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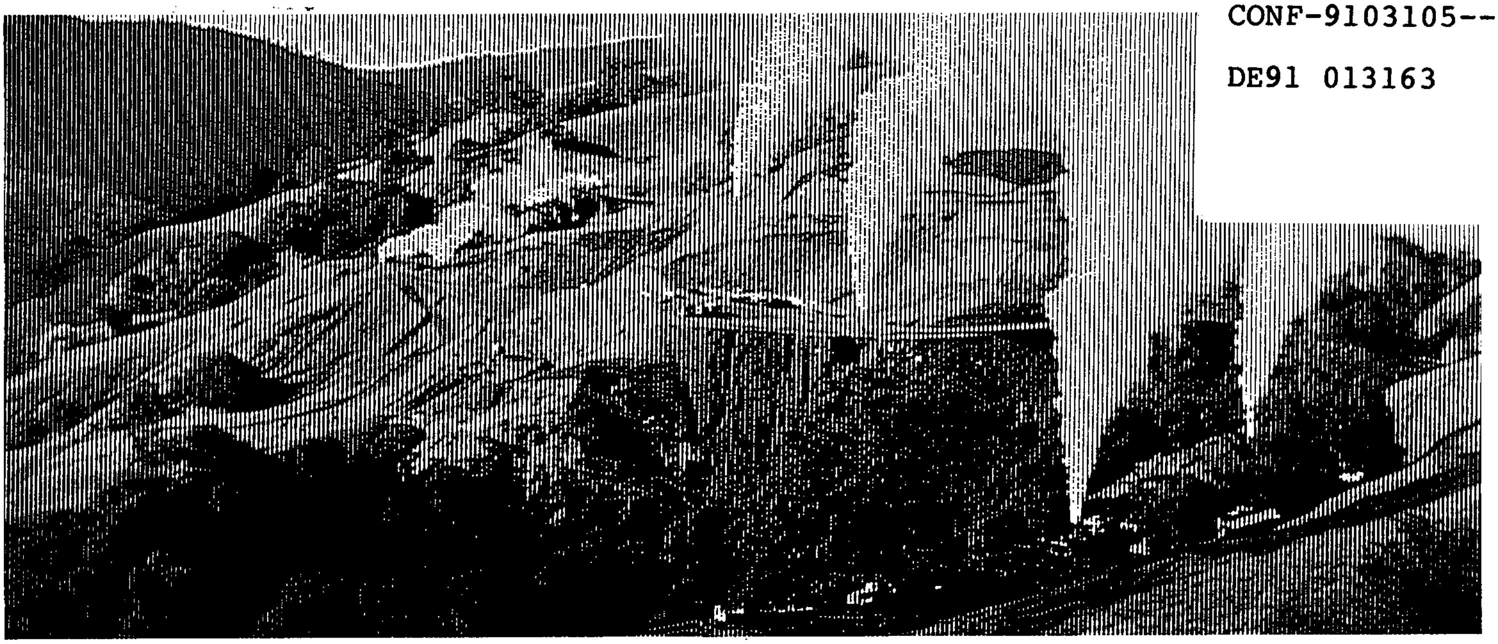

GEOTHERMAL PROGRAM REVIEW IX

PROCEEDINGS

"The Geothermal Partnership— Industry, Utilities, and Government Meeting the Challenges of the 90's"

March 19-21, 1991
San Francisco, CA

MASTER

Sponsored by:

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Division
Washington, DC 20585

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PROGRAM REVIEW IX WRAP-UP

NGA PERSPECTIVES ON GEOTHERMAL TECHNOLOGY DEVELOPMENT

Moderator: Dennis Nielson, University of Utah Research Institute

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 community.

This year's conference, Program Review IX, was held in San Francisco on March 19-21, 1991. The theme of this review was "The Geothermal Partnership -- Industry, Utilities, and Government Meeting the Challenges of the 90's." The importance of this partnership has increased markedly as demands for improved technology must be balanced with available research resources. By working cooperatively, the geothermal community, including industry, utilities, DOE, and other state and federal agencies, can more effectively address common research needs. The challenge currently facing the geothermal partnership is to strengthen the bonds that ultimately will enhance opportunities for future development of geothermal resources.

Program Review IX consisted of eight sessions including an opening session with presentations by Mr. John Motter, Supervisor of Supply/RD&D, Sierra Pacific Gas and Electric, and Mr. Darcel Hulse, President, UNOCAL Geothermal Division. The seven technical sessions included presentations by the relevant field researchers covering DOE-sponsored R&D in hydrothermal, hot dry rock, and geopressured energy and the progress associated with the Long Valley Exploratory Well.

As with previous Program Reviews, a key facet of Program Review IX was an "Industry Critique" session organized and chaired by the National Geothermal Association (NGA). Five NGA representatives were invited to comment on specific areas of DOE's geothermal R&D: Drilling, Exploration/Reserve Development, Power Conversion Technology, Reservoir Engineering, 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 Program Review IX primarily resulted from the individual contributions of the researchers, academia, representatives of federal, state, and local governments, and others in the geothermal community 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 planning the future direction of the geothermal R&D program.

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

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

OVERVIEW

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

CHALLENGES FOR ELECTRIC UTILITIES -- OPPORTUNITIES FOR RENEWABLE ENERGY

Dr. Robert L. San Martin
Deputy Assistant Secretary, Office of Utility Technologies
Office of Conservation and Renewable Energy

U.S. DEPARTMENT OF ENERGY

Good morning and welcome to Geothermal Program Review IX, "The Geothermal Partnership -- Industry, Utilities, and Government Meeting the Challenges of the '90s." The Department of Energy's Office of Utility Technologies works in close cooperation with industry and utilities to promote and develop renewable energy and energy efficient technologies to provide safe, reliable electric energy at a minimum cost. Historically, these services have been in the form of electricity supply from hydroelectric, fossil fuel and nuclear generating sources which supplied about 90 percent of the nation's total electric energy needs in 1989. Today, demands on utilities are changing as a result of the growing public concern with environmental impacts of power generation, transmission and distribution, and utility concerns with uncertainties in the cost of fuels and construction. The challenges which face the nation's electric utilities and the opportunities for renewable energy technologies to help meet those challenges is the topic of my discussion today.

THE ELECTRIC UTILITY SYSTEM

Electricity is a commodity we take for granted as an industrialized country. Because we already have a highly reliable electricity system we tend to overlook the size and complexity of this sector. There are over 685 GW of installed generating capacity in the U.S., at over 10,000 public and privately owned plants, producing energy which is distributed over a transmission system that consists of over 187,000 miles of lines.[1,2,3]

To illustrate the expansive size of today's electric system, total utility plant investment by investor-owned utilities alone amounts to $475 billion dollars.[4] America's vast reliance on the sector is underscored by its hefty dependence on electricity -- about 223 billion kWhs for refrigeration alone;[5] the output of roughly 78 power plants just to chill and preserve our foodstuff.

