combined with available geologic data are providing a better understanding of the structure, the reservoir limiting boundaries, and the depositional environment of the Hulin geopressured-geothermal reservoir.

The bottom 20 ft (20,670-20,690 ft) of the reservoir system have been perforated, and initial production testing will be from this section. As testing proceeds and each zone is completely evaluated, the section gradually will be perforated upwards. Regional geologic work done by Conover (1987) and Hamlin and Tyler (1988) have indicated that the geopressured sands to be tested in the Hulin well (20,120-20,690 ft) represent submarine canyon sandstone facies. It is also possible that the sands are part of a delta deposited in an unstable (subsiding) shelf area--which could account for the thickness of the sandstone.

Results of log interpretation by the University of Texas, Petroleum Engineering Department, indicate that the sandstone section to be tested may contain free gas in addition to solution natural gas at several zones within the section. Additional free gas will provide more income from gas sales, making the operation more economic. Other possible near-term utilizations of such geopressured-geothermal resources include enhanced secondary hydrocarbon recovery using methane depleted brine, direct heating, and electricity generation.

ENVIRONMENTAL CONSIDERATIONS

Concern over the environmental effects of the production and disposal of large volumes of geopressured brine led to the design and implementation of a comprehensive monitoring program to parallel the testing at designed test wells. Subsidence, fault activation, and contamination by produced brines are the chief issues addressed by the environmental monitoring program. Periodic geodetic surveys, continuous microseismic monitoring, and periodic water quality testing of ground and surface waters have been carried out prior to and during testing. The results to date have been very positive: no significant detrimental impacts have been measured. This is encouraging news in a time when the environmental consciousness of the populace is high and the tolerance for energy-related environmental damage is very low.

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GEOPRESSURED-GEOTHERMAL ENERGY FIELD OPERATIONS

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(Eaton Operating Co., Inc., Houston, TX)

ABSTRACT

America's increasing dependence on foreign energy sources and the national environmental initiatives based on the increasing awareness of the need for protection of environment have led to the Department of Energy's (DOE) development of domestic U.S. alternative energy programs.

One of these programs is the current geopressured-geothermal five year program conducted at three sites in Louisiana and Texas. Excellent results have been obtained in reaching the objectives for this well operation and energy conversion project, which are:

- To determine geopressured-geothermal reservoir sizes and drive mechanism by long-term, high volume flow testing.
- Prove long-term injectability of large volumes of spent brine.
- Develop technology for automated operation of geopressured-geothermal production systems.
- Develop modified scale inhibitor treatment procedures.
- Develop technology to produce power economically from the geopressured-geothermal resource.

INTRODUCTION

Over the past 20 years, several factors have shaped America's opinion of its energy requirements. Presently, two factors are dominating most people's minds. These are America's increasing dependence on foreign energy resources and the increasing awareness of the need for protection of the environment.

Currently, America is very concerned with its increasing dependence on foreign energy resources, particularly foreign oil. In recent years, the United States petroleum market has been flooded with inexpensive crude from foreign countries. Many American petroleum producers are struggling greatly because of this low cost oil and high operating costs, and in many cases, have gone out of business. This is resulting in the United States becoming more dependent on foreign oil. Currently, approximately 50% of our oil is being imported. One popular opinion is that foreign petroleum producers will continue to export inexpensive crude to the United States, until America's dependence is great enough that it will be very difficult to shift back to domestic petroleum. At that point, it is believed that the price may be increased greatly. This scenario puts America in a very insecure position for controlling its own energy destiny. Therefore, great efforts are being made in the search for economic domestic U. S. energy resources.

The search for these resources is made more challenging by national initiatives to protect the environment. There are many past examples of how production of energy resources has adversely affected the environment. Pit mining of coal, tanker oil spills, emissions from the burning of fossil fuels, and the disposal of hazardous byproducts constitute a few of these concerns. Therefore, America's search has been for alternative energy resources that limit the impact on the environment.

The United States Department of Energy (DOE) has focused its efforts toward developing a number of alternative energy sources. Included in this effort are Solar Energy, Energy from Municipal Waste, and Geothermal Energy. The purpose of this paper is to describe DOE's field efforts to develop a form of Geothermal Energy that is also abnormally high pressured (geopressured).

Geopressured-Geothermal Energy is produced in the form of a high pressure and temperature fluid (brine) which has natural gas dissolved in solution. This brine exists in formations deep under the earth's crust, at depths ranging from ±12,000' to ±20,000' (±3,657.6 to ±6,096m). The brine temperatures generally range from 250° to 400°F (121.1° to 204.4°C), and the bottom hole pressures range from ±7,800 to ±18,500 psi (±53.79 to ±127.55 Pa). The brine is removed from the earth by production from deep wells. This geopressured-geothermal resource exists in a large number of locations worldwide. Estimates for the amount of geopressured-geothermal energy available in the Gulf Coast region of the United States of America are as follows: 6,000 quads of methane and 11,000 quads of thermal energy.

The DOE's geopressured program has focused on determining the feasibility of producing and utilizing fluids from the geopressured resource. The ultimate goal is to lower the costs of power production to a level where development of the resource is economically feasible. To do this, the current five year program has been divided into two different areas: (1) Well Operations and Energy Conversion; and (2) Geoscience and Engineering Support. The operating data obtained in the Well Operation and Energy Conversion projects is recorded and analyzed and passed onto the Geoscience and Engineering Support projects for additional analysis. The present DOE Well Operation and Energy Conversion project is carried out under a contract to Eaton Operating Company, Inc. (Houston, TX) and their subcontractors: the Institute of Gas Technology (IGT) (Chicago, IL), and The Ben Holt Co. (BHC) (Pasadena, CA). The Geoscience and Engineering support is provided by The University of Texas at Austin, S-Cubed (LaJolla, CA), Louisiana State University (Baton Rouge, LA), University of Southwest Louisiana (Lafayette, LA), and EG&G Idaho, Inc. (Idaho Falls, ID).

The objectives for the Well Operation and Energy Conversion projects are shown below.

- o Determine geopressured-geothermal reservoir size and drive mechanism by long-term, high volume flow testing.
- o Prove long-term injectability of large volumes of spent brine.
- o Develop technology for automated operation of geopressured production systems.
- o Develop modified scale inhibitor treatment procedures.
- o Develop technology to produce power economically from the geopressured resource.

To accomplish these objectives, actual long-term field testing at three well sites has taken place, after previous short-term testing of Wells of Opportunity. These well sites are the present testing ground for the Geopressured-Geothermal Program. The wells are: Gladys McCall (located in Cameron Parish, LA), Pleasant Bayou (located 40 miles south of Houston, TX in Brazoria County), and Hulin (located near Erath, LA in Vermilion Parish). This paper will focus on the activities which have taken place at these well sites during the period FY 1986 through FY 1990.

DISCUSSION

Geothermal (hot) resources exist in many forms throughout the world. One location of huge geothermal energy resources is the U. S. Gulf Coast Sedimentary Basin. This basin contains large reservoirs of abnormally high pressured (geopressured), hot (geothermal) brines. These reservoirs also usually contain gas, primarily methane, dissolved in the brine. In these wells, this has ranged from about 23 to 31 SCF/Bbl (4.1 to 5.5 m^3/m^3). Excess gas above that which is dissolved in solution, or "free" gas, may also be present. This free gas has been commercially exploited by the petroleum industry since the turn of the century, but the geopressured-geothermal brines containing dissolved gas have not been commercially utilized (Goldsberry and Lombard, 1988). Geopressured-geothermal reservoirs were identified through oil and gas operations in Texas and Louisiana.

The Department of Energy began investigating these geopressured-geothermal energy sources in the Gulf Coast in the late 1970's, continuing to the present. The initial "Wells of Opportunity" program, in which nine wells were tested, was only utilized for short-term flow tests of less than a month, to confirm the presence of the brine and to provide some estimate of the producibility and quality of the brine and gas. These wells were acquired by DOE from the petroleum industry before being abandoned as non-commercial for initial or continued hydrocarbon production. The second "Design Wells" program tested four wells for longer terms (see Figures 1 and 2).

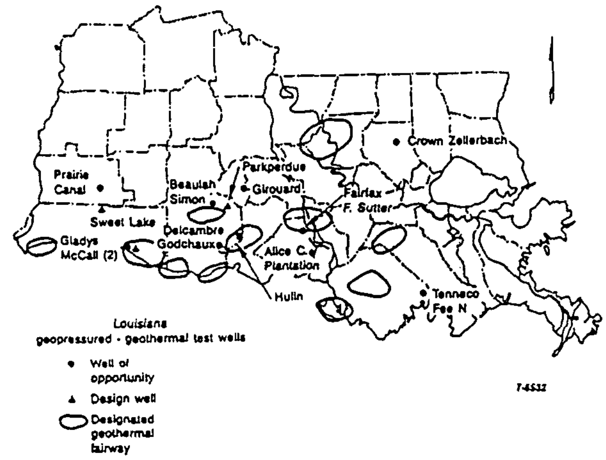


Figure 1. Louisiana geopressure-geothermal test wells.

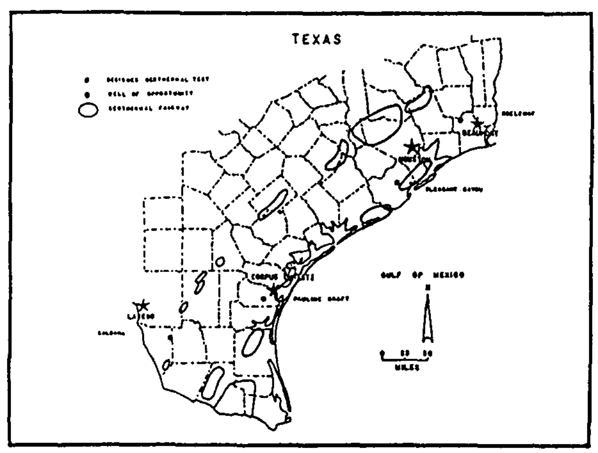


Figure 2. Texas Geopressured-geothermal Fairways and Test Wells.

Two of these, the Gladys McCall Well No. 1 (Cameron Parish, LA), and the Pleasant Bayou Well No. 2 (Brazoria County, TX) are still active. These two wells and the Willis Hulin No. 1 well (Vermilion Parish, LA), a "Well of Opportunity", are the subject of this report covering the period of Fiscal Years 1986 through 1990, the period of the current five year DOE contract for operation of the sites.

A. Gladys McCall Site (Cameron Parish, LA)

1. Production History
The Gladys McCall Well No. 1 (see schematic Figure 3) was completed in the interval 15,160 to 15,470' (4,620 to 4,715m). This well was flow tested and produced 27,318,414 Bbl (4,343,280 m^3) of salt water brine (Figure 4), with associated gas of 676,783 MCF (1,916.4M m^3) (Figure 5). The well has been shut in for over two years of pressure buildup tests and is recovering to almost its original shut-in pressure (Figure 6).

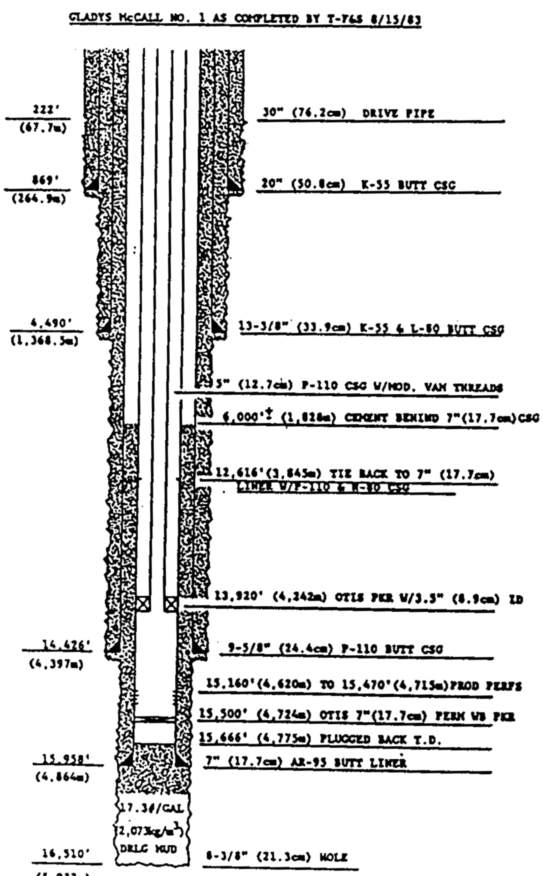


Figure 3

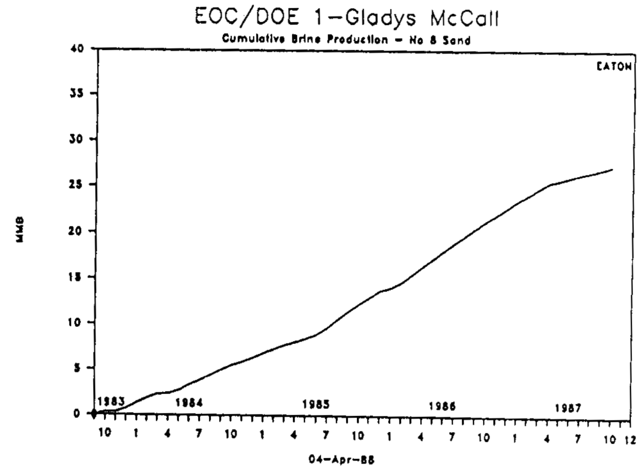


Figure 4

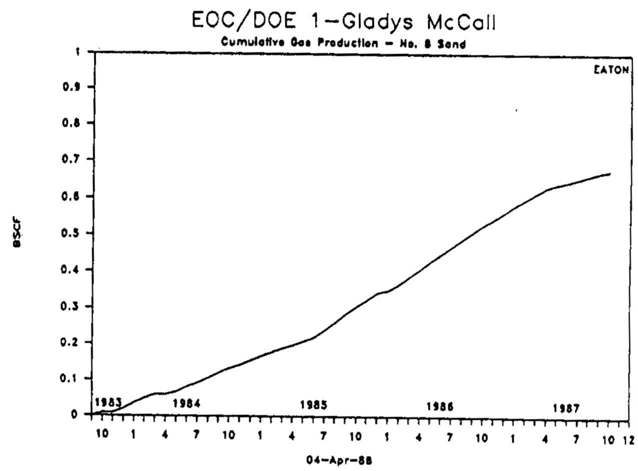


Figure 5

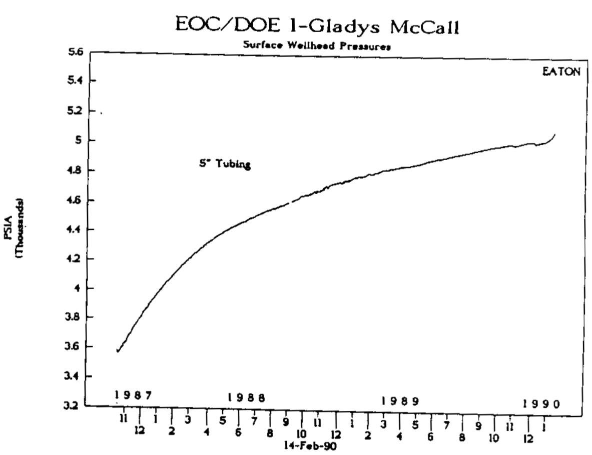


Figure 6

2. Accomplishments

a. Reservoir Analysis
The production of these large volumes of brine was at rates of up to 40,000 Bbl/day (6,360 m^3/day). During the final test period, the well was producing 18,000 Bbl/day (2,862 m^3/day), with no pressure decline apparent in the reservoir. This has established that these reservoirs are even larger than originally anticipated and have a life expectancy of as much as 15 to 20 years.

Valuable data on the brine and gas chemistry, aromatic hydrocarbon and cryocondensate content, and other production factors has also been obtained.

b. Scale and Corrosion Control
Calcium Carbonate ($CaCO_3$) scaling of the tubing and surface facilities and corrosion-erosion of surface piping were significant problems in the early production of this well.

(1) Scaling was virtually eliminated by the development (with Dr. Mason Tomson, Rice University - Houston, TX) of a technique for squeezing phosphonate chemicals ("pill") into the formation, to prevent the formation of scale. Chemical treatment in the surface facilities was also used when the pill began to lose its effectiveness. With two squeeze treatments, costing approximately $30,000 each, a total of 18,690,000 Bbl (2,971,473 m^3) of brine was produced with no scaling in the tubing or high pressure portion of the system. Surface treatment, as necessary, in the low pressure portion was also successful.

(2) Erosion-corrosion, particularly where sharp angle turns were made in the piping, was also a serious problem. This especially occurred if flow rates exceeded 15 ft/sec (2.38 m/sec) in the piping. This problem was reduced significantly by replacing small piping with larger piping where possible and by installing stainless steel sections of piping in critical areas. This experience was of tremendous value in the planning of production facilities at the other sites.

c. Injection
The produced brine was reinjected into a shallower well, about 3,000' (477 m), after removal of the gas. Special techniques were developed, such as providing storage tanks so that a small flow of brine into the well could be maintained during shutdowns of the system to prevent backflow to the well bore. Injection of brine at rates up to 40,000 Bbl/day (6,360 m^3/day) was maintained at pressures of less than 500 psi (3.45 Pa).

3. Future Utility
Sidetracking and coring and logging of the producing sand and adjacent shales has been proposed for future consideration to determine formation alteration, compared to the original cores, from the effects of production, such as compaction and shale alteration, and also to investigate what precipitates and residual chemicals may remain in the formation after scale control "pill" squeezes.

B. Pleasant Bayou Site (Brazoria County, TX)

1. Production History
The Pleasant Bayou No. 2 well (drilled and completed initially in 1979) represented the first full scale production test of a geopressured-geothermal aquifer in the U.S. by DOE. Initially, testing was severely hampered by scale formation in the tubing, which required frequent acidizing. Testing of this well was suspended in 1983 due to failure of the production tubing. Unsuccessful attempts had been made to clean out the well and restore it to production. A total of about 4,500,000 Bbl (715,443 m^3) of brine and 99,000 MCF (2,803M m^3) of gas had been produced. Under this new contract, the well was reworked for production (Figure 7), modified production facilities were installed and the well placed on production in FY 1988. A hybrid power system (HPS) for producing electricity was installed and placed in operation in FY 1990, to operate until July 1990. Projected production for this period is 11,283,469 Bbl (1,793,928 m^3) of brine and 219,759 MCF (6,222M m^3) of gas, as shown on Figures 8 and 9.

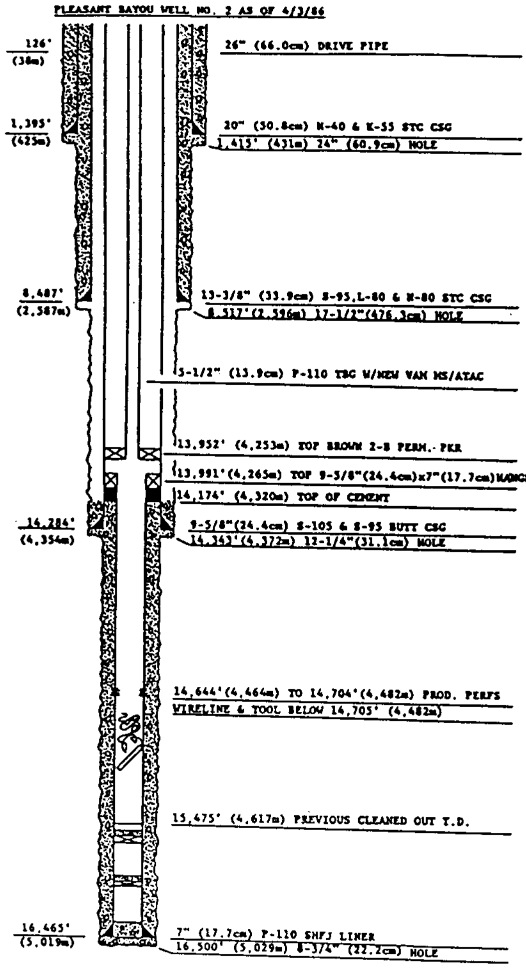


Figure 7

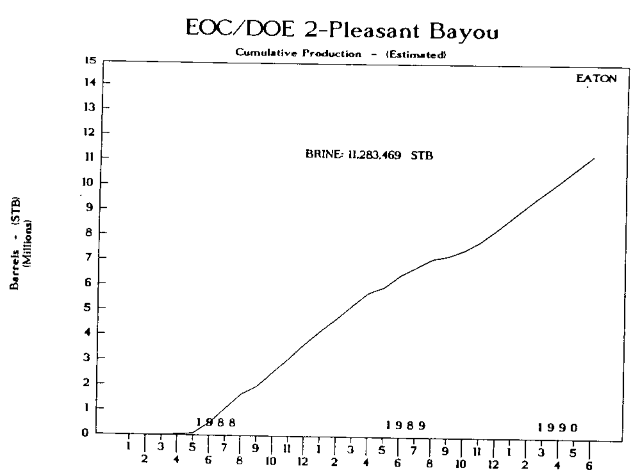


Figure 8

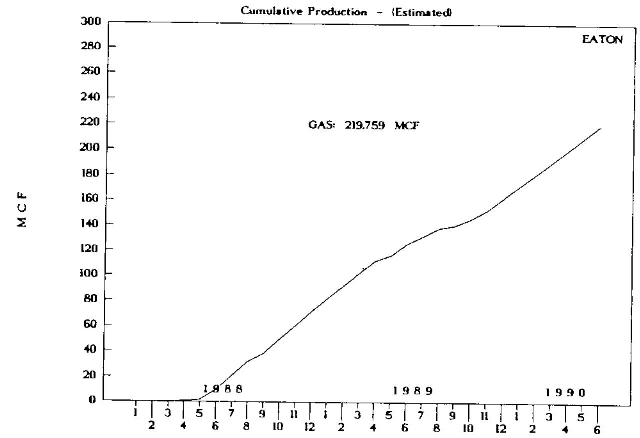


Figure 9

2. Accomplishments

a. Reworking of Production Well
The well was cleaned out and restored to production after being junked and inactive for three years.

b. Reservoir Analysis
During the past year, the wellhead pressure has increased while the well was being produced, at a rate of ±16,000 Bbl/day (2,544 m^3) (as shown in Figure 10), proving the existence of a reservoir capable of many years of high volume production.

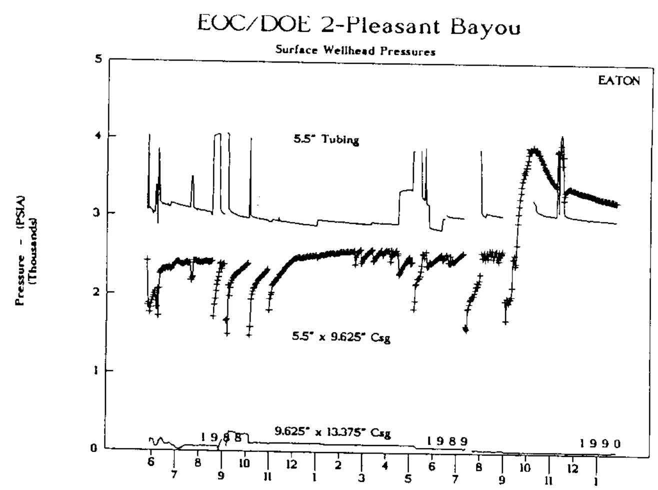


Figure 10

c. Scale and Corrosion Control

(1) Scaling was a very significant problem in the early test phases of this well. By adapting the experience gained at the Gladys McCall site, two scaling "pills" have been injected, which has prevented scaling in the tubing and high pressure system.

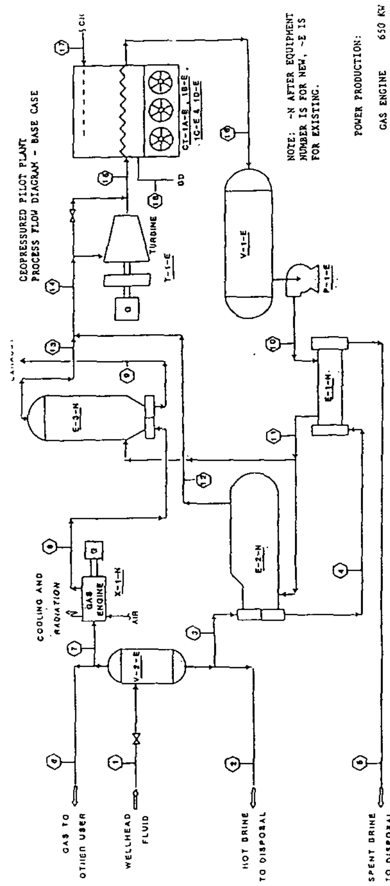
(2) Erosion-corrosion problems have been minimized at this site. Much of the existing production system was disassembled when the well was placed on standby in 1983. Utilizing the experience gained at the Gladys McCall site, piping was resized and stainless steel sections used when the system was rebuilt. These modifications resulted in a significant reduction in these type problems compared to the Gladys McCall site.

d. Hybrid Power System

Operation of the Hybrid Power System for conversion of geopressured-geothermal energy to electrical power has been very successful, both in actual mechanical operation efficiency and the prevention of scale deposition. A schematic of the plant is shown in Figure 11. It has obtained higher efficiencies than originally anticipated. This system is a binary system utilizing isobutane, which is converted from a liquid to a gas, to drive a turbine. The isobutane is cooled and recompressed to a liquid to repeat the cycle. This system is augmented (hybrid) by two gas engine driven generators which operate on part of the gas extracted from the geothermal brine. The very hot exhaust gases from the gas engines pass through heat exchangers to provide additional heat to the isobutane. This system was made up primarily of equipment salvaged from the East Mesa California project. It was ten years old and had been in storage for several years.

e. Injection

The produced brine was disposed of successfully in a disposal well about 6,500' (1,033 m^3) deep. Injection pressures averaged less than 500 psi (3.45 Pa), but were increasing at the end of the flow test. These injection pressures could have been reduced by reworking the well, but it was not desirable to interrupt the HPS operations test.



NOTE: -N AFTER EQUIPMENT NUMBER IS FOR NEW, -E IS FOR EXISTING.

POWER PRODUCTION:

GAS ENGINE	650 KW
BINARY CYCLE	541 KW
TOTAL	1,191 KW
PARASITIC LOADS:	
CONDENSORS	75 KW
CIRCULATING PUMP	63 KW
MISCELLANEOUS	50 KW
TOTAL	188 KW
NET POWER	1,003 KW

STREAM NO.	1	2	3	4	5	6	7	8	9
FLUID	BRINE & GAS	BRINE	BRINE	BRINE	BRINE	GAS	GAS	EXHAUST	EXHAUST
FLOW, MLBS/HR	341	170	170	170	170	.47	.47	6.6	6.6
BPD OR (SCFM)	-	10,000	10,000	10,000	10,000	(153)	(153)	-	-
TEMP OF	295	278	278	220	164	278	278	1,130	300
PRESS., PSIA	1,500	595	595	570	528	595	595	16	15
DENSITY, #/CF	-	64.4	64.4	66.5	68.5	1.50	1.50	.024	.054

STREAM NO.	10	11	12	13	14	15	16	17	18
FLUID	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	CW MAKEUP	BLOW DOWN
FLOW, MLBS/HR	107	107	92	15	107	107	107	30	10
BPD OR (SCFM)	-	-	-	-	-	-	-	-	-
TEMP., OF	96	210	210	210	210	128	94	64	80
PRESS., PSIA	330	300	280	280	280	70	68	30	15
DENSITY, #/CF	34	26.7	3.3	3.3	3.3	.7	33.8	62.4	62.4

Figure 11

3. Future Utility

Reservoir Data

As noted (Figure 10), the surface pressure (and reservoir pressure) increased while the well was producing at a rate of ±16,000 Bbl/day (±2,543 m^3/day). Long-term production at higher rates is needed to determine at what rate the pressure will decline and to establish actual reservoir size. Rework of the injection well to lower injection pressures will be necessary to do this. After completion of any additional flow testing, this well would also be a candidate for sidetracking for coring and logging to determine formation alteration compared to the original cores from this well.

C. Hulin Well Site (Vermilion Parish, LA)

1. Production History

DOE acquired the Willis Hulin Well No. 1 from The Superior Oil Company in 1984 as a "Well of Opportunity". The well had ceased natural gas production in 1983 and had mechanical problems requiring expensive, high risk rework to attempt to restore it to production or to plug and abandon it. The well contains several deep geopressured-geothermal brine reservoirs. These reservoirs were deeper - ±20,700' (6,309 m), hotter - ±340°F (171.1°C), and higher pressured - ±17,350 psi (119.6 Pa) than any well tested to date. The sand is very thick, ±600' (183 m), and a very large reservoir is indicated. The exact size and continuity of the reservoirs can only be determined by testing the well (John and Stevenson, 1989). This well was cleaned out and recompleted as shown in Figure 12 (Featherston, Jones and Meahl, 1989). A disposal well was drilled and completed at ±6,400' (±1,951 m). A short-term flow test was made on the subject well from the end of November 1989 to January 1990. Three intervals were perforated and tested in sequence:

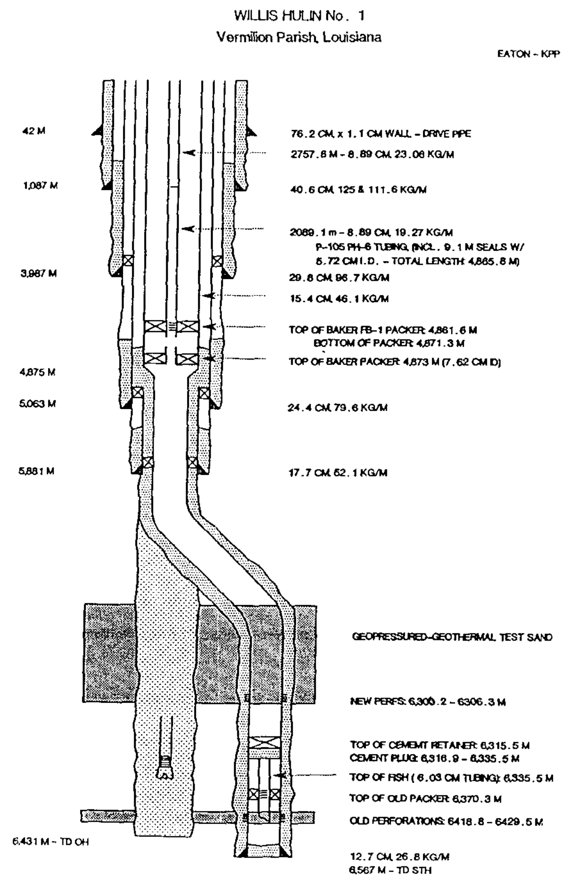
a. 20,670-20,690' (6,300.2-6,306.3 m)
b. 20,602-20,642' (6,279.5-6,291.7 m) and 20,646-20,666' (6,292.9-6,299 m)
c. 20,220-20,260' (6,163-6,175.2 m)

Total production from the well is ±41,000 Bbl (6,518.5 m^3) of brine, and 1,276.5 MCF (36.1M m^3) of gas. The gas in solution ranged from ±29 SCF/Bbl (5.16 m^3/m^3) to 33 SCF/Bbl (5.88 m^3/m^3), which is higher than the other wells. Production rates were limited due to small tubing and wellhead restrictions. Brine and gas analyses were made.

2. Accomplishments

a. Well Rework

The clean-out and recompletion of this well, after its being shut in for six years, was a major engineering feat, overcoming high pressures and temperatures, close tubular clearances, heavy dehydrated mud, extreme depths, and other problems. Even state-of-the-art tools were, in some cases, operating at, and in some case beyond, their design limits. The final workover cost was one-fourth or less of the cost to drill a new well today.



Well Schematic As Completed 2/7/89.

Figure 12

b. Reservoir Data

Even though the flow test was limited due to limited funding, much valuable information was obtained on such things as brine and gas chemistry, pressures, etc.

3. Future Utility

a. Reservoir Analysis

The short-term test was not long enough to make definitive measurement of maximum flow rates and pressure drawdown for deliverability capabilities and reservoir size determinations. Continuation of this program, with adequate funding, should allow testing for initial reservoir size determinations. This should be followed with rework of the well to install larger tubulars and wellhead for high volume, long-term testing.

b. Electrical Conversion System Utility
The high surface pressures of this well, in excess of 7,000 psi (48.3 Pa), and the high temperatures (340°F) (171.1°C) make this the best candidate to date for an electrical energy conversion system utilizing both a pressure reduction turbine and a binary cycle turbine.

c. Additional Gas Potential
A special new form of electric log analysis, ELAN, has been utilized at The University of Texas for analysis of the Hulin logs. The results of this analysis indicate that small amounts of free hydrocarbons appear to be distributed through this sand (Dunlap, UTA, 1989). This may be gas in a liquid state under the high pressures of the reservoir. The short-term flow test was not of sufficient duration to confirm or discount the presence of these hydrocarbons. If they are found to be present in long-term testing, it could significantly increase the economics of production through additional gas sales revenue.

d. Scale and Corrosion Research
The brine chemistry found in this well shows it will present more problems than the other two sites in controlling both scale and corrosion. Long-term testing will allow further development of the techniques now being used for these operational production problems.

e. Automation of Facilities
Automation has been developed and expanded at each test site. Using the experience gained at Gladys McCall and Pleasant Bayou, a system could be developed for much more automation with resulting decrease in site labor at this site, which is one of the prime objectives of this program.

CONCLUSIONS

A large amount of activity has taken place over the past five years in the Geopressured-Geothermal Program's Well Operation and Energy Conversion projects. This activity has resulted in a number of outstanding accomplishments. Some of these accomplishments are listed below:

- Development of effective scale inhibitor treatments.
- Production and reinjection of large volumes of brine from the Gladys McCall and Pleasant Bayou wells.
- Development of technology to deal with the corrosive geopressured-geothermal fluids.
- Design, construction and operation of the Pleasant Bayou Hybrid Power System.
- Limited flow testing of the Hulin well.

These accomplishments are strong steps toward satisfying the DOE Geopressured-Geothermal Program objectives. With continued programmatic success, the probability of making power production from the geopressured resource economic will increase. An Industrial Consortium is already being formed to continue the development and utilization of these resources. This will have a very favorable impact on America's national energy strategy, as the resource can be used to offset the need of foreign energy resources and will have very little, if any, adverse impact on the environment.

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OPERATION OF A GEOPRESSURED HYBRID POWER SYSTEM AT PLEASANT BAYOU

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ABSTRACT

The U.S. Department of Energy and Electric Power Research Institute are co-funding a demonstration of the hybrid cycle power concept on a geopressured resource. The power plant was constructed at the Pleasant Bayou geopressured test facility in Texas and has been operational since August 1989. This paper presents a review of the design and construction and a detailed discussion of plant operation and performance.

INTRODUCTION

In the hybrid cycle power conversion concept, electricity is generated from two or more sources of energy. From a geopressured resource, energy can be recovered from high temperature brine, from dissolved methane, and from hydraulic energy of the high pressure brine. In the demonstration plant, gas is burned in a gas engine to generate electricity directly. Exhaust heat from the gas engine is then combined with heat from the brine to generate additional electricity in a binary cycle. Heat from the gas engine is available at high temperature, thus improving the efficiency of the binary portion of the hybrid cycle.