We rarely appreciate the complex, engineering marvel we have at our fingertips. All of North America from the Rio Grande to Hudson Bay is served by just three interconnected systems, each of which runs synchronously throughout the interconnection at a steady 60 Hz -- 24 hours a day, 365 days a year. Despite the steadfast nature of the nation's electric network, the system is vulnerable to disruption. During the 1965 blackout a series of events collapsed the entire Northeastern grid, leaving parts of New York City in total darkness for more than 13 hours. The breakdown took about 1 minute to run its course, from the first transmission line failure to the last tripped interconnection. The electric utility industry responded to that crisis by building a stronger and more reliable system. The North American Electric Reliability Council (NERC) was established to develop and enforce standards for reliable operation. New technologies were developed for controlling and protecting transmission systems.

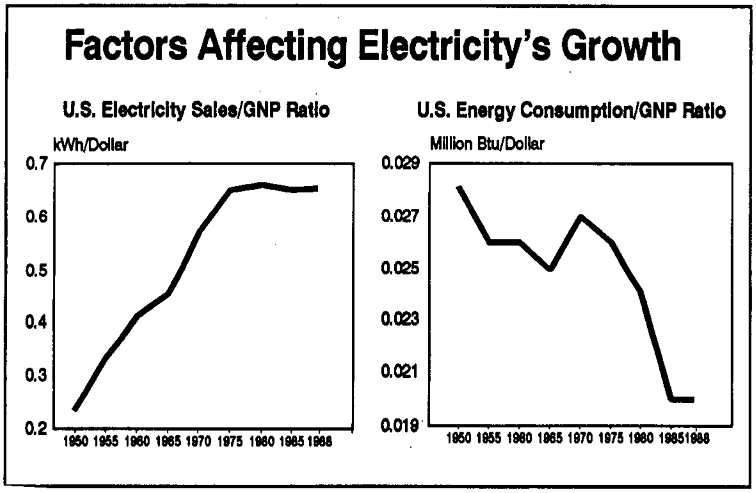
Individual utilities worked in concert to establish a new level of cooperation and coordination that would drastically reduce the possibility of such an occurrence from happening again.

Today's challenges are different, extending beyond vulnerabilities in the transmission system to encompass regulatory, environmental and financial challenges that threaten the reliability of the U.S. electric system. The same principles of cooperation, coordination, and technological innovation that led to a stronger electric system following the 1965 blackout can lead to a more fortified and reliable electricity sector after this period of challenge.

ELECTRICITY GROWTH AND THE U.S.ECONOMY

Electricity production accounted for 36% of U.S. primary energy consumption in 1989, 29.14 out of 81.3 Quads.[6] This is about three times greater than consumption figures, because the conversion efficiency for electricity is about 33 percent. In turn, electricity accounts for almost one third of industrial primary energy consumption and almost two thirds of building primary energy consumption, again taking into account the efficiency losses in generation.

Electricity consumption is expected to grow steadily across the commercial buildings, residential, and industrial sectors. According to recent National Energy Strategy projections, primary energy consumption for electricity consumption is expected to continue to grow to between 50 and 69 Quads by 2030 -- 50 Quads if aggressive conservation is pursued, 69 Quads if electricity tracks GNP growth closely, with corresponding growth in end-use energy consumption. While the overall energy/GNP relationship has been interrupted, electricity and GNP growth continue to track closely. And although electricity and GNP continue to correlate strongly, the ratio has declined --the U.S. is extracting more GNP from the electricity it does use.



What these broad indicators tend to mask are the significant micro- and macroeconomic adjustments that underlie these highly aggregated indicators. Success in deploying renewable energy technologies and conservation in the electric utility sector will depend on understanding these finer details and trends and their impacts on the electric utilities and individual energy users who will buy our technologies.

ELECTRICITY AND INDUSTRY

Sectoral shifts in the economy impact electricity use across broad sectors of the economy. For example, shifts in the output of aluminum smelting operations between U.S. and overseas plants has major influence on electricity demand. Movements in electricity intensive industries have a significant influence on overall demand. This influence can either increase or decrease electricity demand, depending on how sectoral demand tends to shift.

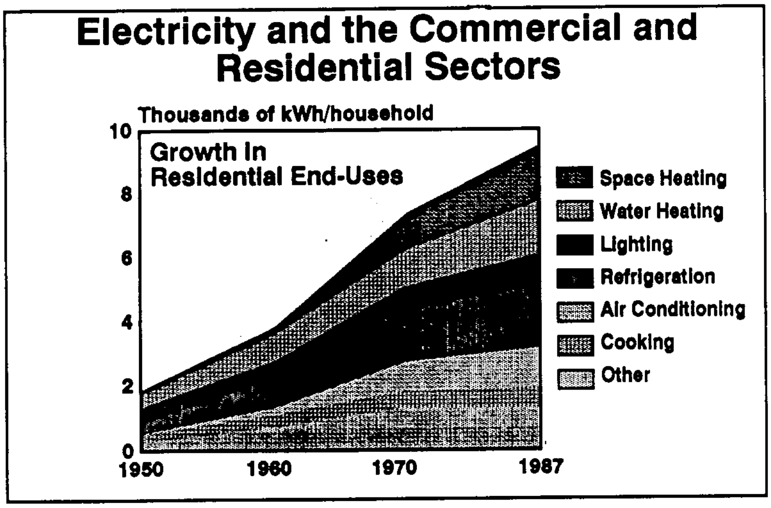
Technological change within industry sectors influences sectoral shifts, and can also fundamentally change the nature of demand. In some cases electricity conserving process substitutions can significantly drive down demand, as is the case with the substitution of more efficient motor drives. In other cases new technologies create new electricity demand, and new sectoral growth, as in the mini-revival of the steel industry based on electric arc furnaces. The use of geothermal heat pumps in residential and commercial sectors is an example of change that tends to reduce overall electricity consumption.

Future electricity demand will be shaped by both changes in our economic structure and by technological change. While these two influences are easy to understand intuitively, their complex influence on electricity demand is difficult to predict. The key point is that our forecasts are just best estimates. They are indicators of what might happen, but to be successful our technologies need to be influential at the micro-economic level, contributing positively to economic shifts and technological trends. Our objectives are oriented toward influencing the future, and to be successful we must be in the market, shaping our technologies to meet changing conditions.

ELECTRICITY AND THE COMMERCIAL AND RESIDENTIAL SECTORS

The following chart shows the growing electricification of the residential sector and its end uses. We are using many more kWhs per households, and the number of households is growing. Commercial sector floorspace and electricity demand also continues to grow, with increasing electricity demand from microcomputers and related HVAC loads. In commercial and residential buildings, new lighting technologies and energy management systems as well as more efficient residential appliances, are reducing the amount of kWh required to perform services such as heating, cooling and lighting. Utilities are increasing their efforts in load control and the use of conservation programs to shape and control the loads from commercial and residential customers.