The Ben Holt Co., under contract to EPRI, refurbished equipment from DOE's Direct Contact Heat Exchange facility in East Mesa, California for use at Pleasant Bayou. In addition, Holt purchased new heat exchangers and other equipment required for a hybrid cycle plant. Construction and operation are under a separate contract funded by DOE. For this work, Holt teamed with Eaton Operating Company (Houston, Texas) and Institute of Gas Technology (Chicago, Illinois).

The primary objective of this project is to demonstrate the hybrid concept for electricity generation. Other objectives include demonstrating electricity generation from a geopressured resource and obtaining data from operating a power plant using geopressured fluids.

SYSTEM DESCRIPTION

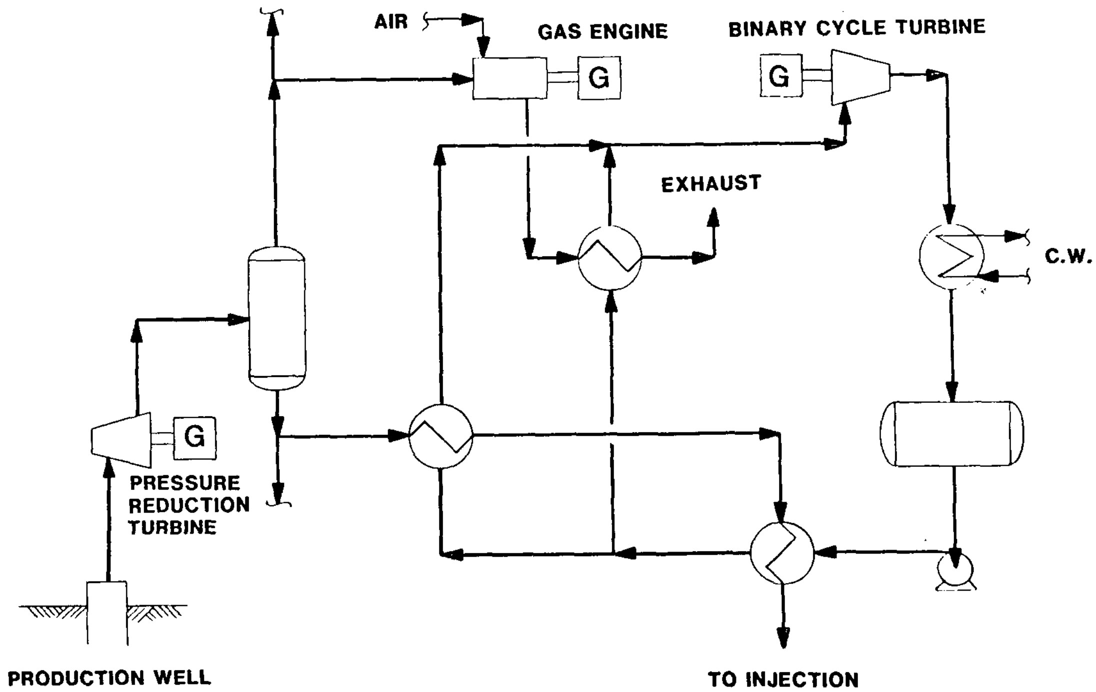
Figure 1 is a flow diagram of the hybrid power cycle which was installed at Pleasant Bayou. The system is designed to operate on 10,000 BBL/day of geopressured brine containing 22 SCF of gas/BBL. This flow is approximately one half of the total flow from the Pleasant Bayou well. The gas is approximately 87 percent methane with the balance mostly carbon dioxide.

Power can be produced from three forms of energy in the cycle as shown. The first form is hydraulic energy, which can be recovered in the pressure reduction turbine. A pressure reduction turbine was not included in the Pleasant Bayou experiment.

The second form of energy is chemical energy, recovered by burning the methane in a gas engine. A gas turbine could be used instead with minor changes to the process. Two gas engines, each with fifty percent capacity, are used at Pleasant Bayou.

The final form of energy recovered is heat. The high temperature engine exhaust gas and the hot geothermal brine provide heat to a binary cycle.

Figure 1
HYBRID CYCLE FLOW DIAGRAM



Design power generation from the system without the pressure reduction turbine is:

Gas Engine	650 kW
Binary Cycle Turbine	540 kW
Parasitic Power	(210 kW)
Net Power	980 kW

DESIGN AND CONSTRUCTION

Beginning in 1984, The Ben Holt Co., under contract first to EPRI and later to DOE, completed the system design and procured equipment.

Much of the equipment for the binary cycle was furnished by DOE from the Direct Contact Heat Exchange (DCHX) test facility at East Mesa, California. Isobutane, used as the working fluid in the DCHX, was selected for use in the hybrid experiment. Operating conditions were chosen to allow reuse of existing equipment with minimum modifications. Equipment from the DCHX facility was dismantled, refurbished, and shipped to Pleasant Bayou. New equipment, including three heat exchangers, firewater pump, gas-freeing compressor, electrical switchgear, and several instruments were purchased to complete the system.

A concrete foundation was installed in 1986, after which equipment was shipped to the site. The remaining construction began December 1988 and was completed June 1989.

During construction, the major problems encountered were with corrosion of equipment from the DCHX facility. All equipment was cleaned and put into operating condition during the construction period. The evaporative condensers were in the worst condition, with leaks occuring in approximately 12% of the tubes. Leaky tubes were sealed off to prevent the loss of isobutane during operation. Sealing off the tubes decreased the condenser surface area, but the range of operating conditions encountered at Pleasant Bayou allowed the objectives of this test program to be met anyway.

An area of concern for operation on a geopressured resource is corrosion of the tubes in shell-and-tube heat exchangers. Testing has shown that corrosion is most severe in areas of high turbulence. Therefore, ferrules were inserted into the inlets of heat exchanger tubes which have brine flowing through the tube side. These ferrules are in the area of highest turbulence and are exposed to the highest corrosion. Brine leaving the ferrule has a smooth velocity profile so corrosion should be reduced.

SYSTEM PERFORMANCE

System check-out was performed in September 1989, and the turbine and gas engines have been operational since October 26, 1989. As of February 28, 1990, the Geopressure Hybrid Power System has been on line over 2600 hours and exported nearly 1770 MW/hrs to Houston Lighting and Power. The plant has been reliable as have commercial binary cycle power plants.

Typical power generation from the system at design flows is:

Gas Engines	690 kW
Binary Cycle Turbine	535 kW
Parasitic Power	(270 kW)
Net Power	955 kW

The gas engines and turbine are meeting their predicted design performance. However, parastic loads are higher than predicted due to higher pumping power and higher incidental power loads.

Maximum net power is generated at maximum isobutane flowrate. The brine flow required to heat the isobutane has not changed over the life of the test. At 60°F, 3.8 kW are produced by the turbine for every 1000 lb/hr of brine circulated. This is greater than the design value of 3.2 kW per 1000 lb/hr of brine. The primary reason for this high performance is that the brine temperature at 290°F is 12°F higher than the design temperature of 278°F.

The table below compares system performance with and without the gas engines running.

	Engines On	Engines Off
Brine Flow (lb/hr)	139,000	159,000
Isobutane Flow (lb/hr)	118,900	118,900
Turbine Output (kW)	520	520
Gas Engines Output (kW)	680	0
Net Sale (kW)	920	305

A significant portion of the power is produced by the gas engines. Also, by using the energy available from the exhaust 15% more energy is produced per pound of brine.

COMPONENT PERFORMANCE

GAS ENGINES

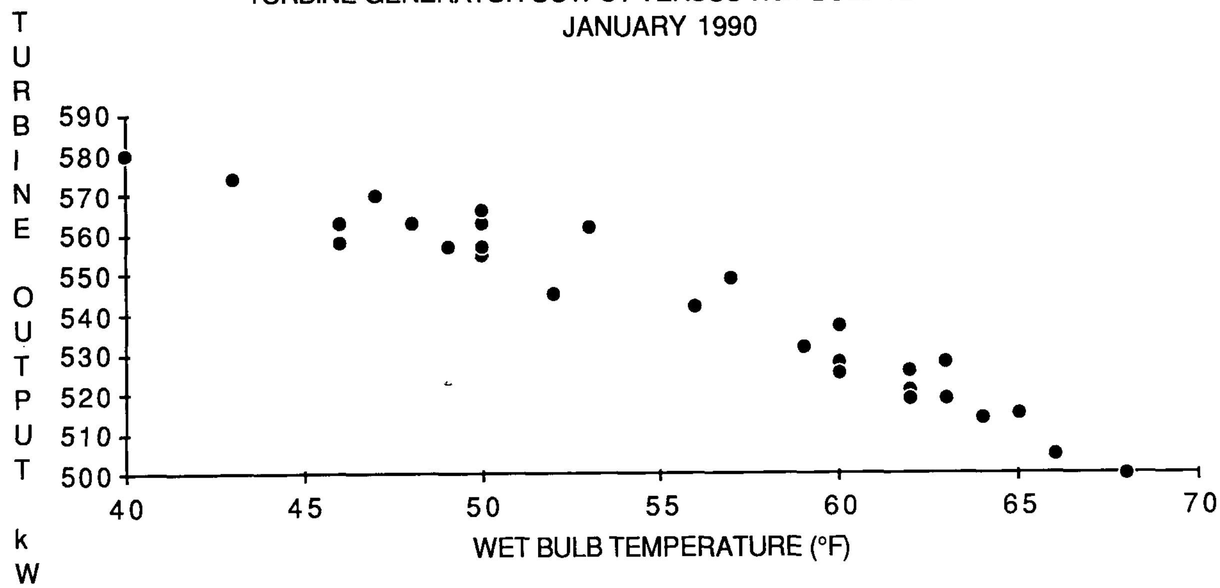
The engines have operated at their rated output for more than 2400 hours with only routine maintenance. Gas utilization has remained constant at the design value of 1.38 kW each per lb/hr of gas flow. Gas utilization is optimized at maximum gas flow. Gas utilization per engine decreases at lower gas input to that engine. There have been no operational difficulties associated with operating on impure wellhead gas.

TURBINE

A major source of problems during operation of the DCHX test facility was the turbine. In an attempt to avoid similar problems in the geopressured program, a finite element analysis was made of the turbine rotor. Results of this analysis showed that the existing rotor may be overstressed and would be operating close to critical frequencies. As a result, a new rotor was designed and fabricated for operation in the existing housing. A finite element analysis of the design showed the new rotor to be well designed with respect to strength and critical frequencies. Over 1300 hours of successful turbine operation validated the new rotor design.

Late in February, during a roll-down after an electrical outage the turbine seal overheated due to a loss of seal oil. An automatic monitoring system had been

FIGURE 2
GEOPRESSURED HYBRID POWER SYSTEM
TURBINE-GENERATOR OUTPUT VERSUS WET BULB TEMPERATURE
JANUARY 1990



installed as part of the Pleasant Bayou test facility. This system shut down the turbine and prevented serious damage to the turbine seal, bearing and rotor. The automatic high vibration shutdown of the turbine was the only indication of the overheated seal.

Turbine output varies with wet bulb temperature as shown in Figure 2. At the design back pressure of 55 psig, the design output of 540 kW is produced by the turbine. Since an evaporative condenser is used in this system, the isobutane condensing temperature and consequently the turbine back pressure are set by the wet bulb temperature.

HEAT EXCHANGERS

Geopressured resource utilization requires that problems due to corrosion and scaling be overcome. The brine has approximately 130,000 ppm of total dissolved solids and has shown severe scaling tendencies when untreated. In addition, carbon steel in untreated brine has been corroded at rates as high as one inch per year. Eaton Operating Company and the Institute of Gas Technology worked together to come up with a combination of scale and corrosion inhibitors which was successful at production temperatures with heavy-walled carbon steel pipe. This combination also appears to be effective at preventing scaling and corrosion at lower brine temperatures in thin-walled carbon steel heat exchangers.

Heat transfer coefficients have been closely tracked to monitor scaling. Isobutane is heated to its bubble point in a brine-to-isobutane heat exchanger. This is a shell-and-tube exchanger with single tube and shell passes with true counter current flow. 90% of the isobutane is vaporized in the brine-to-isobutane boiler. This heat exchanger is a reboiler with isobutane on the shell side and brine on the tube side. Exhaust gas from the gas engines is used to vaporize the remaining portion of isobutane.

No appreciable fouling with time has been noted in either of the brine to isobutane exchangers. At design flow, the overall heat transfer coefficient is consistently slightly better than design.

The exhaust gas-to-isobutane boiler has shown consistently lower overall heat transfer than expected. Visual inspection during a shutdown showed significant fouling. Cleaning this exchanger lowered the calculated fouling resistance from 0.027 hr-sq ft-^{o}F/Btu down to 0.006 hr-sq ft-^{o}F/Btu. However, shortly after the clean exchanger was put back into operation the fouling resistance increased to its previous value. The primary cause of fouling is thought to be thick soot created by backfiring of the gas engines.

CONCLUSIONS AND RECOMMENDATIONS

The geopressured hybrid power system at Pleasant Bayou has demonstrated the viability of the hybrid concept for electricity generation from a geopressured resource. The turbine has operated over 1300 hours and has met its specified design performance. The gas engines have operated over 2400 hours and have met their specified design performance. No evidence of scaling or corrosion problems were found in the brine exchangers. Additional operation is recommended to characterize the performance of the exhaust gas-to-isobutane exchanger. No difficulties were related to operation on a geopressured resource. The success of this program indicates that commercial utilization of geopressured resources is attainable.

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MAGMA ENERGY TECHNOLOGY

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

OVERVIEW: MAGMA ENERGY

James C. Dunn
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ABSTRACT

A national energy strategy for the U. S. should include development of short, intermediate, and long term resources. Crustal magma bodies located in the crust at shallow depth represent an enormous potential resource that deserves to be evaluated for development within the next 10 to 15 years. The estimate of the potential magma resource base in the U. S. is as high as 500,000 quads. This estimate is larger than our fossil resources and approximately 6500 times the total annual U. S. energy consumption.

Several years of DOE supported R & D in magma energy extraction have changed the prevailing attitude about this concept from: "Of course there is a major magma resource, but it cannot be harnessed" to: "if there is a major body of magma at shallow depths, energy can be extracted." The engineering details are by no means all worked out. But, the important questions have been addressed and satisfactorily answered in a preliminary sense. This includes designing insulated drill pipe to extend drilling techniques used successfully in molten lava at Kilauea Iki lava lake to depths typical of crustal magma bodies. Materials research has identified and tested several common superalloys that will survive the expected energy extraction environment for several years. Extensive experimental and numerical analyses of energy extraction processes have resulted in projections of single well energy extraction rates of 25 to 45 MW_e.

The primary unanswered question at this stage of development is: What is the nature of the crustal magma resource? (How deep? What volume? What thermal state?) These questions can only be answered by deep drilling into the magmatic regime. The Long Valley caldera deep exploratory well is designed as a beginning to address these important issues. Long Valley is a very large silicic caldera that best typifies the magma resource estimate. The well, located on the resurgent dome, will provide a stringent test of the hypothesis that magma is still present within the central plutonic complex of this active caldera.

INTRODUCTION

Volcanism is one of the major forces of our planet and is the reason why the Earth is viewed as "alive" rather than "dead" like the moon. Magma, which is responsible for this activity, is the ultimate geothermal resource. But what is the connection between magma that emerges as eruptive products on the surface and a high quality, geothermal resource that could supply vast quantities of useful power for mankind?

We suspect that most magmas are derived from the upper mantle and lower crust. But with depths of 30 km or more, this source region is not viable for energy recovery. The key to magma energy utilization is the existence of magma reservoirs that have accumulated at relatively shallow depth in the crust.

In its assessment of geothermal resources of the United States (White and Williams, 1975; Muffler, 1979), the U. S. Geological Survey addressed the magma resource base. Their estimate is that 50,000 to 500,000 Quads of thermal energy are contained in molten or partially molten magma residing in the crust at depths less than 10 km. This estimate of the potential magma resource is larger than the U. S. fossil resource and roughly 650 to 6500 times the total annual U. S. energy consumption.

During FY 84, the Geothermal Technology Division of DOE initiated the Magma Energy Extraction Program to investigate engineering feasibility. The primary goal of this program is to develop and demonstrate the technology needed to produce power from magma resources so that industry can evaluate economic viability (Dunn, 1988). In the United States, the major potential for magma energy is in the form of silicic melts that have accumulated in the crust at relatively shallow depths (Eichelberger and Dunn, 1990). The current engineering program is directed at utilization of this potential resource. We are developing specific technologies in energy extraction, materials, drilling, and source definition so that wells can be drilled into large magma bodies and energy extracted for power production.

The current focus of the magma energy program is the drilling of a deep exploration well in Long Valley caldera (See Figure 1.). The location of the well is on the resurgent dome, coincident with a large number of shallow (5 to 7 km depth) geophysical anomalies and near the point of maximum inflation (See discussion below.). This well is targeted for the near-magmatic regime at a temperature of 500°C and is designed for a depth of 20,000 feet. Measurements obtained from the well will enable definition of magma at depth, an assessment of the significance of the observed geophysical anomalies, and investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor. Deep wellbore measurements will provide important new information about the hydrothermal system at Long

Valley, and perhaps shed light on why a major hydrothermal resource has not been discovered.

Since this well will be the first deep well drilled into the the margins of an active magma system, there is important scientific interest as well. Through signed agreements among the Department of Energy, the National Science Foundation, and the U. S. Geological Survey, the Magma Energy Exploratory Well has been designated part of the U. S. Continental Scientific Drilling Program. Scientific issues that can be addressed by the magma well were developed during a workshop held in Albuquerque during June 1988. The results are published in a science guide for the Long Valley caldera deep hole (Rundle and Eichelberger, 1989).

Project Objectives

The Long Valley well has a number of project objectives that address either source location and definition or engineering hardware development. The primary objective is confirmation of the existence of magma at drillable depths beneath the surface. This well will test the very foundation of the magma energy concept - that huge quantities of partially molten magma reside in the crust at relatively shallow depth. Because of its size and recent activity, Long Valley caldera is one of the best locations in the U. S. to test this hypothesis.

An additional objective is the testing and calibration of surface geophysical methods for magma location and definition. Numerous surveys have been completed in Long Valley with conflicting results (Rundle and Hill, 1988). Most geophysical measurements detect anomalies beneath the caldera but interpretations do not agree. The deep well will provide hard evidence of structure beneath the resurgent dome and wellbore measurements of density, electrical conductivity, and seismic velocity will greatly improve the accuracy of geophysical data analysis. Furthermore, wellbore geophysical measurements will provide a means to infer structures and properties at depths greater than those penetrated by the well.

Energy extraction from an active magma body presents a number of formidable engineering challenges. Several new drilling technology ideas, such as insulated drillpipe, will be tested and evaluated in the less severe environment of the exploratory well. Likewise, materials selected through laboratory experiments for magma compatibility will be tested in the actual near-magma environment.

The magma program is organized to address engineering feasibility by investigating four primary areas: 1) geophysics, 2) drilling, 3) energy extraction, and 4) geochemistry. The following sections summarize work completed in these areas and point out the needs for future studies.

Geophysics

Long Valley caldera has been the site of intensive geophysical and geological investigations for the past 15 years. (See, for example, Rundle and Hill, 1988.) These investigations assumed much greater importance beginning in 1980 due to the major earthquake sequences, ground deformation, and renewed hydrothermal activity which began at that time. Figure 1 is a map of the Long Valley - Mono Craters - Mono Lake region showing the principal physiographic and geologic features.

During May 25-27, 1980, four earthquakes of magnitude greater than 6 occurred within and to the immediate south of Long Valley. Uplift of as much as .25 meter, centered on the old resurgent dome of the caldera (Figures 1 & 2), was subsequently measured by extensive leveling observations, and has been inferred to have accompanied the earthquake sequence.

Since 1980, considerable seismic activity has been occurring, albeit at a variable pace. The south moat swarm which began on January 6, 1983, had two events with magnitudes in excess of 5. Subsequent events included the November 23, 1984, Round Valley earthquake of magnitude 5.8, and the July 20, 1986, Chalfant earthquake sequence, which included three events of magnitude 6 or greater. While these two earthquake sequences were located to the south and east of the caldera, respectively, seismicity within the caldera has also been a continuing feature of the regional activity (Figure 3).

Uplift observed by leveling along Highway 395 has grown to a peak value of at least half a meter (Figure 2), and extensive surveys covering the entire caldera demonstrate that it remains centered on the resurgent dome. Most recently, two-color geodolite surveys spanning the last 6 years indicate that hori- zontal straining has increased by a factor of 5 since September 1989, centered over the southern margin of the resurgent dome (D. P. Hill, personal communication, 1990). These higher rates are typical of those observed 6 years ago, when the seismic activity within the caldera was considerably more intense. For comparison, the current rate of strain is a factor of 30-50 higher than rates typified by the San Andreas fault system in southern California. Associated seismic activity has also begun to spread in a gradual northward migration under the resurgent dome.

As a result of the frequent tectonic and renewed volcanic activity, an extensive series of geophysical and geological activities were planned in conjunction with the U. S. Geological Survey's Volcanic Hazards Program and the U. S. Department of Energy's Continental Scientific Drilling and Magma Energy Programs. Work began in 1982, with a comprehensive seismic refraction experiment throughout the Long Valley - Mono Craters region, gravity surveys, heat flow measurements, greatly increased passive seismic observations through densification of existing networks, electromagnetic, hydrothermal, and a variety of geochemical and geologic surface investigations (Rundle and Hill, 1988).

Seismic refraction experiments were completed during the summers of 1982 and 1983, and results were supplemented by deployments of arrays of seismometers during the frequently occurring earthquake swarms, such as that of January 1983. Sources for the active experiments were a series of 1-ton shots distributed throughout the caldera and along a major east-west profile intersecting the Mono Craters to the north. Average depth of ray penetration in the active experiments was typically about 4-5 km; thus the refraction studies have principally contributed to defining the structure of the uppermost part of the crust (Hill et al., 1985b).

Data from passive studies have been more successfully used in constructing models for regions of the caldera deeper than 5 km, but the results continue to be controversial. One of the first of these experiments was a shear wave shadowing study (Sanders, 1984), in which earthquakes occurring within the Sierra Nevada Mountains to the south of the caldera were recorded on the University of Nevada seismic network with stations located to the west, north, and east. Results from these observations indicated that the shear wave energy appeared to be systematically removed from the wave trains for raypaths penetrating the central part of the caldera at depths below 5-6 km. These results may imply the existence of a partially molten body of rock at depths in excess of 5 km beneath the central and south central part of the old resurgent dome. Other kinds of observations (summarized in Rundle and Hill, 1988), including P-wave tomography and teleseismic wave reflection measurements, have contributed to the general picture of a substantial geophysical anomaly at Long Valley. This anomaly, inferred to be magma, lies beneath the central resurgent dome, at depths possibly as shallow as 5-6 km. The peak of the recent uplift as defined by both leveling and gravity observations is roughly coincident with the site chosen for deep drilling. Estimates for the volume of the anomaly range from a few tens of km^3 on the low side to a thousand km^3 or so at the upper end.

Drilling

Technology used to drill into molten lava at Kilauea Iki can be applied to deeper drilling into silicic magma bodies. A major problem posed by deep drilling is that the drill string serves as a heat exchanger and drilling fluids are heated to an unacceptable level. Drilling fluid temperature influences almost all aspects of drilling, especially fluid selection, tubular selection, bit cooling, and hole stability. Our current work in drilling technology addresses this problem area and has resulted in the concept of insulated drillpipe (IDP). IDP is essential for maintaining reasonable drilling fluid temperatures when magma is penetrated. Although the Long Valley exploratory well will stop short of magma, the performance of IDP can be effectively evaluated during deep drilling.

Many fluids are unsuitable for use at high temperatures either because a property (such as viscosity) changes reversibly to an unusable state, or because the fluid and its additives are permanently degraded by the heat. Casing and drillpipe can be significantly affected by high temperature for at least two reasons. Strengths of the various steels not only drop as they get hotter but sometimes also have a time-dependent strength loss. Also, corrosion will be a severe problem in a magma well since chemical reaction rates are accelerated at high temperature.

Regardless of the type of bit used for drilling, lower temperatures will improve bit life. Roller cone bits will have longer-lived bearings, seals, and lubricants; drag bits will have better diamond (natural or synthetic) life at lower temperatures. This becomes increasingly important as depth increases.

As the hole approaches magma, the wellbore walls become more plastic, reducing the wellbore stability. When the magma is actually penetrated, there will be no wellbore at all if the fluid circulation does not keep the rock chilled into solidity. The radius of the solidified rock around the wellbore in the magma chamber depends on the temperature of the fluid and the length of time that it has been circulated. Stability is especially crucial when the wellbore has recently entered magma.

Thermal analyses of drilling into magma show that even deep within the molten body, drilling fluid and tubular temperatures can be maintained below 230°C by circulating the fluids through insulated drillpipe (Finger 1986). Figure 4 shows the inward creep in the wellbore wall calculated as a function of time after fluid circulation is lost; the longer collapse time at the shallower depth reflects the longer exposure time to relatively cool drilling fluid.

Preliminary designs for insulated drillpipe have been analyzed for thermal and mechanical performance. Construction of the pipe body (between the tool joints) is relatively straightforward, with technology similar to the double-wall insulated tubing used for steam injection in enhanced oil recovery. The quality of the insulation in the pipe body is not even very important, since a thermal conductivity equal to or lower than that of Teflon is adequate. The major structural and thermal challenge comes at the tool joints, where the design must be rugged enough to handle the extra loads imposed by the heavier drillpipe and must have enough insulation to preserve the advantages of the IDP principle. Proposed designs for the tool joints incorporate ceramic liners at the inside diameter of the joints; although design concepts exist, they will require considerable analysis and prototype development.

Energy Extraction

The rate at which energy can be extracted from a magma well is a major factor in evaluating its economic viability. Determining such rates, however, is complex because of uncertainties in the nature and properties of in situ magma bodies and the complexity of potential heat-exchange processes within the magma. Our approach has been to perform fundamental engineering analyses in conjunction with phenomenological experiments so that we can develop conceptual models of the magma heat exchanger to obtain estimates of potential rates of energy extraction.

Figure 5 shows our current conceptual representation of a single well during steady operation in a direct-contact heat exchanger mode. The solidified magma surrounding the borehole is fractured by thermal stresses or can be hydraulically fractured by pressure build-up. Energy is extracted by circulating a working fluid from the surface through the mass of fractured magma.

In order for the direct-contact heat exchanger to work effectively, the solidified magma surrounding the injection tube must be sufficiently fractured to provide a large heat transfer area. Initial thermal stress fracturing experiments were performed using a high-silica content aluminosilicate glass as a magma simulant. The test samples were upright cylinders fitted with a stainless steel tube so that water could be injected into the center bore of the preheated cylinders. Extensive fracturing of the specimen occurred within seconds after cooling was initiated (Figure 6a). The fractures were typically centimeters apart, in general agreement with theoretical predictions (Wemple and Longscope, 1986).

In more recent tests using a low-temperature simulant in glass test vessels, we were able to make direct observations of thermal stress fracturing during solidification. The material used was a terpene phenolic resin, which has a softening point at approximately 125°C. When cooled from an elevated temperature, the resin exhibits fracturing behavior qualitatively similar to glass. When cooled from 160°C by a central probe, material solidified and fractured under thermal stress, forming a more or less regular, cellular fracture pattern (Figure 6b). Typically, the cells are polygons with four to six sides, quite similar to the fracture patterns found in solidified lava flows (Aydin and DeGraff, 1988). A close-up of the polygonal fracture pattern is shown in Figure 6c.

As seen in Figure 5, the direct-contact heat exchanger is surrounded by convective molten magma. The rate of energy extraction ultimately depends on the convective heat transfer between the molten magma and the solidified magma comprising the direct-contact heat exchanger. One outstanding feature of convection in magma is the extremely large viscosity variation with temperature. This feature was examined by performing an enclosed convection experiment using corn syrup as a magma simulant (Chu and Hickox, 1988). The experiments covered top-to-bottom viscosity ratios ranging from 3 to 1400. In addition to measuring the overall heat transfer between the heated strip and the top surface, velocity and temperature distributions were obtained. From the heat transfer data, we were able to derive a viscosity correction factor that can be applied to standard constant property heat transfer correlations. This result is important in that it allows use of the large body of literature dealing with constant property heat transfer in convecting fluids.

The experiment was numerically simulated through the use of a state-of-the-art finite element computer program. Figure 7 shows a typical isotherm pattern and a comparison between numerically and experimentally obtained streamline patterns. The flow is characterized by two counter-rotating cells driven by a plume rising from the heated strip. The agreement between prediction and experiment is very good over the entire range of viscosity variations. With this experiment, we established the capability to calculate convective transport in magma.

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

A numerical code called MAGMAXT was developed to simulate the flow of compressible, homogeneous water/vapor within the well and heat exchanger, with heat transfer to and from the convecting magma and the overlying formation. Heat transfer between the injected water and the fractured body of magma comprising the direct-contact heat exchanger is modeled as flow through a porous annulus. MAGMAXT has been used to simulate the energy extraction process in a reference well configuration with a total well depth of 6 km, of which the bottom 1 km is a heat exchanger in the molten magma. The heat flux between the convecting magma and the heat exchanger is calculated to be 1 kW/m^2, using the result of the magma convection study.

By specifying the injection pressure and mass flow rate, the flow state throughout the circulation path can be computed by MAGMAXT using an iterative marching procedure. Figure 8 shows the temperature of the circulating water at a flow rate of 40 kg/s (640 gal/min). Within the heat exchanger, the net temperature increase is 400°C. It should be noted that Figure 8 shows one of a family of calculations; under the most favorable assumptions, the net temperature rise can be as large as 530°C for this flow rate.

As the fluid is heated in the heat exchange region, its density decreases, resulting in a density imbalance between the injection and return flow paths. The flow loop, therefore, has the capacity for natural thermosyphoning.

Power Plant

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

The results of the closed-loop cycle analysis in terms of net power output as a function of well mass flow rate are shown in Figure 9. A shaded region rather than a single curve is presented, reflecting the uncertainty in estimating the energy-extraction rate. Generally speaking, the net power output initially increases with mass flow rate because of increased energy extraction. However, the output temperature of the well decreases with flow rate, and the second law efficiency decreases. As a result, an optimal flow rate exists for maximum net energy extraction, which is on the order of 50 kg/s with a corresponding net power output of 25 MW_e to 45 MW_e.

Optimization

At this point, two important areas remain to be examined. First, there is a remaining aspect of system optimization. Magma is a finite temperature resource, i.e., no matter how deep the well, the output temperature of the well is limited by the magma temperature. Furthermore, the incremental heat transfer between the injected water and the heat exchanger per well depth decreases more than linearly with well depth. Thus, as the well depth increases, a point of diminishing return is reached in terms of the gain in additional energy extraction and the cost of drilling. A parametric study of the net power output as a function of well depth and well configuration is needed to determine optimum performance. Secondly, an integrated energy extraction experiment is needed. Thus far, we have performed benchtop phenomenological experiments and the results have been used to construct the system model for energy extraction from silicic magma. However, a need still exists to perform an integrated experiment that involves the entire process from drilling to energy extraction. The integrated experiment should be sized to give results in the kilowatt range, bridging the gap between laboratory experiments (watts range) and the expected field experiment (megawatt range).

Geochemistry

Successful extraction of heat from a shallow magma body depends, in part, upon the results of ongoing geochemical and materials compatibility studies. This research involves chemical characterization of the Inyo magma, experimental evaluation of alloy compatibility in magma and exsolved volatiles, and high temperature dissolution measurements of silicate minerals in hydrothermal fluids. The direction of geochemical research in support of this project is constrained by the geochemistry of the magmatic and hydrothermal environments as well as the response of engineering materials to those environments.

The Inyo magma is thought to be rhyolitic in composition (Bailey, 1984) and contrasts dramatically with the basaltic magma encountered during drilling in Hawaii (Hardee et al., 1981), especially in regard to volatile components dissolved in the magma at high pressures (200 MPa; Table 1). The pre-eruptive volatile content of the Long Valley magma has been estimated from analyses of bulk glasses and glass inclusions from the Inyo Domes and the Long Valley caldera (Westrich et al., 1988) while those of basaltic magmas have been calculated from fumarolic gas analyses (Gerlach and Graeber, 1985). Rhyolitic magmas are known to be more oxidizing than basaltic magmas (Whitney, 1984), and probably have very low sulfur contents (Carroll and Rutherford, 1985). The compatibility of engineering materials in basalt buffered by C-O-H-S gas typical of a basaltic lava lake (<1.0 MPa) has been investigated at magmatic temperatures (Douglass, 1983). These studies demonstrated the importance of magmatic volatile constituents, especially sulfur, to downhole corrosion problems in basaltic magma at low pressure.

The chemical nature of hydrothermal fluids that might be encountered during energy extraction is less clear. Presumably, the bulk of the magmatic fluids (water) will come from in-situ degassing of the rhyolite magma, although some fluids could originate from an underlying basaltic heat source. This degassing process can occur during drilling as the volatile-rich magma experiences isothermal decompression or, more likely, during heat extraction as the magma undergoes isobaric crystallization of anhydrous phases. Early exsolved magmatic fluids will be chlorine-rich, but the exact composition of the fluids in contact with the heat exchanger would depend upon the kinetics of magma degassing as well as upon the composition and flow rate of the heat transfer fluid. As a further complication, these magmatic fluids could also be enriched in carbon dioxide if the contribution from an underlying basaltic magma were large.

It is crucial when choosing an alloy for construction of a downhole heat exchanger that it have sufficient mechanical and chemical durability in the magmatic and hydrothermal environments present during drilling and energy extraction. The mechanical strengths of most alloys are sufficient to support the weight of the heat exchanger in the rhyolite magma as long as downhole temperatures do not exceed normal operating temperatures (400- 500°C). Loss of fluid circulation could lead to melting of the fractured chillrind surrounding the drillpipe/heat exchanger, where magmatic temperatures as high as 850-925°C could be reached. Only the superalloys have sufficient high temperature strengths to survive a loss-of-coolant accident.

The heat exchanger alloy also should be corrosion resistant over its 20-year lifetime in a magmatic or hydrothermal environment. A series of magma-metal compatibility tests were conducted at 850°C and 150-200 MPa to evaluate the general corrosion resistance of several classes of potential drillpipe alloys, including carbon and stainless steels as well as Fe-, Ni-, and Co-base superalloys, after reaction with simulated, Long Valley magma (Westrich and Weirick, 1986). These compatibility tests, using rhyolite melts with restored magmatic volatiles, have demonstrated that oxidation, not sulfidation, will be the main corrosion process for drillpipe in the Long Valley magma. Oxidation of carbon steel was found to be unacceptably high in these tests. In contrast, Cr-bearing alloys simply oxidize to form a solid solution of Cr-, Mn-, and Fe-oxides adjacent to the metal, thereby inhibiting further reaction. Parabolic growth and metal penetration rates for Cr-bearing alloys are significantly reduced (by an order of magnitude) compared with those observed for carbon steel (Figure 10).