The energy conservation potential in the commercial and residential sectors is enormous. For example, the average refrigerator now in place consumes about twice as much energy as the best currently available commercial models. The average air conditioner is only half as efficient as the best models.


Electricity and the Commercial and Residential Sectors

This enormous conservation potential is a competitive opening for technologies such as geothermal heat pumps, which are now finding utility markets as demand side management tools. At the same time, conservation is setting new competitive standards for generating technologies. For example, the Northwest Power Planning Council's highest priority conservation investments in the residential sector come in at levelized costs of between 1.3 and 1.7 cents/kWh. Roughly 350 MW of geothermal energy also show up in their resource supply, at costs of roughly 7.6 cents/kWh.[7] Integrated Resource Planning and competition from demand side management are real factors that need to influence our research and development. The competition is broader now.

CHALLENGES TO THE ELECTRICITY SECTOR

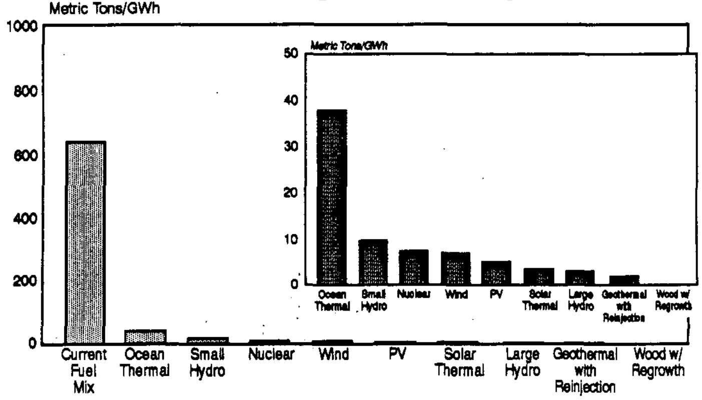
Although the electric utility sector faces growing demand for its product, the industry's ability to meet that demand is seriously impaired by the current state of transition in the regulatory, financial, and technological structure of the industry. Cost overruns on major fossil and nuclear facilities, overbuilding, and prudence reviews in the late 1970s and early 1980s discouraged utility building programs to the point that no major coal or nuclear facility orders are in process today.

The need for new capacity is beginning to grow acute in some regions, while others still maintain adequate capacity margins. Of 86.2 GW of needed capacity additions between now and 2000, 63.1 GW have yet to begin construction. The average age of electric generating equipment is approaching 25 years. Without major refurbishment and life extension the U.S. will have no nuclear capacity by 2030.

In the environmental arena, utilities face enormous costs in complying with the new Clean Air Act which will further exacerbate capacity problems. Global climate change could imply major readjustments in fuel and operating practices for utilities in the future. In addition, regulatory structures are changing rapidly as integrated resource planning, bidding systems, and actions to incorporate external costs into resource decisions are opening the utility system to new supply and demand technologies and producers.

OPPORTUNITY: ENVIRONMENTAL QUALITY
Solar, geothermal, biomass, hydroelectric and advanced storage and energy management and control technologies are in a good position to take advantage of the utility sector's transition because of their inherent attributes. The Clean Air Act has created a new reserve of sulfur emission allowances available for renewable energy and conservation technologies, which, if implemented effectively, could increase the Clean Air Act's favorable impact on alternative technology.

CO_2 Emissions from Electric Generating Technologies



Renewable energy technologies are environmentally benign, with far fewer NOx, SOx, or CO_2 emissions than any competing fossil technology. As the public and regulators increase the emphasis on including external costs in resource planning the cost differential between renewables and conventional competitors will narrow.

OPPORTUNITY: STATE AND FEDERAL ACTIONS -- IRP AND EXTERNAL COSTS
More than 19 states are now considering external costs in their resource planning. FERC and EPA are mandated by the Clean Air Act to study means of incorporating renewable energy's environmental benefits into resource planning and recommend models for implementing their findings. California has specifically set aside a block of its future capacity for conservation and renewable energy.

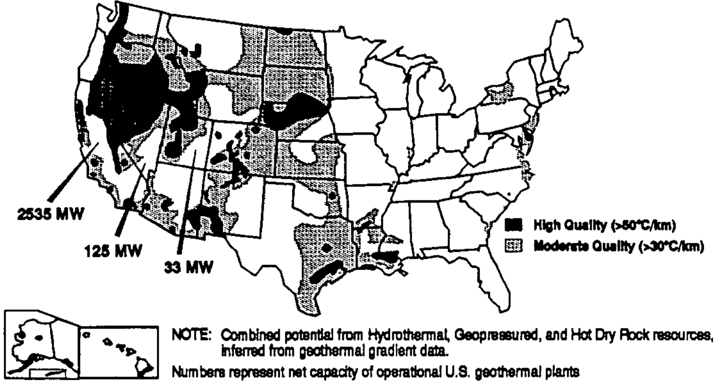
Renewable energy technologies, including geothermal, ranked high in the supply option rankings of the latest Northwest Power Plan, which for the first time anticipates a need for new capacity in the Northwest. With capacity shortfalls looming and the need for extended construction schedules for fossil and nuclear stations, utilities are increasingly seeking technology options that can be put on line quickly and in small increments that limit financial exposure. As modular systems that can be built quickly in small increments to meet demand as it emerges, renewable energy technologies satisfy these criteria, especially when developed by non-utility generators that assume the risks of financing and construction for the utility. Recent PURPA reforms removing artificial size constraints for renewable energy will benefit non-utility generators by allowing them to size projects in response to utility needs rather than to fit the PURPA size caps.

OUR APPROACH: TECHNOLOGY DEVELOPMENT AND MARKET CONDITIONING

Our approach to turning these challenges into opportunities is based on two major efforts. The first approach concentrates on pushing our technologies to new levels of technical and economic performance while the other focuses on conditioning markets in order to maximize opportunities for our technologies. Our major technology push is to continue the research and development progress needed to make our renewable energy and conservation technologies competitive alternatives to other generating options. Our technologies have enormous natural advantages.

This map shows the capacity of operational geothermal plants in the U.S. in juxtaposition with the enormous geothermal resource that could be tapped. Resources are not a constraint on our potential contribution. You might also note that none of the resources we are targeting on this map are located in Iraq, an advantage that deserves more attention considering our recently successful, but very expensive involvement in that region.

LOCATION OF U.S. GEOTHERMAL ELECTRIC RESOURCES



NOTE: Combined potential from Hydrothermal, Geopressured, and Hot Dry Rock resources, inferred from geothermal gradient data.