Of equal concern is the long-term corrosion resistance of the metal alloy to a hydrothermal environment during normal heat extraction. This may include interactions of the heat exchanger alloy with the chilled magma (volatile-bearing glass) or with hydrothermal fluids. Several glass-metal tests were run at anticipated operating conditions for a direct contact heat exchange system (500°C and 50 MPa). Examination of the glass-metal interface indicates that resistance to corrosion was excellent for all alloy compositions. No metal oxidation was observed for Cr-bearing alloys in these tests even after run durations as long as 42 days (Figure 11).

Fluid-metal compatibility tests were completed to simulate an environment where heat exchanger material is directly exposed to a hydrothermal fluid at 500°C and 50 MPa. Solutions added to fluid-metal tests span the range of fluids in contact with the heat exchanger from pumped-in water to exsolved magmatic volatiles. Just a few Fe-base superalloys exhibited any evidence of corrosion; the Ni-rich alloys were only slightly tarnished, even after 45 days in a simulated magmatic brine.

Completion of the Magma Energy exploratory well in Long Valley caldera is critical to ongoing materials compatibility and geochemical research because of the unique downhole samples that could be collected. Chemical characterization of these samples, especially in regard to the sulfur content of the magma, and the pH and Cl content of hydrothermal fluids, will allow us to refine site-specific materials compatibility tests. While general corrosion rates for most Cr-bearing alloys in short-term compatibility tests at magmatic and hydrothermal conditions are low, other tests have shown that these alloys can experience severe pitting and stress corrosion cracking (SCC) in a hydrothermal brine (Cramer and Carter, 1980). Obviously, future compatibility studies will have to be longer in duration and quite specialized in order to address specific types of localized corrosion (pitting or crevice), as well as metallurgical and environmental effects (fatigue and stress corrosion cracking) upon heat exchanger alloys.

Conclusions

The concept that large bodies of silicic magma exist at shallow depths in the earth's crust is well supported by an abundance of geologic and geophysical data. Long Valley, one of the most impressive expressions of quaternary volcanism in the world, is an ideal site to conduct the first major drilling activity of the Magma Energy program. The technology under development in the Magma Energy program can, in principle, make the vast energy potential of these magma bodies available for the benefit of the nation. If we are successful in locating and eventually penetrating molten or semi-molten magma within the caldera, an actual field demonstration of this technology will then be feasible. Continuation of this program will combine the uniquely valuable scientific insight into crustal magmatic processes with the potential for stimulating commercial development by defining the hydrothermal system and by demonstrating magma energy extraction.

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Table 1. Composition of common rhyolites and basalts in magma chambers

Oxide (wt.%)	Rhyolite[a]	Basalt[b]
SiO_2	70.35	52.62
TiO_2	0.13	2.13
Al_2O_3	13.54	13.90
Fe_2O_3[c]	1.68	12.15
MgO	0.10	6.74
CaO	0.74	10.44
MnO	0.04	0.17
K_2O	5.02	0.43
Na_2O	4.11	2.41
P_2O_5	0.01	0.23
H_2O	4.00	0.27
F	0.050	0.035
Cl	0.120	0.009
S	<0.010	0.070
CO_2	≤0.003	0.034
Total	99.90	101.64

a) Typical rhyolite from Inyo domes, CA with added magmatic volatiles (Westrich et al., 1988).
b) Typical basalt from Kilauea crater, HI with reservoir-equilibrated magmatic volatiles (Gerlach and Graeber, 1985).
c) Fe reported as Fe_2O_3.

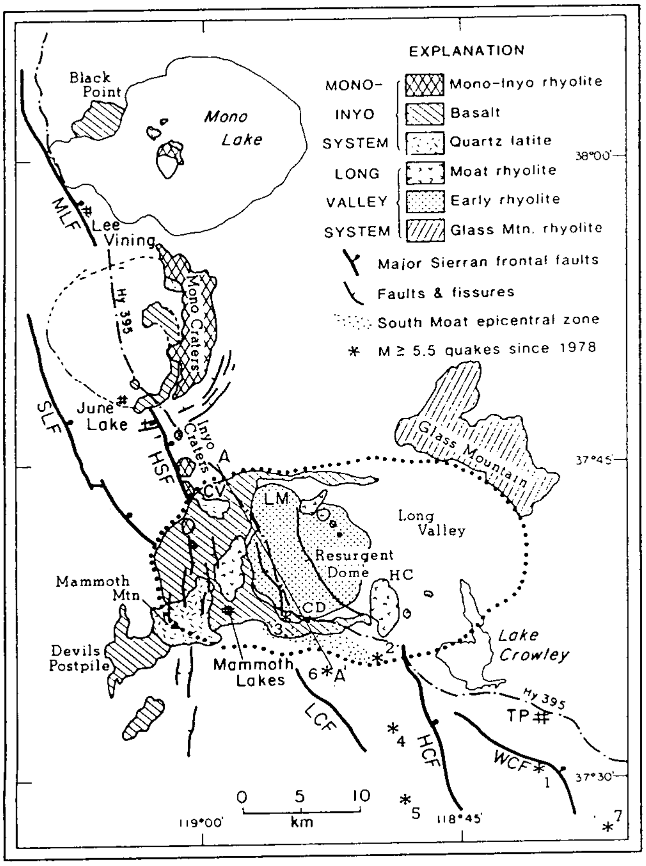

Figure 1

Regional geological and tectonic map of Long Valley caldera (after Hill and others, 1985a).

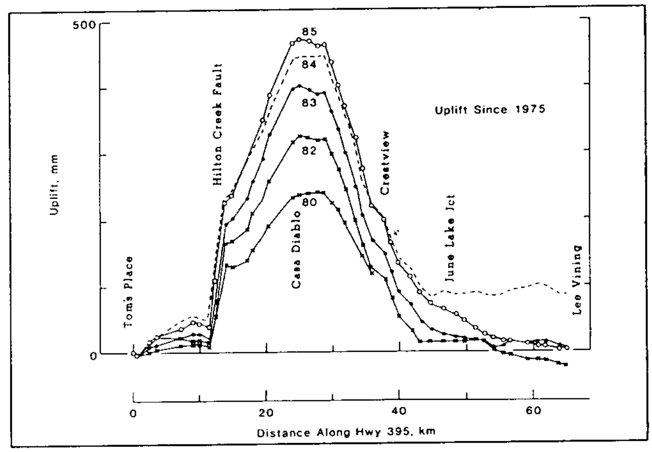

Figure 2

Leveling data along Highway 395 through Long Valley caldera (after Savage and others, 1987).

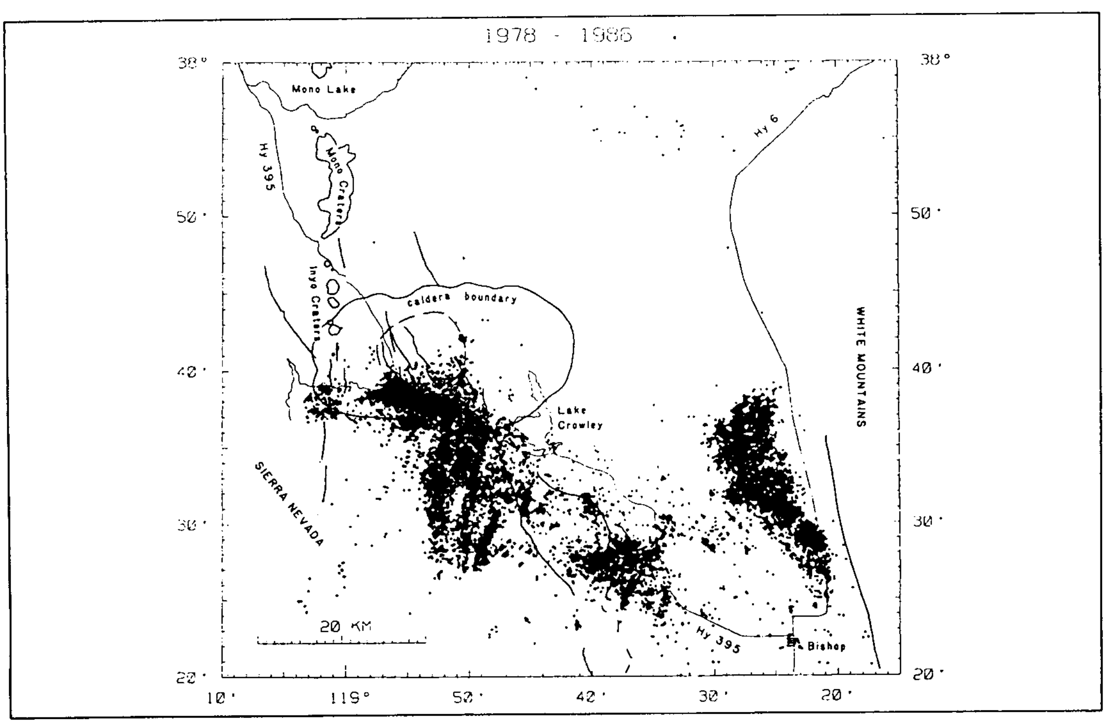

Figure 3

Map of Long Valley regional seismicity from 1978 through 1986 (from Rundle and Hill, 1988).

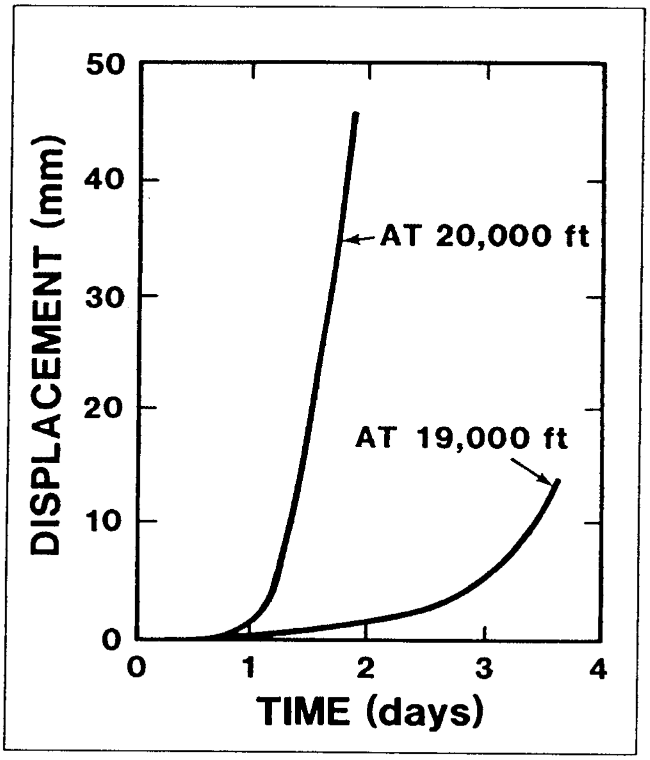

Figure 4
Theoretical displacement of wellbore wall after stopping circulation in a magma well with an initial magma temperature of 900°C.

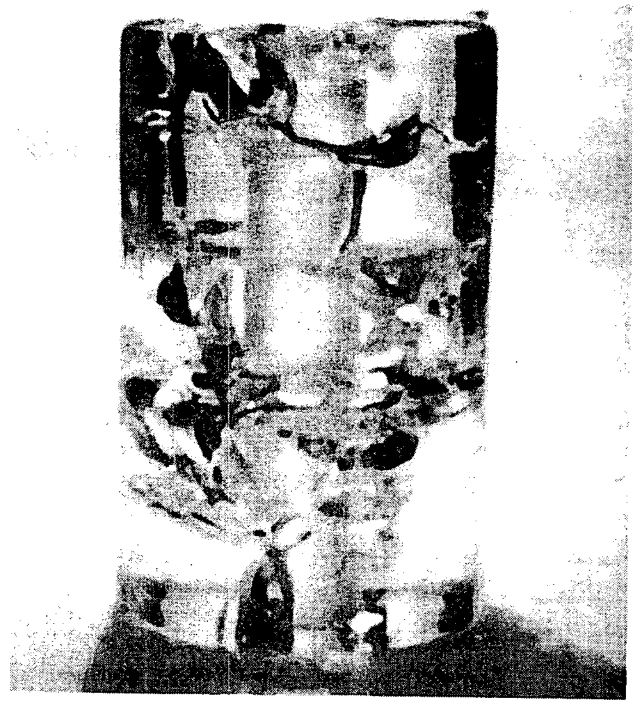

Figure 6a
Examples of thermal fracturing - (a) Typical thick-walled glass cylinder fractured by thermal stress.

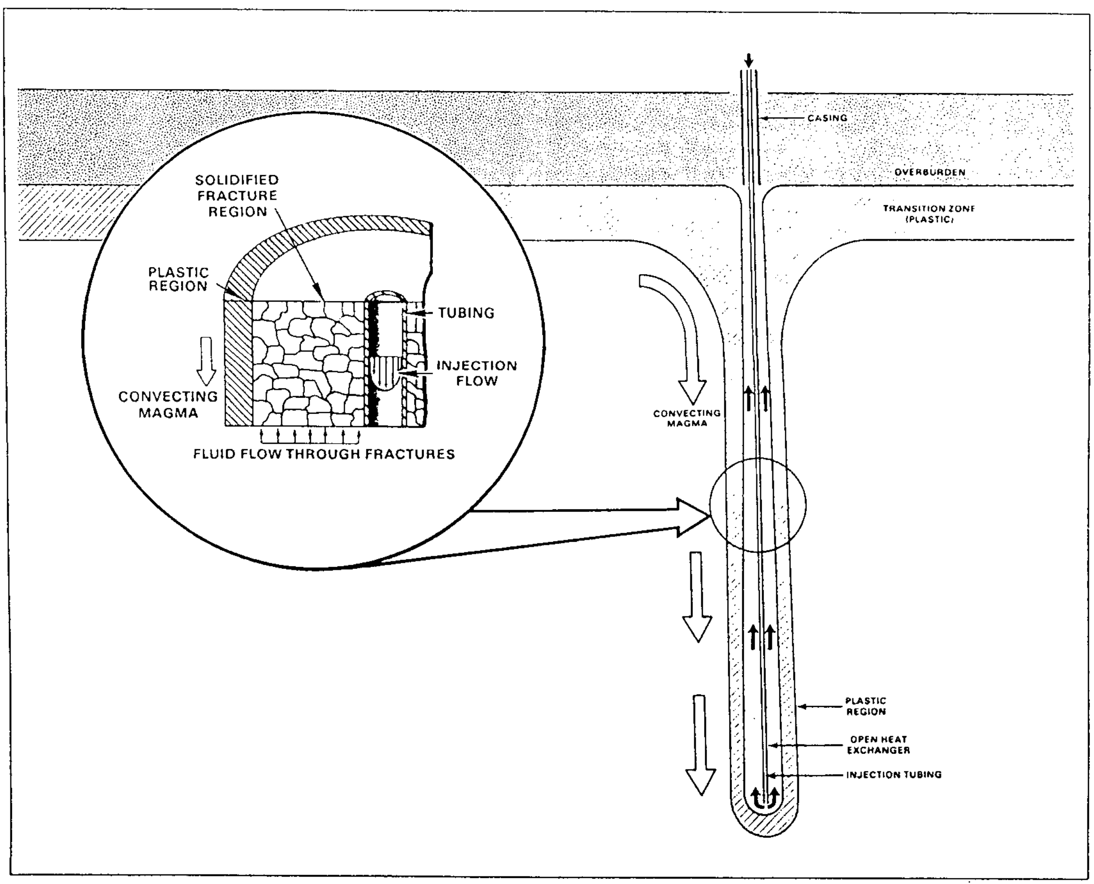

Figure 5
Current conceptual representation of a single well during steady operation of a direct-contact heat exchanger.

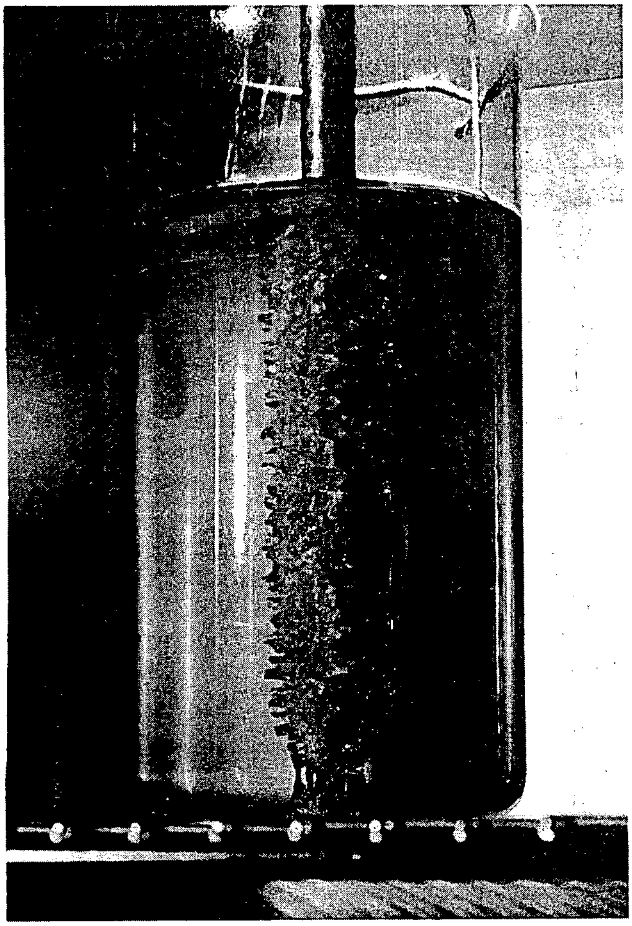

Figure 6b
Fracture pattern formed in a low-temperature simulant as solidification occurred around probe.

Figure 6c
Close-up of a polygonal fracture pattern.

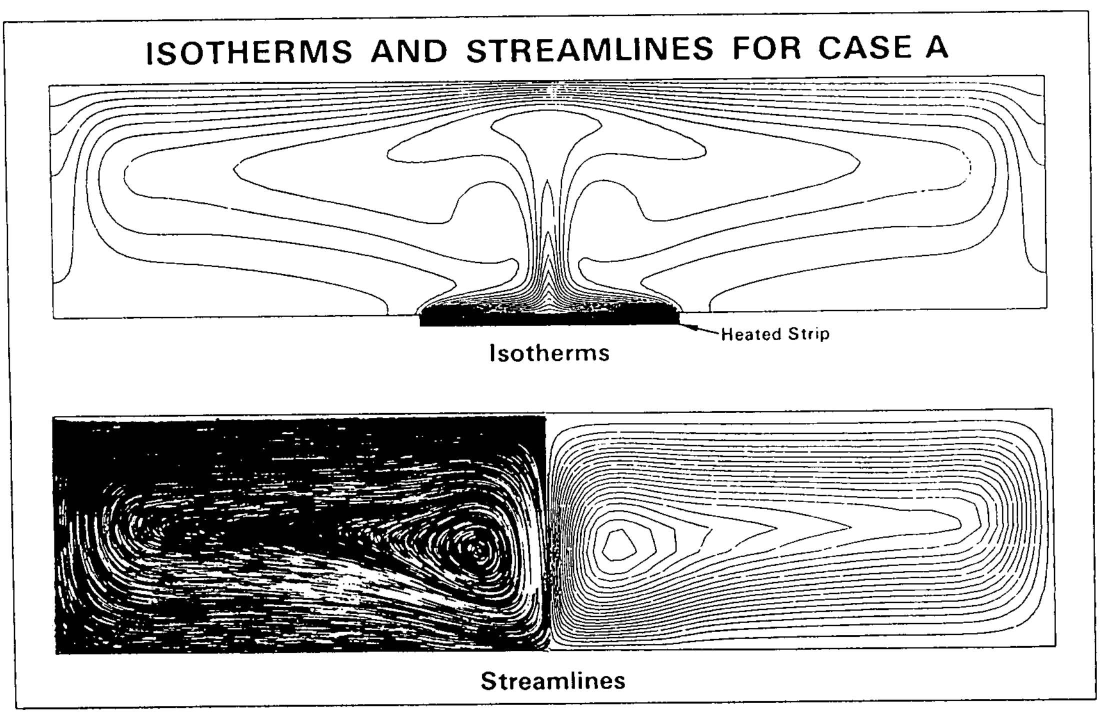

Figure 7
Typical isotherm pattern and comparison between numerically and experimentally obtained streamline patterns.

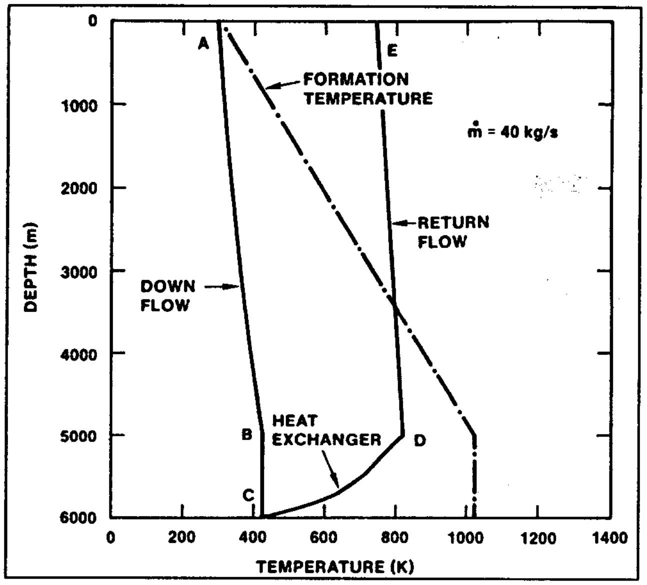

Figure 8

Calculated temperature of circulating water in a magma flow rate of 40 kg/s.

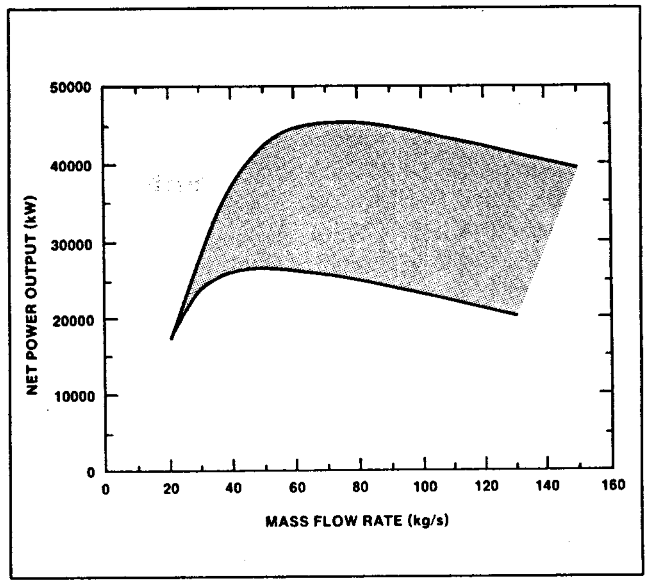

Figure 9

Net power output as a function of mass flow rate for a single magma well.

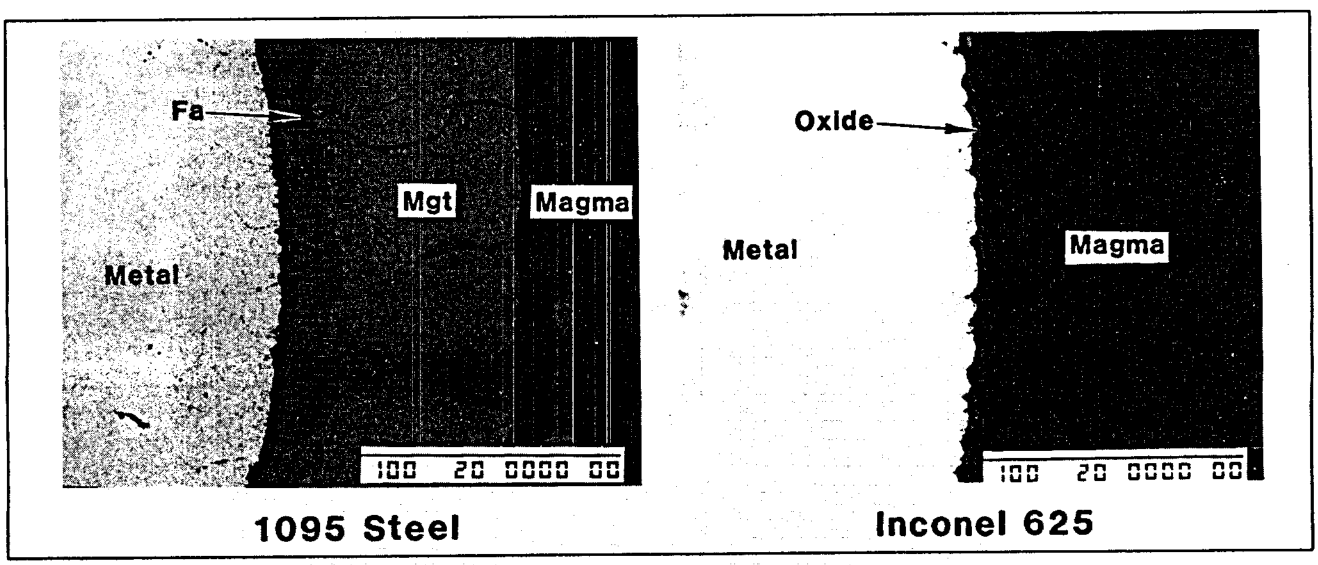

Figure 10

Comparison of the oxide rinds (fayalite, Fa and magnetite, Mgt) for 1095 carbon steel and Inconel 625 after reaction with a volatile-saturated rhyolite magma at 850°C and a 200 MPa for 7 days (scale bar is 100μm).

Table 1
Composition of common rhyolites and basalts in magma chambers

Oxide (wt.%)	Rhyolite[a]	Basalt[b]
SiO_2	70.3 5	52.62
TiO_2	0.13	2.13
Al_2O_3	13.54	13.90
Fe_2O_3	1.68	12.15
MgO	0.10	6.74
CaO	0.74	10.44
MnO	0.04	0.17
K_2O	5.02	0.43
Na_2O	4.11	2.41
P_2O_5	0:01	0.23
H_2O	4.00	0.27
F	0.050	0.035
Cl	0.120	0.009
S	<0.010	0.070
CO_2	<0.003	0.034
Total	99.00	101.64

a). Typical rhyolite from Inyo domes, CA with added magmatic volatiles (Westrich and others, 1988).
b). Typical basalt from Kilauea crater, HI with reservoir-equilibrated magmatic volatiles (Gerlach and Graeber, 1985).
c). Fe reported as Fe_2O_2.

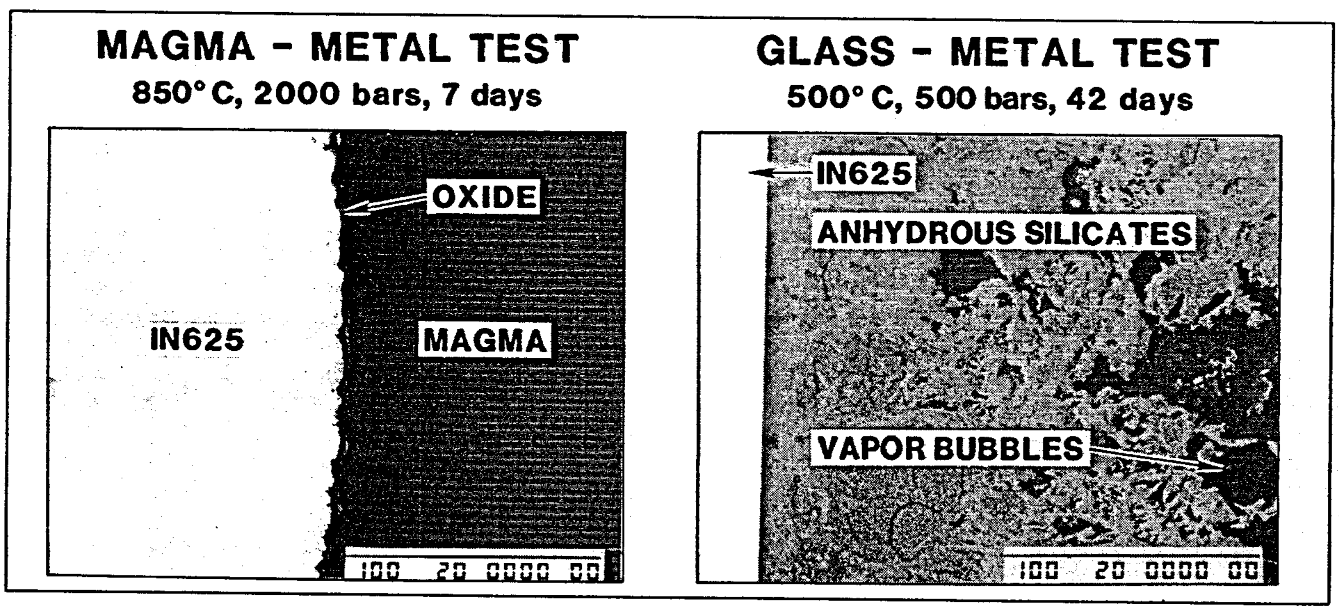

Figure 11
Comparison of Inconel 625 corrosion in a volatile-saturated rhyolite magma (850°C, 200 MPa, 7 days) and glass (500°C, 50 MPa, 42 days; scale bar is 100 μm).

SILICIC MAGMA IN THE CRUST

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In its assessment of geothermal resources of the United States (White and Williams, 1975; Muffler, 1979), the U. S. Geological Survey addressed the magma resource base. Their estimate is that 50,000 to 500,000 Quads of thermal energy are contained in molten or partially molten magma residing in the crust at depths less than 10 km. This estimate of the potential magma resource is larger than the U. S. fossil resource and roughly 650 to 6500 times the total annual U. S. energy consumption.

Thus, magma is an alternative energy resource with enormous potential. Engineering technology can be developed to recover this energy for depths less than 10 km. The critical need at this stage of development is a verification of the existence, character, and size of the magma resource. We know from the geologic record that magma reservoirs that develop at accessible depth are commonly of silicic rather than basaltic composition. This paper summarizes what is known and could be learned about silicic magma bodies.

There can be no question that vast volumes of silicic magma exist today at numerous sites in the upper crust of the continents. The frozen remnants of such chambers, granitic plutons, have characteristic vertical and horizontal dimensions on the order of kilometers. Through tectonism sustained over tens of millions of years, such bodies accumulate in batholithic masses covering areas up to a hundred thousand square kilometers. These are a distinguishing structural and lithologic feature of continental crust. That the process of high-level emplacement of granitic magmas is ongoing is shown by numerous catastrophic outbursts in recent geologic time, with individual volumes on the North American continent of up to 1000 km^3 (Lipman, 1984). These are not "partial melt zones", though even larger zones of crystal/melt mushes must exist. The volcanic record demonstrates that coherent batches of granitic magma, free of layers or screens of basement rock and only sparsely populated by growing crystals exist in volumes exceeding 1000 km^3. The depth of these bodies varies greatly, but stratigraphic observations from plutons and the local subsidence that accompanies most large-volume eruptions show that a significant proportion of silicic diapirs penetrate to within a few kilometers of the surface, that is, to within reach by drilling.

Despite the persuasive evidence of where silicic magma has existed in the past, saying where it is today is a formidable task. Understanding of the spatial relationship of surface volcanic features to magma chambers is incomplete, even though geologic cartoons displaying such relationships imply clarity. Chambers are presumed to lie directly beneath vents, which are presumed to leak chemically representative samples of the evolving magma (e.g. Smith, 1979; Bacon, 1985). Although useful, an example of how wrong this approach can be is illustrated by the great eruption of 1912 on the Alaska Peninsula. Venting of several cubic kilometers of high-silica rhyolite, the planet's most viscous magma, caused within hours the collapse of a wholly mafic to intermediate-composition volcano 10 km distant (Hildreth, 1983). Where centers of eruption and collapse coincide and intrusive analogs are well established, as is the case for large epicontinental calderas like Long Valley, there can be reasonable confidence that the chamber lies beneath the vents (Smith and Bailey, 1968; Rundle and Eichelberger, 1989).

Of greater uncertainty than geometry is chamber life span. Is a chamber that contained $10^4 km^3$ of magma 10^6 years ago still molten today? There are two primary problems to answering this question: the mechanism of cooling and the extent of replenishment. The answer is affirmative if magma cools wholly by conduction (Kolstad and McGetchin, 1978), but sites with strong geologic evidence for large magma chambers also exhibit evidence for extensive hydrothermal systems, which represent convective cooling of magma. Cooling can be fast if a thin conductive zone separates magma from a convective zone, as was found at Kilauea Iki lava lake (Hardee et al., 1981), or even faster if hydrothermal fluids penetrate magma, for which there is isotopic evidence at Yellowstone (Hildreth et al., 1984). Almost nothing is known about the coupling of magma systems to hydrothermal systems.

Rapid loss of heat from high-level silicic chambers is in many cases offset by replenishment by hotter, less evolved magma from a deep source. The evidence for this is that silicic eruptive centers are localized within broader regions of upward flux of basalt, silicic eruptives often contain injected and quenched mafic magmatic material, and silicic plutons exhibit clear evidence of mafic magma injection ranging from mildly disrupted mafic dikes to thoroughly admixed mafic debris (Eichelberger, 1978; Hildreth, 1981). Moreover, such replenishment is required by thermal calculations showing that silicic centers outlive plausible lifespans of closed-system chambers. Replenishment events also account in part for the varied chemical history of silicic volcanic fields. Major replenishment events are easily recognized by the flooding of areas peripheral to the silicic center with mafic lavas, as with the mafic eruptions of the Jemez Mountains Volcanic Field about 2 my ago (Smith et al., 1970) and the mafic eruptions in the west moat of Long Valley Caldera about 0.1 my ago (Bailey et al., 1976). Because mafic magma erupts around but not through silicic centers while such centers are active, but appears as entrained and partly crystallized debris in silicic eruptives, it is presumed that silicic chambers trap rising mafic intrusions, effectively incorporating their large heat content. Geologically, we must rely on peripheral magma injections that miss the main chamber to see that this process is occurring. Probably replenishment events occur for which there are no surface geologic evidence. The unrest at Long Valley Caldera during the 1980s may be such an event. Thus, hydrothermal systems can be seen as merely the shallowest and coolest of a series of stacked systems which transport heat upward from the Earth's interior. Hydrothermal systems are sustained by silicic magma systems which in turn are sustained by deep-rooted basaltic magmas.

Geological considerations can be used to point toward likely locations of high-level silicic chambers, but cannot establish with confidence their present-day existence. There are, however, a number of promising, though as yet untested, geophysical approaches to the problem. Several seismic techniques including teleseismic P-wave delay, shear-wave shadowing, and P-wave tomography have been successfully used to delineate suspected magma chambers beneath a number of volcanic centers throughout the world. However, verification of these techniques for melt location remains to be done. Heat flow would seem to be the most direct indication of proximity to magma, but the masking effect of shallow groundwater systems and the fine scale of deeper hydrothermal circulation make this approach invalid unless the deeper system is penetrated. Unfortunately for purposes of detection, high-level chambers tend to develop after long periods of sustained volcanism and tectonism, and this gives rise to a geological complexity that is an obstacle to geophysical interpretation. At the present stage of understanding, it is necessary to look for positive indications from a number of techniques. The situation is facilitated if magma is currently on the move, yielding a center of measurable surface inflation that coincides with a past center of major eruption, as is the case at Long Valley caldera.