Numbers represent net capacity of operational U.S. geothermal plants

Research on key components is targeted at reducing costs and boosting performance levels to ranges where renewable energy can provide the same reliable baseload, intermediate, and peaking energy as conventional alternatives, at comparable costs. In geothermal energy, specific attention is being paid to reservoir and advanced technology designed to expand the availability of cost-effective resources, so that geothermal energy can meet more of our expanding electric needs.

With the Pacific Northwest now considering expanding generating options, the importance of technologies to take advantage of the Calderas resources is heightened, and our research should help the industry take advantage of the situation. Trends in the utility sector are favoring renewable energy and conservation, but to realize them we need technological and economic performance capable of pushing these alternatives into use.

The second major approach of the Office of Utility Technologies is to encourage market conditions that give renewable energy and conservation technologies fair opportunities to compete on their own merits. The merits of renewable energy and conservation are often simply not recognized by decision makers. Thus, we are devoting major efforts to documenting the environmental and other benefits of our technologies and developing integrated resource planning methodologies that will help users compare supply and demand side options systematically and fairly.

Artificial barriers to competition tend to work against renewable energy and conservation technologies. The Office of Utility Technologies argued long and successfully in favor of removing the PURPA size caps, and we are just as vigorously advocating integrated resource planning and bidding mechanisms that give non-utility generators greater access to the market for new capacity.

Information is also a key component of effective free markets -- the Office of Utility Technologies is acting through CORECT, PVUSA, and cooperative efforts with industry and utilities to demonstrate the effective capabilities of renewable energy and to break down informational barriers to greater market acceptance of renewable energy. Given geothermal energy's resource potential, strong industry base, and competitive technology there is no limit to its potential for growth, and the same applies to the other renewable energy technologies.

TARGET OF OPPORTUNITY

The Office of Utility Technologies' programs are at a crossroads of opportunity. Trends in the electric utility sector are very promising, and technologies such as geothermal energy are poised to take advantage of the opportunities the future offers. We have already made enormous progress as seen in our growing contribution to electricity output, the technical cost and performance gains registered by our researchers, and the growing acceptance and support for renewable technology provided by the public. The challenge is for industry, utilities, and our programs to work in concert to realize these opportunities and achieve the more diversified, environmentally benign, and cost-effective electric generating sector that is now possible.

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Challenges Facing Utilities in the 1990s
Role of the Geothermal Partnership

John W. Motter
Sierra Pacific Power Company

INTRODUCTION

Good Morning. I appreciate the opportunity today to talk to you about the challenges facing electric utilities in the 1990s, and the role that the Geothermal partnership can play in meeting those challenges. What do I mean by the geothermal partnership? As I'll suggest in more detail in a few minutes, I see the geothermal partnership as having 4 major players: industry, government, utilities, and regulatory agencies. Each of these has a vital and evolving role to play in contributing to the sustainable development of geothermal power. Each also has unique challenges to overcome. I'll be talking today about some of the challenges facing utilities.

Before specifically addressing the nature of those challenges, I'd like to take just a moment to tell you a little about Sierra Pacific Power Company, to provide some perspective on our utility's involvement in the geothermal field.

ABOUT SIERRA PACIFIC POWER COMPANY

Sierra Pacific Power Company is the investor-owned utility serving about 60,000 square miles of northern and central Nevada, and northeastern California. Our peakload is about 1,000 megawatts, and in recent years sales have been growing at a rate of almost 10% annually. Our summer and winter peaks are almost equal, and we have an annual load factor of almost 72%. This unusually high load factor is driven largely by our large commercial and industrial customers -- with hotel-casinos and gold mines both being 24-hour-per-day operations! We are meeting this load through a variety of generation resources, including a growing amount of geothermal power.

Sierra Pacific Power, like many utilities, uses a mix of its own generation facilities and purchased power to meet load requirements. Our own generating plants include coal, oil/gas, and small hydroelectric plants. Since the construction of our last coal-fired power plant (North Valmy Unit #2) in 1985, we have utilized purchased power to supplement our own generation. Geothermal power is an important and increasing part of that purchased power.

Geothermal power generation in our service area has been growing at a steadily increasing rate. As recently as 1983, there was no commercial geothermal power generation in Nevada. Now, we have about 70 MW of grid-interconnected geothermal power. This is exclusive of 50 MW from operations in Dixie Valley and Beowawe, which is sold to southern California Edison.

Sierra Pacific's reasons for an increasing use of geothermal power have evolved over time. Around 1985, we signed purchase power contracts with three geothermal developers in order to foster the development and demonstration of three different technologies, at three considerably different reservoirs. Two of the three came on-line in 1986, and since then, we have been monitoring the performance of both these "trial" plants. Performance, which was good initially, has continued to improve, and has convincingly demonstrated the feasibility and economics of power generation from western U.S.-type, moderate temperature, liquid dominated reservoirs. This experience is being echoed in the commercial operations of many other geothermal developments in the west.

In 1987, we were ordered by the Our Public Service Commission to purchase 85 MW of power from qualifying facilities. Most of that 85 MW is being obtained from geothermal developments. More significantly, however, is Sierra Pacific's use of two competitive bidding processes, known as request for proposals, or RFPs, to meet additional capacity requirements. These RFPs were open to all bidders, including utilities, independent power producers (IPPs), as well as qualifying facilities. As a result of these two RFPs, Sierra has signed contracts for a total of over 275 MW of new capacity, of which 100 MW is new geothermal.

Thus, the relationship between the utility and other power producers is developing. We see our relationship with geothermal developers and others from whom we purchase power, as evolving from an occasionally adversarial relationship, to one of true partnership with mutual concerns and benefits. The reasons for this shift are many, and reflect a variety of challenges which face the electric utility as a whole.

I'd like to share my view of some of these challenges with you. Finally, I'll reflect on the possible roles of utilities, our regulators, industry, and government, as well as other segments of our nation in forming a partnership for geothermal development.

SOME CHALLENGES FACING ELECTRIC UTILITIES IN THE 1990S

The decade of the 1990s promises to hold unique opportunities, as well as significant challenges for electric utilities, and their partners in geothermal power. In Figure 1, I have listed several factors which I believe are facing many utilities as we move forward in the 1990s. Although most utilities will be facing each of these challenges in one form or another, it is most important to realize that each utility's response will be unique, and will reflect that particular utility's existing situation, goals, regulatory environment, and expectations about the future. The "one size fits all" concept clearly won't do in this complex environment.

The 1990s

Challenges and Opportunities for Electric Utilities

- Competition
- Environmental Issues
- Capacity Requirements
- Effects of Purchase Power on Utility Financial Ratings
- Fuel Mix

Figure 1

Competition certainly has to be one of the challenges near the top of the list. Contrary to the popular view of electric utilities as "pure" monopolies, we are facing more competitive pressures than ever in our past. The nature of this competition is certainly worth an entire discussion in and of itself, but I will just list several of the factors driving that competition.