Locating and drilling into the magmatic environment is the necessary next step to develop and test engineering techniques for extraction of magmatic energy. This would also permit a number of "quantum-leap" advances in the scientific understanding of magma-hydrothermal systems. Some of these areas were discussed by the Thermal Regimes Panel (1984) of the National Academy of Science's Continental Scientific Drilling Committee.

1. Validation of geophysical techniques. Direct verification of the presence of magma at a geophysically and geologically well-characterized site would be immediately applicable to a large set of volcanic fields. It would show which geophysical anomalies suggestive of magma do actually reflect the presence of magma. Scientifically, it would greatly advance understanding of the relationship of surface volcanic phenomena to the presence of shallow chambers.

2. Coupling of magma and hydrothermal systems. This is currently an environment of almost complete ignorance. It is commonly envisioned as a plastic, near-solidus conductive zone separating the convective zone from the magmatic regime. Drilling can verify its existence and determine its thickness and conditions. Do metals-bearing magmatic vapors cross this zone to generate hydrothermal ore deposits? Does the zone control the rate of heat loss from magma bodies and hence the rate of heat gain to hydrothermal systems? Reaching this level is important to understanding the size and life of the hydrothermal resource.

3. Validation of high-temperature geochemical techniques. Our ideas about the conditions under which magma is stored in the crust are based on thermodynamic treatment of phase assemblages and laboratory replication of magmatic conditions. Volatile contents are reconstructed from phase stability arguments and from analysis of glass inclusions in phenocrysts in quenched magma. These approaches are indirect and untested. Drilling would permit determination of depth and hence pressure of storage, measurement of temperature, and chemical analysis of magma quenched and sampled in situ with its volatile components fully retained (Eichelberger, 1989). Some physical and mechanical properties of magma could also be measured or at least estimated much better than is now possible.

4. Magmatic processes. One of the central questions of igneous petrology, how silicic magma chemically evolves, remains largely unsolved. Explaining chemical evolution will go far to solve a major problem of volcanology as well: why volcanoes erupt as they do. The answer widely accepted until the mid 1970s, that silicic magmas fractionate through crystal settling, has been largely dismissed through lack of persuasive geologic evidence and through the physical impossibility of tiny crystals raining out of such viscous magma. Recently postulated mechanisms involve a chemical boundary zone at the chamber margins, where crystals plate out on the wall and buoyant fractionated melt ascends to accumulate at the chamber roof (McBirney et al., 1985; Nilson et al., 1985). Counterbuoyant flow with a thin upward hydrated and perhaps wallrock-melt-contaminated stream outside a broader cooled, dry downward stream has also been suggested (Shaw, 1974). Whatever is the case, the boundary zone is a transitory feature which sweeps inward and vanishes as the magma body cools. By penetrating the margin of an active chamber, drilling can test critical aspects of these models for chemical evolution. By comparing magma sampled in situ with recent eruptives of known age, we can measure how fast these processes operate. The kind of samples needed to solve this problem, continuous core quenched to glass in-situ, has been successfully recovered from the lava-lake environment (Hardee et al., 1981). Although a lava lake presents a much shallower magmatic

target than do silicic magma reservoirs, it also presents a hotter and probably less stable environment for coring.

Given the magnitude of the resource and the key process of crustal evolution that silicic magmas represent, it is difficult to suggest a more promising target for exploratory drilling.

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PHASE I DRILLING OPERATIONS FOR THE MAGMA ENERGY EXPLORATORY WELL

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ABSTRACT

This paper describes the drilling operations for Phase I of the Magma Energy Exploratory Well in Long Valley caldera, near Mammoth Lakes, California. The hole is to be drilled in four yearly phases, with time for scientific experiments between the drilling intervals. Phase I was conducted during August - September 1989, and resulted in a 20" cased hole to 2550 feet. Although the drilling encountered fractured zones with massive lost circulation, the hole is in excellent condition and is at the depth and diameter specified in the original design.

INTRODUCTION

The centerpiece of the Magma Energy Program is the exploratory well in Long Valley caldera. This well will be drilled in four yearly phases, with scientific work in the borehole during the intervals between drilling operations. (See Figure 1 for the well design.)

Testing the fundamental hypothesis of the magma energy concept, that large bodies of partially-molten magma reside at relatively shallow depths, is clearly an essential step in advancement of the Magma Energy Program. Although extensive geophysical evidence indicates that a magma body lies beneath Long Valley caldera, this must be confirmed by drilling so close to the body that downhole thermal and seismic measurements will give unequivocal results. Engineers will gain crucial insight into the realities of the magma energy concept and scientists will have a unique opportunity to observe the near-magmatic environment in this well, but it has additional payoffs. Definition of the hydrothermal regime could stimulate commercial geothermal development above this massive resource and the ability to test advanced high-temperature drilling hardware in the hottest big hole ever drilled will improve the tools available for geothermal drilling in hot reservoirs.

Selection of this drilling location in Long Valley followed the review of 21 other potential sites in the United States (Hardee, 1984, and Carson, 1985). The actual drill site lies just south of the center of the resurgent dome. The location was prepared by a commercial geothermal company for drilling a 10,000 foot exploratory well; their drilling plans did not materialize, and they signed an agreement for Sandia to use the site. In return, we will furnish complete logs and other data on the well, and will offer Santa Fe Geothermal an opportunity to take control of the hole once drilling and scientific investigations are complete.

DRILLING ACTIVITIES

We spudded the hole for the first exploratory drilling phase on August 2, 1989, just south of the center of the resurgent dome in Long Valley caldera. Target depth for this phase was 2500 feet, the 20" casing point shown in Figure 1. The drill site, approximately 300 by 600 feet in size, was originally prepared in 1984 for a commercial exploratory well.

Loffland Brothers Company, headquartered in Tulsa but managing our project from their Bakersfield office, received the contract for this phase of the operation. The rig was Loffland's Number 202, famous in the oil patch for having drilled the two deepest wells (both below 30,000 feet) in the United States. With three 1100 horsepower diesels as prime movers and a 750-ton hook load rating, this rig has ample capacity to drill the complete well to 20,000 feet.

Since a 40" mud riser was already in place to a depth of 39 feet, the first rotary drilling was a 36" hole for 30" casing to a depth of approximately 300 feet. A 26" bit with a 36" hole opener was the drilling assembly for this interval. We had not drilled more than 15 feet out of the mud riser when we encountered massive lost circulation. There were no returns, and in fact the bottom of the hole was dry. Conventional lost circulation material (LCM) was ineffective, so unopened bags of bentonite and cement, along with approximately 400 empty mud sacks, were thrown into the hole and milled into a slurry with the drilling assembly. This provided enough of a plug that a conventional cement job could be placed, restoring circulation and allowing drilling to continue.

This experience was a harbinger for the next three weeks of drilling, for we placed 29 cement plugs to fight lost circulation between 70 and 1000 feet. Fluid losses were generally extreme (hundreds of barrels in a few minutes) and a wide variety of LCM gave little benefit. Once below 1000 feet, however, the formation became much more competent, and we had no further lost circulation to the 20" casing point.

Persistent northward drift in the wellbore also required considerable use of a downhole mud motor to keep deviation at or under one degree. Once we entered the Bishop Tuff at approximately 2000 feet, this problem also diminished and we drilled the last 500 feet with conventional rotary methods. Drilling in the Bishop Tuff was generally good, although penetration rate varied from 10 to 30 feet/hour, apparently because of hard intrusions.

After reaching TD of 2568 feet on September 4, we conditioned the hole, ran a small suite of wireline logs, and rigged to run the 20" casing. This went smoothly; the casing crew ran 66 joints in 12 hours and we got a good cement job with full returns and little evidence of mud contamination. Installation and testing of the wellhead completed the major part of the Phase I exploratory drilling, but we continued with a 200 foot coring run for preliminary scientific investigation.

At present, the data available from this hole comprises the daily drilling reports, the mud logs (including the lithology from cuttings), the wireline logs done in the 26" hole (acoustic, gamma, dual induction, temperature, and caliper), the analysis of the core, and a series of long-term temperature measurements made in the core hole.

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

NGA PERSPECTIVES ON GEOTHERMAL TECHNOLOGY DEVELOPMENT

Moderator: Dave Anderson
National Geothermal Association

CRITIQUE OF DRILLING, COMPLETION AND PRODUCTION R&D PROJECTS

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Northern California Power Agency

Because of my particular situation, I am gratified to see significant progress being made on short-term programs aimed at technological advances and cost reduction relative to both exploratory & development drilling. Improved technology in high temperature lost circulation control techniques, rotating head seals, blowout prevention equipment, and pneumatic downhole drill motors are examples of projects for which there is immediate need and which can significantly reduce drilling costs.

It was noted that the aggregate drilling cost reduction objectives of three of the projects total 48% by 1994. It is felt that this is somewhat over optimistic and can probably be attributed to enthusiasm and zealousness on the part of those directly involved in the projects. Quite frankly, if these projects result in cost reductions 1/4 to 1/3 of that amount, which I feel is more realistic, they will still have been most worthwhile and highly successful.

If is unfortunate that because geothermal drilling makes up such a small percentage of total drilling dollars spent (as opposed to oil and gas) and with the continued depressed state of the drilling industry, there is little economic incentive for industry development of specialty equipment oriented primarily towards geothermal application. Therefore, the participation of DOE in this area is welcomed and greatly appreciated.

It is further gratifying to note the concern of the Department for the problems presently being experienced in the Geysers. This concern is evidenced by the number of projects with objectives oriented toward the Geysers with its basic problems of pressure/productivity decline and the severe corrosion present in some areas of the field.

It is noteworthy that there is a new spirit of cooperation among both steam supply and power generation operators in the Geysers which certainly was not present as recently as two years ago.

At present PG&E and its steam suppliers Unocal and Geysers Geothermal Company are conducting tests to determine the reservoir effects and operational feasibility of the load following mode of generation in their areas.

Another noteworthy project is a pilot reinjection project that NCPA, GGC, and Unocal are jointly conducting in a severely depleted portion of the reservoir in the southeast Geysers. This project has been in operation for 6 months and progress to date is extremely encouraging. Hopefully, the project will be expanded in the near future. DOE has expressed interest in this project and their participation in its technical aspects would be welcomed.

While I do not feel qualified to comment on the long term projects i.e., Hot Dry Rock, Geo Pressured, and Magma Energy, it is assumed that these projects are necessary if the nation is to continue in its quest for significant viable alternative energy sources in order to minimize our dependency on foreign oil.

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COMMENTS ON THE DOE GEOTHERMAL EXPLORATION R&D PROGRAM

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The Department of Energy has supported many important and exciting R & D programs over the past several years, relating to drilling and production of geothermal fluids, fluid treatment, energy conversion, and future energy sources. All of this is as it should be. Exploration is encompassed in certain aspects of the research into magma energy and hot dry rock; and exploration is assessed inferentially in the course of well logging or drilling technology. There is, however, almost no geothermal exploration program per se. The reason for this is not hard to see: there is almost no demand for exploration of new geothermal systems in the United States today.

During the 1960s and 1970s, exploration companies were remarkably successful in discovering geothermal fields in a variety of geologic settings in the western United States. However, the market for geothermal power lagged far behind the discovery rate. With the decline in energy prices in the '80s, exploration all but ceased. All emphasis was placed upon the commercial development of already discovered fields; and there were very many of them, as the result of American technical ingenuity and persistence. This trend to commercialization was enhanced by various government policies (PURPA Standard Offer contracts, for example), and by the introduction of binary-cycle technology to allow utilization of low-temperature systems (120° - 180°C) that previously had been dismissed as uneconomical.

The 1980s, therefore, was the decade of commercial development. However, an interesting thing now has occurred: almost all of the previously discovered, easily accessible geothermal fields in the United States have been committed for development. There are still a few discovered fields waiting for commercialization in the Cascade Range of California and Oregon, and at a couple of places in Nevada and New Mexico. Once these have been contracted for development, there is just the fill-in drilling and development to be done at other fields. That is, unless there is a new program of exploration by industry and government.

The exploration successes of the 1960s and 1970s were based on a very simple formulation: start where boiling water or steam is pouring out of the ground, and explore and drill outwards from those spots. Simple and effective; except in those places where cold groundwater masked the upward flow of hot fluid, or where steep topography resulted in long outflow tongues, far from the geothermal upwelling, or where complex mixing of several non-thermal and thermal aquifers was occurring. For the 1990s, we will still have a few undrilled areas where steam or boiling water comes out of the ground at us. But we will need to accept the challenge that other geothermal systems may have much more subtle signatures, and perhaps cannot be found by our traditional techniques.

The astonishing thing in a brief retrospective view of geothermal exploration is how few fields were discovered by geophysics, and how many were discovered by almost-random drilling of water wells, temperature-gradient holes, oil tests, and geothermal go-for-broke exploration wells. Perhaps this was inevitable in an industry that had no antecedent methodology, but which borrowed from the oil industry, and improvised as it went along.

We see today that temperature-gradient drilling, to ever greater depth, has become the standard method for exploration in the Cascade Range, the Basin and Range, even The Geysers, and now in Hawaii. However, drilling, even drilling slim holes, is expensive; and with larger target circles being drawn, now that the boiling springs are largely drilled, drilling may not be sufficiently regional a tool for the future.

Where do we go from here?

I suggest that four things should be done, beginning now. The first is to survey exploration methodology and practice in many places around the world today. Despite the absence of new exploration in our country, geothermal exploration flourished in the '80s in the Philippines, Japan, Mexico, Kenya, Turkey, Guatemala, Tibet, El Salvador and elsewhere. Data from dozens of projects have piled up in the files of international lenders, research institutes, private companies, and government agencies. It is time now to obtain and compile those data into usable case histories; and to analyze and synthesize those case histories into sets of understandable principles for exploration practice.

I expect that we will find that for each type of geothermal environment (for example, active volcanic, or basin-and-range, or geopressured, or semi-arid rift), a different and specific suite of exploration principles are applicable. No single set will suffice for all areas. Unlike the "universal" Italian geothermal methodology (widely touted in Latin America, with relatively little success in application), one cook book will not serve all cooks. However, we must begin the search for underlying principles now, if we are to have abundant new geothermal resources to offer our country in the '90s.

Second, I continue to urge that there be support for the compilation of basic earth science data for the United States: complete topographic coverage at useful scales; local and regional gravimetric surveys at corresponding scales; ditto for geologic mapping; structural cross-sections, based on extensive drillhole data available in the oil and minerals industries; regional and detailed groundwater maps (piezometric surfaces, aquifer characteristics, etc.). These basic data are lacking for large and potentially significant areas of the United States. It is disturbing that this work has not previously been completed. By contrast, in Japan, there are nationwide programs to obtain, compile and publish such materials for use in geothermal exploration and regional resource assessment. Perhaps this is the role of the U. S. Geological Survey, and not the DOE; however, in the absence of a USGS program, I urge that DOE accept this important challenge. Its value to an American energy program can easily be demonstrated.

Third, as a part of data compilation, I recommend that new emphasis be given to regional and local groundwater studies. Groundwater is an intimate constituent of all geothermal systems; indeed, it interferes with and dominates the Cascadian geothermal systems. But we know less in detail about groundwater quantities, qualities, storage, movement, recharge or age than we know about the surface of the moon. This is unacceptable.

Fourth, I suggest that there be a cooperative program with industry to share exploration data and interpretations, for the development of exploration programs suitable for the '90s and thereafter. There have been successful industry-government data-sharing programs previously. Exploration must be cost-effective to be successful. It cannot be too arcane, too academic, too theoretical. It must be accessible, practical in its application, and above all, it must be economically feasible. Until a cost-effective exploration methodology can be demonstrated, I believe that we will have no significant geothermal exploration in this country. An industry-led program is a step in the right direction towards a cost-effective program.

I close by extending my thanks and appreciation to Dr. Ted Mock and his associates in DOE, and to the various contractors and researchers that have made this conference successful. Special thanks, of course, go to Meridian Corporation for their fine efforts with program logistics. I hope that these review conferences will continue in future years, and that together we will be successful in creating a powerful geothermal industry for the 21st Century.

COMMENTARY ON THE GEOTHERMAL TECHNOLOGY PROGRAM
OF THE
DEPARTMENT OF ENERGY PROGRAM REVIEW VIII

Myron Tribus
Exergy, Inc.

General Remarks

From time to time over the last 25 years I have either participated in or reviewed various Governmental technical programs. I must say at the outset that this review has been one of the best I have seen. I refer specifically to the generally high technical level of the presentations, the open spirit of inquiry and discussion and the efforts of the presenters to make clear to the audience and themselves the relevance of their work to the objectives of the Congress when the programs of the DOE were funded. Having worked in Government myself, I know how difficult it is to manage large complex programs such as the Geothermal Technology Program and I hope that the efforts of the management team will be properly recognized in the DOE in the future.

Of course, every program can be improved and in the following remarks I shall concentrate on things which, in my opinion could have been and should be done better. However, at the outset I do want to say that the program, as it has been carried forward, deserves our praise and admiration.

The Need for Better Economic Measures of Progress in Geothermal R&D

In government and industry there is usually a gulf between those who do research and those who pay for it. Economists and managers, in general, have great difficulty in assigning a dollar value to technology which has not yet been put to use. Once a technology has been wrapped up in a product or a service, in retrospect we have no difficulty saying how much it is worth. But before the fact of application, the task is much more difficult. Therefore, it is up to research and development people, themselves, to provide measures which are at least indicative of progress towards the goal of providing less expensive electric power.