> Fuel Switching. If utilities don't provide the right services to customers, at the right prices and with the level of reliability the customer needs, those customers will respond by changing their preference from electricity to gas, fuel oil, or other fuels. Utilities, and our partners, will end up losing!
>
> Cogeneration. Similarly, if utilities lose touch with their customers' needs, those customers (especially large customers with significant heating requirements) have cogeneration as an option -- again to the potential detriment of utilities and their bulk power suppliers.
>
> Increasing Deregulation. Most utilities are still in that evolving "neither fish nor fowl" period where we are regulated, but still facing increasing competition. Nevertheless, I believe the handwriting is on the wall. We are already seeing significant deregulation (and competition) in the bulk power markets. If any of you doubt this, you need look back no further than 1990, when Sierra Pacific Power Company, in a competitive process, selected offers from geothermal power producers while declining to purchase coal-generated power. An example of the kind of decision necessary to remain competitive into the 1990s and beyond. Similarly, there is increasing deregulation in the transmission arena. FERC has been clear in its intention to promote broader transmission access -- not just for "QFs," but for a wide range of players.
>
> Competition With Other Utilities. For better or worse (depending on one's individual perspective), gone are the days of gentlemanly agreements between utilities, and a "hands off" policy on your neighboring utility's service territory and customers. A quick glance at almost any trade journal, or the Wall Street Journal, shows examples of the new competition, including takeovers, mergers, and yes, even coveting thy neighbor's prime customers.

So, what does all this competition have to do with the geothermal partnership? A lot! Both the short- and long-term health of utilities, and I think also of our industry partners, will be determined by how we respond to these competitive pressures. Remaining cost-competitive is certainly a major part of this picture. Keeping costs low is important, but not at the expense of all else. Both utilities, and our regulators, have a responsibility to allow our industry partners to make a fair profit -- as well as providing incentive to them to reinvest a portion of that profit in research and development to ensure the successful long-term development of resources, and to keep striving towards more efficient, and environmentally protective methods for resource development, extraction, and production.

Over the next several days, you will be hearing in detail about R&D work being performed by, or in partnership with the Department of Energy, our National Laboratories, Academia, as well as state agencies. It appears from my utility perspective that this work is positioned "on target" to help industry reduce costs; and to ensure the reliability, efficiency, and availability of today's and tomorrow's geothermal power needs. In short, this research should help utilities and industry remain healthy and competitive, and to help fulfill the promise of geothermal power in meeting the nation's power needs.

Environmental issues are a critical challenge facing utilities in the 1990s -- one in which geothermal power, along with other renewables and demand side management, can play a major role in shaping the utilities' responses to these issues. Like the issue of competition, within the time constraints of this presentation, all I can do is simply list several major environmental factors affecting the industry today.

The Clean Air Act, visibility issues associated with pristine wilderness areas and national parks, and air toxics legislation ... These are huge, national environmental issues which will result in utilities spending billions of dollars for compliance through installation of scrubbers, and other control system measures. Geothermal power can be part of a cost-effective strategy to provide for energy needs with minimal environmental impacts. To date, although several bills have been introduced, we have no national legislation which limits carbon dioxide emissions. These emissions have been implicated as a major culprit in global warming. Although scientific opinion is still divided as to the reality of this effect, and particularly the magnitude of warming which may occur, it may be just a question of time until some legislation is passed. Such legislation could have profound impacts on the electric utility as it now exists, and could reshape the way the utility industry does business, as well as having major impacts on utility ratepayers. Clearly, to the extent that a global warming problem may exist, its effects will be far broader than just to the electric utility industry. However, any effective response designed to mitigate global warming will have to be framed within national and international contexts.

A number of states, including Nevada, have adopted or are considering regulations designed to promote environmentally benign generation technologies by assigning a dollar value to environmental, or other social costs ("externalities"). These costs are to be considered, as well as direct capital and operating costs, in conducting resource planning evaluations. The Nevada Case, which I am most familiar with, is summarized in Figure 2. The "societal cost" would add nearly zero, in the case of a geothermal producer (especially a binary system), but would add 1.6¢ per kilowatt-hour (kWh) to a natural gas-fueled combustion turbine, and about 5¢ per kWh to a conventional, coal-fired generating station. These numbers are in 1990 dollars, and escalate with inflation. Carbon dioxide constitutes a significant portion of the environmental cost. The Nevada rule was written with the foresight to provide for subsequent changes in emission rates and values as technology changes, or as better information develops on the true value of the external costs.

Environmental Externalities
SB 497/G.O. 65: Nevada Example

- Provides for incorporation of environmental (societal) costs in evaluating resource options
- Cost (PWRR) retained as primary criterion (relative weighting of costs not yet defined)
- Includes valuation of 10 air pollutants, land and water
- Value ($ per lb. of pollutant) stated in order
  Examples: Conventional Coal - 5¢/KWH
  Combustion Turbine - 1.6¢/KWH
  Geothermal - nil

Figure 2

Meeting capacity requirements in a cost-effective way is obviously a concern to any utility. Increasingly, utilities will be looking to geothermal industry partners to provide more flexibility of operation and dispatchability as well as "firmer" capacity.

It is not uncommon now for utilities to pay geothermal developers for both capacity and energy, often on a "take or pay" basis. That is, the utility is obligated to pay for whatever power the project contract specifies, regardless of the utility's need at the time, or economic dispatch considerations. As discussed in a recent article in the geothermal resource bulletin, dispatchability may well be a "plus" factor when evaluating two otherwise similar bids. All other things equal, you'd like to be able to run the geothermal plant all the time because of the low fuel cost. However, it may make more sense to pay for geothermal dispatchability, than to thermally cycle a large fossil or nuclear unit. And yes, the utility should be prepared to pay a fair premium for that dispatchability.

There are some operating risks associated with dependence on purchased power. To a significant extent, these risks will be dependent upon the type of fuel, type and maturity of the specific technology, and upon the specific operator -- his experience, quality and financial strength.

Is all capacity equal, or is one source "more equal" than another? The utility has an obligation to serve the maximum load that occurs any of the 8,760 hours in a year. It is not an uncommon practice now in contracting for geothermal to define a capacity payment based on something other than how much capacity is provided at the utility's time of maximum demand. For example, geothermal capacity could be based on a daily average, an average of "n" days, or even an average monthly capacity. Yet, the capacity of a geothermal plant, particularly one using "dry" or air-cooled condensers may be as little as 35 or 40% of the design rating at the time of a summer peaking utility's maximum demand. Increasingly, I think utilities will be challenging our geothermal industry partners to provide firmer capacity. This may require improvements in heat rejection technology, use of hybrid "wet-dry" cooling towers, deluge flooding of air-cooled units, or other design changes. R&D should be instrumental in developing cost-effective ways of providing this firmer capacity.