There are three important customers for DOE sponsored R&D: Designers, Systems Engineers and Entrepreneurs. These three form the teams of people who put together the total system for power generation. They are concerned with finding the geothermal source, drilling the wells, positioning the power plant, disposing of the brine, rejecting the heat, connecting the equipment together, driving the generators and connecting to the grid. They worry about whether the system will operate reliably and with only a small crew. They are concerned over safety and environmental impact. And last, but not least, they are the people who have to convince the bankers, and the others who control financial resources, that a proposed operation will return sufficient capital that the investment makes good sense.

A good systems engineer needs to be able to subdivide the plant by its processes and for each process needs to be able to compute its contribution to the overall system cost. In our company, Exergy, we do this by evaluating all energy resources in terms of their potential to provide electrical energy and their contribution to overall cost.

Therefore, in reviewing the presentations by several speakers, I was struck by the fact that too often energy resources are presented in terms of their HEAT EQUIVALENTS, which can be a misleading comparison. As is well known from the second law of thermodynamics, not all heat sources of the same heating value are equivalent. It makes a difference at which temperature the heat is supplied.

The technical term, "exergy" (from which our company derives its name) was coined in Europe just after World War II to denote the capability of a heat source to deliver work. It represents a generalization of the Carnot principle applied to sources of variable temperature. In the USA a similar concept has been called "Availability" and "Lost Work". Exergy and "exergetic analysis" are now becoming popular in the USA as part of what is commonly called "second law analysis". My first proposal to the Geothermal Technology Program therefore is:

PROPOSAL #1: In presenting data on geothermal resources do not use thermal energy as a measure of value. Instead, convert all heat measures to exergy and report exergetic values. It is suggested that units such as Megawatt days or Gigawatt-days be used as these are most readily translatable without need for computing.

PROPOSAL #2. When presenting information on power, convert all deliveries of energy to exergetic units per unit of time. It is suggested that the units be Megawatt or Gigawatts.

PROPOSAL #3. When advances are made which appear to affect the cost of delivering energy or power, that the measures be given in terms of changes in cents/kw hr.

The Need for Additional Work on Properties of Working Fluids

The chain of activities, which begins with looking for where to drill and ends with the conversion of the exergy of geothermal fluids into useful electricity, includes the all important step of converting thermal energy to work. This step always entails a working fluid. Most of the power plants of the world operate on steam and millions of dollars have been spent over the years determining the thermophysical properties of water and steam, culminating in internationally accepted "steam tables".

Geothermal systems are much more likely to operate on working fluids other than steam and, in fact, are more likely to operate on mixtures of fluids.

The theoretical foundations for the calculation of the thermophysical properties of mixtures is not on a very good basis. The disagreements between measurements and theory are too large for careful power plant design. Geothermal power plants are required to have very high efficiencies because the return on investment in such plants is a very sensitive function of the overall plant efficiency.

PROPOSAL #4. It is recommended that the DOE, in cooperation with the National Institute of Standards and Technology, develop an accurate data base of thermophysical properties of working fluids most likely to be useful in geothermal energy conversion systems. Ammonia-water mixtures, which have thus far been shown to yield systems of the highest known thermal efficiencies should be among the mixtures investigated. Other mixtures should also be investigated so as to advance the theory of mixtures.

The Need for Additional Work on Heat Transfer

When the costs of energy conversion systems are examined it is found that geothermal plants require a considerable expenditure on heat exchangers. It is necessary to wring out of these systems every possible saving in geothermal exergy and this means large, carefully designed heat exchangers.

There is very little good information on heat exchange involving mixtures which are condensing and evaporating. While it is true that there are many industrial processes which use condensing and boiling mixtures, the investigations we have made at Exergy indicate that the methods of design are much too crude for power plant practice. As attempts are made to decrease the cost of power plants by using smaller temperature differences and more efficient heat exchangers, we have found that there may be differences of as much as 50% in estimates of surface required, depending upon the method of analysis employed.

In addition, in recent years, significant advances have been made in the design of high performance surfaces (integral finning, convoluted tubing, etc.) for condensers and boilers.

PROPOSAL #5. The DOE should sponsor fundamental investigations into the performance of enhanced heat exchanger surfaces for use with mixtures of fluids in condensation and boiling. These investigations should be designed to contribute to our understanding of the fundamental processes involved in the use of these surfaces and should not be "demonstrations".

A proposed change in the perspective from which the DOE examines Progress in Geothermal Energy

Since leaving Government and becoming active as an entrepreneur who is attempting to bring a new power system to the marketplace, I have become more understanding of the differences in perspective of a Federal employee, charged with the responsibility to keep a program alive and supported by the Congress, and the perspective of an entrepreneur attempting to achieve a similar end point through the forces of the market. Based on things said at the conference, I have no doubt that my colleagues in the government are as anxious as I am to see a vigorous and healthy private industry based on geothermal resources. We have the same objectives. But whereas the Federal employee has to satisfy the Congress and the Administration that what is done will be approved by voters, we who are trying to introduce new technologies have to worry about whether what is proposed will be approved by bankers. If we don't succeed, the work of the DOE will come to naught.

I believe, therefore, that it would be of considerable help if the DOE were to support a few independent studies in areas in which there is hope that a new technology will be brought forward through the marketplace. These studies should center their attention on the problems of the entrepreneur who is trying to move the technology from the laboratory to the marketplace. Such studies need not be expensive. Indeed, they should involve only a few people and will be based mostly on interviews and, perhaps, some computer simulations. Their objective should be to help the DOE managers to "walk in the other fellows moccasins" for a little ways. I believe that many of the barriers to progress are structural and the solutions to many of the problems we face are not going to be expensive. They will involve steps the Government can take, probably at no cost at all, to make the path of the entrepreneur less hazardous.

My final recommendation, therefore, is:

PROPOSAL #6: The DOE should sponsor simple studies of the problems of the technological entrepreneurs who are attempting to bring new technologies to the market place. By studying their problems the DOE will be better able to help the entrepreneurs overcome the many problems attendant to the introduction of new and improved technologies.

RESERVOIR ENGINEERING CRITIQUE

Mohinder S. Gulati
Unocal Geothermal

Understandably, The Geysers has dominated the discussion at this year's Geothermal Energy Review. Accelerated decline rates manifested themselves at The Geysers in the last 3 - 4 years. This has prompted a re-orientation of priorities on the part of the Department of Energy and California Energy Commission in the last 1 - 2 years. Ted Mock and Marshall Reed sought the industry input at several "townhall" meetings and came up with pertinent research projects. These projects are intended to be short term and result oriented. I welcome this approach.

I found Hank Ramey's proposal on adsorption very intriguing. While the peak of The Geysers is behind us, it is generally believed that the production rate is going to have a long tail. The production and decline rates could be strongly influenced by adsorption. This research could, therefore, help us in better prediction of the future performance.

In addition to depletion, corrosion is another problem at The Geysers. Several companies are engaged in mitigating corrosion at the surface, before the steam goes into the power plant. Corrosion abatement in the subsurface is an obvious next step. If subsurface corrosion abatement by injection is successful, it will also accomplish the objective of reservoir recharging.

This experiment will be expensive. This seems like a good project for DOE and/or CEC funding. Some elements of this project may be accomplished under the Hot Dry Rock project. In that case, both Hydrothermal and Hot Dry Rock groups within the DOE can join forces.

Compared to oil and gas, the geothermal industry is very young. No geothermal field has yet been abandoned. But some projects have been on line for many years. A lot of data has been generated but it is scattered. It will be very useful to gather all the data on projects like Larderello, Wairakei, The Geysers, Matsukawa and Cerro Prieto, analyze and publish it. It will be a very useful effort and DOE is the most appropriate organization to undertake it.

CRITIQUE PANEL COMMENTS ON DOE GEOTHERMAL FLUID HANDLING

Olin Whitescarver
UNOCAL

I join my colleagues in complimenting Ted Mock for putting together an excellent program. The speakers presentations were prepared, well presented, interesting and informative.

Conference attendance is down and geothermal seems to have slipped from its heretofore prominent position in the national energy strategy. That is hard to comprehend when geothermal is contributing nearly 3,000 MW to our national power grid. It means that we have to redouble our effort in spreading the word on the viability of geothermal.

There was little presented in this conference related to fluid handling, i.e., pipes, valves, vessels and pumps. This speaks to the success and commercialization of prior efforts, as evidenced by the number of new facilities that have come on line recently. Even so, there is a need to improve and optimize facilities to achieve the lowest unit cost of production so that competition can be met. There is also a need to modify the rules to provide a level playing field, so that geothermal plants can be designed to thermodynamic rules, rather than being unduly burdened by political rules.

Brookhaven Laboratories presented the majority of work in the area of fluid handling. Most things that they have developed in the way of elastomers and material of construction such as polymer concrete have become common place in our operations.

The minimization or elimination of hazardous waste will continue to become an increasingly important element to geothermal development. The biotechnology research to breakdown heavy metals may be of significant future value.

The cross fertilization of applying hot dry rock technology to enhance recovery from existing vapor dominated fields was quite interesting and could lead to more effective use of the resource. Geothermal has always been on the forefront of environmental issues, it should also be the model of conservation and efficient use of resource. This exchange of technology may help geothermal achieve that goal.

Thank you for the opportunity to comment on the program.

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SUMMARY OF CONCLUDING REMARKS

Ronald Loose
DOE Office of Renewable Technologies

Members of industry are to be highly commended for their willingness to participate in PR VIII and for sharing their views on the Department of Energy's (DOE) geothermal program. Their views are important to us and will be given consideration in the development of future plans.

Because today's commercial energy environment is very competitive, geothermal energy must surmount not only technical barriers, but institutional and educational barriers as well. The geothermal industry can play a decisive role in increasing the awareness of geothermal energy and improving its image in the public, federal, and private arenas. The following five suggestions or "challenges" are offered as initial steps to overcome some of these obstacles:

- Geothermal energy must compete for DOE funding with other end-use renewable technologies in the utility sector. In order to compete effectively, the return-on-investment from geothermal resources must be presented to DOE management both understandably and favorably.

- The National Energy Strategy (NES) will have a major influence on DOE's decision-making process, particularly in the case of renewable energy. More specific input to the NES is needed, especially by industry, to make the views of those involved in geothermal energy known.

- DOE has both a short-term and long-term strategy. Positive initiatives must be presented to DOE management. Additionally, DOE cannot be the sole source of funding for these initiatives; cost-shared support with industry is necessary.

- For geothermal programs to be competitive with other renewables, there must be an awareness of geothermal energy. It is in industry's interest to keep executives in DOE and other agencies informed on how government-sponsored research has and could assist them.

- The geothermal industry should be more concerned with improving the public's perception of geothermal energy. DOE receives letters from individuals and organizations that contain misinformation and convey a poor perception of geothermal energy. Industry should make a greater effort to educate the public and inform them about geothermal resources and the technology used to convert the heat into a useful form of energy.

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FINAL AGENDA

FINAL AGENDA

U.S. DEPARTMENT OF ENERGY
GEOTHERMAL PROGRAM REVIEW VIII

"The National Energy Strategy -- The Role of Geothermal Technology Development"

TUESDAY (April 17)

7:00pm	**Registration and Reception** (Cash Bar)	

WEDNESDAY (April 18)

7:30am	**Registration and Continental Breakfast**	

OVERVIEW

Chairman: **John E. Mock, Director, DOE Geothermal Division**

9:00am	**DOE Welcome and Announcements**	John E. Mock, Director, DOE Geothermal Division
9:05am	**Welcome**, by DOE San Francisco Operations Office	Pat Bernard, Acting Deputy Manager, DOE San Francisco Operations Office
9:15am	*The National Energy Strategy -- The Role of Geothermal Technology Development*	Stephen C. Lipman, President, UNOCAL Geothermal Division, UNOCAL Corporation
9:45am	*Geothermal Energy Development in the Pacific Northwest*	Michael H. Heys, President, California Energy Company
10:00am	*The Role of The California Energy Commission in Geothermal Research and Development*	Michael A. Smith, California Energy Commission
10:15am	**Break**	
10:45am	*The Role of Geothermal Technology Development In Expanding Our Energy Reserves*	John E. Mock, Director, DOE Geothermal Technology Division
11:15am	*Geothermal Projections for the National Energy Strategy*	Alan J. Jelacic, DOE Geothermal Technology Division
11:30pm	**NGA-Sponsored Lunch** *Linking Financial Institutions to Certificate of Review Export Trading Company*	Scott D. Morse, Morse Merchant Agribusiness

WEDNESDAY (April 18) continued

HYDROTHERMAL ENERGY CONVERSION TECHNOLOGY

Chairperson: **Kenneth J. Taylor, Project Manager, DOE Idaho Operations Office**

1:30pm	*Hydrothermal Energy - An Important Part of America's Energy Strategy*	Kenneth J. Taylor, DOE Idaho Operations Office
1:40pm	*Advanced Binary Geothermal Power Plants -- Limits of Performance*	Carl J. Bliem, Idaho National Engineering Laboratory
2:00pm	*Advanced Materials for Geothermal Applications*	Lawrence E. Kukacka, Brookhaven National Laboratory
2:20pm	*Developments in Geothermal Waste Treatment Biotechnology*	Eugene T. Premuzic, Brookhaven National Laboratory
2:40pm	*Chemical Models for Optimizing Geothermal Power Production*	John H. Weare, University of California, San Diego
3:00pm	**Break**	

HYDROTHERMAL RESERVOIR TECHNOLOGY

Chairperson: **Kenneth J. Taylor, Project Manager, DOE Idaho Operations Office**

3:30pm	*Reservoir Technology Research at LBL Addressing Geysers Issues*	Marcelo J. Lippmann, Lawrence Berkeley Laboratory
4:00pm	*Adsorption in Vapor-Dominated Systems*	Henry J. Ramey, Stanford University
4:20pm	*Management of Geothermal Resources*	Dennis L. Nielson, University of Utah Research Institute
4:40pm	*Reservoir Related Research at Idaho National Engineering Laboratory, Lawrence Livermore National Laboratory, and Oak Ridge National Laboratory*	Joel L. Renner, Idaho National Engineering Laboratory
5:00pm	**Adjourn for the Day**	

THURSDAY (April 19)

7:30am	**Continental Breakfast**	

HYDROTHERMAL HARD ROCK PENETRATION TECHNOLOGY

Chairperson: **George P. Tennyson, Jr., Program Manager, DOE Albuquerque Operations Office**

8:30am	*Overview - Hard Rock Penetration*	James C. Dunn, Sandia National Laboratories
9:00am	*Borehole Directional Radar*	Paul J. Hommert, Sandia National Laboratories
9:30am	*Lost Circulation Technology Development Projects*	David A. Glowka, Sandia National Laboratories
10:00am	**Break**	

THURSDAY (April 19) continued

HOT DRY ROCK TECHNOLOGY

Chairperson: **George P. Tennyson, Jr., Program Manager, DOE Albuquerque Operations Office**

10:30am	***Status of the Hot Dry Rock Geothermal Energy Development Program at Los Alamos***	David V. Duchane, Los Alamos National Laboratory
10:55am	***Using HDR Technology to Recharge The Geysers***	Donald W. Brown, Los Alamos National Laboratory
11:20am	***HDR Technology Transfer Activities in the Clearlake Area, California***	Kerry L. Burns, Los Alamos National Laboratory
12:00	**Lunch** (not hosted)	

GEOPRESSURED-GEOTHERMAL TECHNOLOGY

Chairperson: **Kenneth J. Taylor, Project Manager, DOE Idaho Operations Office**

1:30pm	***Geopressured Energy - An Environmentally Safe Alternative***	Kenneth J. Taylor, DOE Idaho Operations Office
1:40pm	***The Geopressured-Geothermal Resource, Research, and Use***	Jane Negus-de Wys, Idaho National Engineering Laboratory
2:00pm	***Assessment of Geopressured-Geothermal Resources for Near-Term Utilization***	Charles G. Groat, Louisiana Geological Survey
2:20pm	***Geopressured-Geothermal Energy Field Operations***	Ben A. Eaton, Eaton Operating Company, Inc.
2:40pm	***Operation of a Geopressured Hybrid Power System at Pleasant Bayou***	Ben Holt, The Ben Holt Company
3:00pm	**Break**	

MAGMA ENERGY TECHNOLOGY

Chairperson: **George P. Tennyson, Jr., Program Manager, DOE Albuquerque Operations Office**

3:30pm	***Overview - Magma Energy***	James C. Dunn, Sandia National Laboratories
4:00pm	***Silicic Magma in the Crust***	John C. Eichelberger, Sandia National Laboratories
4:30pm	***Phase I Drilling Operations for the Magma Energy Exploratory Well***	John T. Finger, Sandia National Laboratories
5:00pm	**Adjourn for the Day**	

FRIDAY (April 20)

7:30am	**Continental Breakfast**	

NGA PERSPECTIVES ON GEOTHERMAL TECHNOLOGY DEVELOPMENT

8:30am	**NGA/CORECT Presentation: Developments in International Geothermal Energy Opportunities**	
9:00am	**NGA Industry Critique Panel**	
	Moderator	Dave Anderson, NGA
	Drilling and Completion R&D	Dick Yarter, No. CA Power Agency
	Exploration and Resource Development	James Koenig, GeothermEx Corporation
	Power Conversion Technology	Myron Tribus, Exergy, Inc.
	Reservoir Engineering	Mohinder Gulati, UNOCAL
	Fluid Handling	Olin Whitescarver, UNOCAL
	Break (as time permits)	
11:15am	**Concluding Remarks**	Ron R. Loose, Director, DOE Office of Renewable Technologies John E. Mock, Director, DOE Geothermal Division
11:30am	**Conference Adjourns**	

11:30am - 12:00	**DOE Management Meeting -- Executive Session**	

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April 18-20, 1990

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