<u>The effects of purchased power</u> on a utility's financial rating enter into the decision-making process when evaluating geothermal power. Purchase of power can be categorized into two general types of "take <u>and</u> pay," or "take <u>or</u> pay" purchases. "Economy" energy purchases, because of their "take and pay" nature, are purchased only when the utility needs the energy or capacity. Many geothermal contracts (as well as certain other purchases) are "take or pay" in nature. As discussed recently by two major bond rating agencies: Moody's, and Standard & Poors -- contracts of this type are viewed essentially as debt by the market and, thus, act to dilute interest coverage ratios. This concern is especially important if the amount of purchased power exceeds about 10% of the utility's total generation.

What <u>fuel mix</u> should a utility maintain, and what is the value of fuels diversity? Clearly, having a diverse fuel mix can minimize the risk associated with the heavy utilization of a single fuel. On the other hand, having a mix of fuels means that a utility is never "optimal" at any particular time. Further, each fuel has unique risks characteristics associated with it (technical risk, price risk, environmental attributes, etc.). I believe that environmental and regulatory factors will drive prices, and, in turn, drive fuel utilization over the coming decade. In particular, many forecasts expect fossil fuels including coal, oil, and natural gas to escalate at rates greater than renewable energy increases. Will geothermal power be increasingly viewed as a price-competitive, reliable generation resource? And, will it achieve significantly greater utilization in the western United States?

These then, are a few of the challenges facing utilities as we move through the 1990s. First, what role can research and development play in meeting these challenges? Second, how can the geothermal partnership facilitate that research and development? And, third, how can this partnership improve overall R&D effectiveness through collaboration and cooperation?

R&D AND THE ROLE OF THE GEOTHERMAL PARTNERSHIP IN THE 1990S

As we've discussed, a number of parties have important roles to play in continuing to foster the development of geothermal power in the United States, and in supporting or conducting geothermal research and development. At the risk of overlooking someone, I'd suggest that there are at least four major principals in this partnership (although perhaps we should say five, and add educational institutions to this list).

The geothermal industry will continue to play a critical role in promoting cost-effective geothermal research and development. Often, as wellfield and plant operators, they are the ones closest to much of the information on geothermal reservoirs, as well as plant operational data. I suggest that the industry should continue in this data collection, and in performing R&D specific to individual reservoirs or techniques. Operators also need to have appropriate incentives to demonstrate new technologies.

Industry organizations, such as the National Geothermal Association, the Geothermal Resources Council, and other groups deserve much credit for promoting the development of this important national resource, and for playing a major role in information sharing and dissemination.

Government also continues to play a major role in developing the geothermal industry, and in supporting and conducting the research to develop new resources, reducing costs of both new and existing facilities and resources, and improving the understanding and management of reservoirs. Over the next several days, we'll be hearing a lot from researchers about these efforts. Some of this research, such as drilling penetration improvements may even have broader implications, as in the case of reducing costs for deeper drilling for natural gas.

Utilities, by and large, have been viewed in the past as less than enthusiastic participants in the geothermal partnership. There were questions as to the amount of geothermal power which could be developed cost-effectively and at relatively low risk. Some technology aspects were unproven, as were many of the resources. The perceived risk of geothermal power was not, in general, well matched to utilities' allowed rates of return. Coupled with an excess of traditional generation capacity, and with few restrictions on the use of coal and other fossil fuels, many utilities chose not to heavily invest in geothermal power. The advent of PURPA regulations "encouraged" utilities to purchase power from qualifying facilities at their "avoided cost." Utilities, QFs, and regulators had a series of interesting discussions as to what that cost really was. Not until the 1980s did the utility industry, by thinking on a larger scale, come to see geothermal power as a real part of a solution to its problems. With the challenges of the 1990s, I think that we'll see increasing interest in geothermal power and other renewables.

Our utility regulators, while possibly not thought of as "principals," are important, and are sometimes overlooked as a part of the geothermal partnership. Regulatory interest in, and treatment of utility investments in geothermal power (whether in terms of purchased power, utility capacity additions, or geothermal R&D) is critical to the partnership success. Our regulators can provide direction to utility R&D, and ensure that work is being conducted in accordance with state policy and directions. Regulators can provide support to R&D collaboration, and ensure that work is non-duplicative and that results are shared with others. Regulatory recognition that R&D can benefit ratepayers, both in the short and long term, can lead to appropriate cost recovery and incentives to utilities to stimulate investment in renewables R&D.

In conclusion, and as an overall summation, we can say that the long-term success of the partnership between geothermal producers and the utilities will relate to several critical factors. Among them are the perpetuation of the utility industry, successfully meeting the difficult and uncommon challenges ahead, and working together to solve problems which affect us both individually and in common.

Our challenges will bind our partnership, and our partnership will overcome the challenges! Thank you.

Challenges Facing The Geothermal Industry in the 1990s and the Role of The Geothermal Partnership

Darcel Hulse
President, UNOCAL Geothermal Division

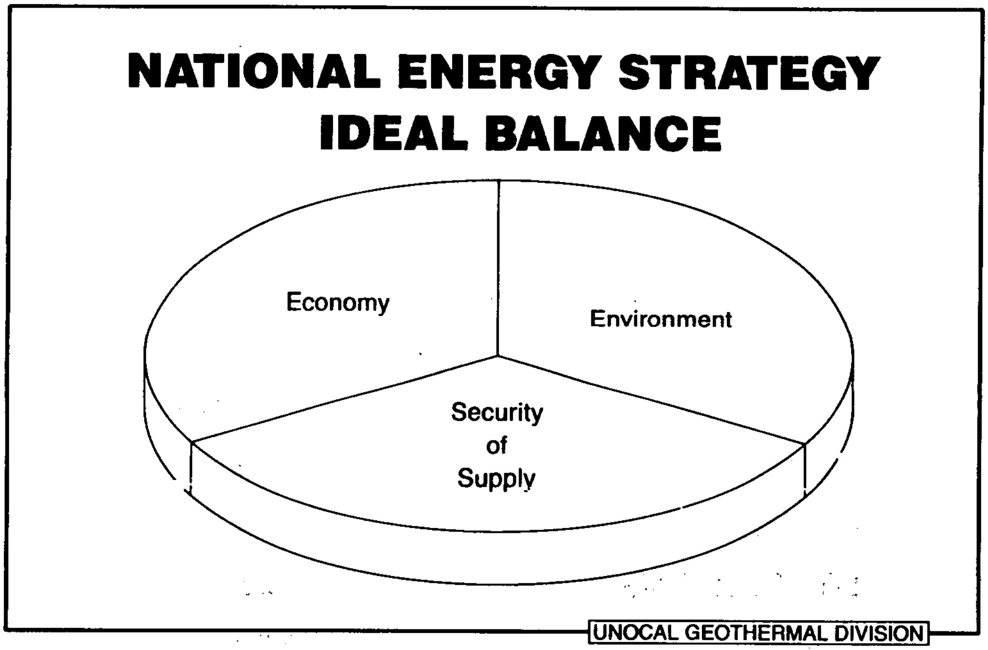
Good Morning.

I appreciate the opportunity to attend this conference and be among so many outstanding people who have contributed so much to the development of the geothermal industry. You're the ones who were willing to dream dreams, develop visions, and put up the money to bring the benefits of geothermal energy to mankind. You are also the ones who -- through loving and dedicated work -- have made your dreams a reality.

UNOCAL has travelled the rough and bumpy geothermal road with you for almost 25 years. However, I'm just in my "rookie" season in the geothermal business. I've met some of you. I hope to get to know each of you better. UNOCAL looks forward to doing whatever we can to contribute to the success of this business -- although I must say the road ahead will have many more bumps before it becomes smooth.

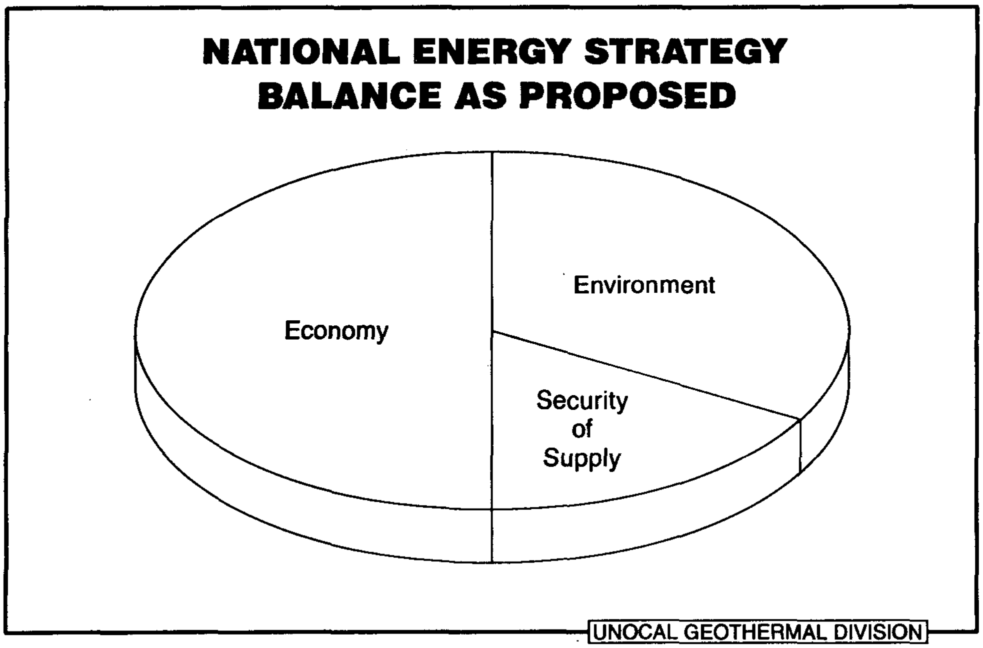
Our industry has fewer players than just a few years ago. If ever there were a time for those in government, industry and the utilities to work closely together in a partnership -- the time is now. The burden is on us. We understand the real benefits geothermal energy has to offer. We must continue working together to make sure those benefits are realized. The battle will be long and at times frustrating -- but we must never give up. By pulling together as partners should, we will eventually win.

Just under a year ago, my predecessor -- Steve Lipman -- addressed this forum. Steve's topic was the development of a national energy strategy and the role of geothermal energy. In July of 1989, President Bush stated the objective of the National Energy Strategy as: "Achieving balance among our increasing need for energy at reasonable prices; our commitment to a safer, healthier environment; our determination to maintain an economy second to none; and our goal to reduce dependence by ourselves and our friends and allies on potentially unreliable energy suppliers." What was envisioned was a policy that would strive for balance between economy, environment, and security of supply -- as this chart illustrates.



(Figure 1)

Ideally, the geothermal industry should have a very bright future under a policy which bases energy use on the contributions of various options to improving the environment, energy security, and price. But after studying the proposed National Energy Strategy that was recently introduced, I have to say that it is <u>not</u> ideally balanced. Emphasis is placed on economic concerns for low-cost energy with much less attention paid to concerns for environmental quality and secure energy supplies -- as this chart illustrates.



(Figure 2)

Let me quote a few excerpts from the prologue of the National Energy Strategy: "Energy is closely linked to economic prosperity -- at home and abroad. The linkage exists for all countries, but particularly for the United States. Our country is not only the world's largest energy consumer, but also the second largest energy producer." To continue quoting: "The entire infrastructure of our cities, highways, and industries was developed with abundant and relatively inexpensive energy sources. Differences in how Americans use energy compared to other nations are due largely to a multitude of physical, cultural, and structural differences rather than to technological advantage." The Strategy states: "U.S. Residents have greater personal space in homes and offices, a greater number of single-family homes, better heating and cooling systems, and a wider range of labor-saving appliances." And finally, "Our historical economic strength has been due in part to <u>low energy costs</u> as a factor of production."

These statements seem to me to make a case for Americans having some "inalienable right" to cheap energy. But do we? Can we safely make such an assumption in a world where 65 percent of the known crude oil reserves are in the volatile Middle East? I'm afraid that our American way of life -- based on our perceived inalienable right to cheap energy -- has undercut our ability to agree on an ideally balanced energy policy with a long-term focus. Americans demand cheap and plentiful energy. Let me give you a couple of examples of just how inexpensive energy is in the United States.

COMPARATIVE COST OF LIQUIDS

	USA INCLUDING TAX PRICE / GALLON
Gasoline	$ 0.92
Distilled Water	1.05
Diet Coca Cola	1.96
Milk	2.50
Orange Juice	4.52
Beer	5.59
Whiskey	61.55

(Figure 3)

American drivers don't pay much for gasoline. In fact, gasoline costs less per gallon than bottled water.

COMPARATIVE GASOLINE TAXES

(PER GALLON)

COUNTRY	CONSUMER COST *	TAX COMPONENT
United States	$0.92	$0.36
West Germany	2.53	1.60
Japan	3.41	1.60
Britain	2.59	1.74
France	3.11	2.44
Italy	3.91	3.31

*Including Tax

(Figure 4)

In countries that are even more dependent on imported oil than we are, gasoline costs consumers two to four times what it does in the U.S. -- with a greater percentage of the total cost being government taxes. Let me state again that our perceived inalienable right to cheap energy hampers our ability to develop a balanced energy policy. The least-cost option will always focus our attention on short-term band-aids rather than long-term solutions to our energy problems. We must do all we can to promote a balanced energy strategy -- one that focuses on security of supply and benefits to the environment, as much as it does on price. The overwhelming demand for cheap energy must not be allowed to dominate the strategy.

I know that everyone here understands the benefits of geothermal, particularly its value as a clean domestic resource. The more important question is -- does the public understand? Does geothermal get credit for its inherent benefits when we compete for new electric generation? To date, The Geysers has produced more than 128 million megawatt-hours of electricity. If coal had been used instead of geothermal steam to produce the same energy, 117 to 120 million tons of air pollutants would have been emitted.

ENVIRONMENTAL COMPARISON

ANNUAL TONNAGE

COMPARABLE 250 MW BASE LOAD PLANTS

	GEOTHERMAL	GAS COMB. CYCLE	COAL	
AIR EMISSIONS			ABATED*	NO CONTROLS
CO_2	100,000	1,000,000	2,000,000	2,000,000
SO_2	0	3	4,000	27,500
NO_x	0	1,400	2,400	2,400
Particulates	<10	<10	200	20,000
OTHER POLLUTANTS				
Sludge	<100	0	170,000	0
Ash	0	0	60,000	40,000

*Electro-static Precipitator (99% Efficient)
*Flue Gas Desulfurization (85% Efficient)

(Figure 5)

The chart illustrates the environmental benefits of geothermal energy versus other resources. From an environmental standpoint, geothermal compares very favorably to gas and coal. There are environmental and social costs in the energy resources that America relies on most heavily. These costs are incurred later in cleaning up the air and nursing rivers, lakes and forests back to good health. These costs need to be added before we can consider what is truly the "cheapest" energy source. There is a procedure now in Massachusetts to address this situation. It involves adding on an assessment for future pollution when evaluating fuels for new power plants.

ENVIRONMENTAL INCENTIVES

Massachusetts
Penalties for Air Emissions

CO_2	\$22 / Ton
NO_x	\$6,500 / Ton
SO_2	\$1,500 / Ton

Translates Into Cost "Adders" for Generation

Coal	Oil	Gas	Geothermal
4¢ / kwh	2¢ / kwh	1¢ / kwh	0

UNOCAL GEOTHERMAL DIVISION

(Figure 6)

This chart breaks out some of these assessments. While we recognize that Massachusetts has no geothermal opportunities, this analysis would assess zero penalties against geothermal where it was a viable energy option. In other words, geothermal could be priced 4 cents per kilowatt-hour higher than coal and still be competitive in the evaluation process.

In 1985, the United States imported 32 percent of its petroleum. That's about the same percentage we were importing in 1973, when OPEC delivered the oil price shocks that quadrupled oil prices. In 1987, imports made up 39 percent of our petroleum demand. Last year, it was nearly 50 percent -- the highest level in our history. And by the mid-1990s, it is predicted that the United States will import 60 percent or more of its petroleum supplies. While our country will continue to depend on fossil fuels for the foreseeable future, it is essential that we gain a larger share of the energy mix for alternatives such as geothermal. The U.S. needs a secure and reliable energy supply. Where geothermal is available for power generation, supplies of fossil fuels can be put to more valuable use -- as transportation fuels, for example. Generation from The Geysers field to date has saved the nation the energy equivalent of almost 200 million barrels of oil. In 1990, the United States consumed 17 million barrels of oil per day -- 25 percent of total world consumption.

On first glance, geothermal may not be the cheapest energy source -- but when everything is considered in the proper balance, it stands out as one of the least-cost options. Several people recognize this and are actively doing something to ensure that America reaps the benefits of geothermal energy. The U.S. Department of Energy has played -- and will continue to play -- a key role in supporting geothermal resource research and development. We've already done a lot -- but our work is certainly not finished. We need to improve our exploration and production methods and technology in order to expand geothermal development and strengthen our industry. Such research and development efforts should be directed at reducing our costs and improving our recovery of geothermal resources. This involves more efficient drilling methods and improvements that will prevent the degradation over time of the injectivity of wells. There is also work to be done to improve the efficiency of the energy conversion process. We spend a lot to find and produce geothermal resources. We can't afford to use them inefficiently. DOE's support has been vital, and we look forward to continuing a very successful partnership in research and development.

I'm also encouraged by House Bill 780, introduced by Congressman Sharp. This Bill would provide a 2.5-cents-per kilowatt-hour tax credit for electricity generated from wind, solar, and geothermal. This goes well beyond any of the incentives proposed in the National Energy Strategy. Even more encouraging is the very positive position taken by the key decision makers of the California Energy Commission. In their view, non-fossil fuels -- like geothermal -- should and will make up 50 percent of all new electric power generation in California. Should this come to pass, California utilities will be able to focus on long-term total cost options -- instead of concentrating on short-term solutions that provide, at least for today, the lowest cost to rate payers.

As evidenced by the fact that many players have left the geothermal industry, it's obvious that in today's cheap energy environment the industry's business needs are not being met. In order to be a totally viable business, geothermal must be able to deliver a return on investment with a reasonable profit -- and should also provide enough support for research and development for long-term growth. Cheap energy competition prohibits the plowback of funds necessary for improved efficiency and growth.

America's energy mix for the next decade and the next century is a complicated equation. However, I'm convinced that if we can overcome our short-sighted focus on cheap energy and balance energy price with environmental and security concerns, geothermal will play a vital role in our energy strategy. Geothermal energy used as a source for electricity is less than a century old -- and the greatest strides in harnessing the resource for efficient power production have been made in the last 25 years.

The potential for the future is great -- provided we're willing to work together until enough people begin to see the light.

Thank you for inviting me here today. I look forward to working together with you toward the long-term success of the geothermal industry.

THE GEOTHERMAL EDUCATION OFFICE

Marilyn Nemzer
Geothermal Education Office

Good morning ! I hear there's a new book in town . It's called The *"National Energy Strategy ."* I like the chapter entitled "Education: Investing in Human Resources" . It talks about the need for "a scientifically literate public." It talks about helping people understand about energy options; and it talks about giving everyone a basic understanding of energy-related subjects.

This *"National Energy Strategy"* talks not only to scientists, but to everyone . Maybe you can put yourselves in the shoes of your wives, children and teachers for a few minutes and see what it's like to learn about geothermal energy.

To get an overview of what the Geothermal Education Office has been up to, let's have a look inside the red and white envelope that's in front of you. First, notice the envelope . If you were one of the 2,000 students or teachers who contact our office each year to request information about geothermal energy, this would be what you'd see with your first glimpse at the the mail: "HERE'S SOME HOT NEWS ABOUT GEOTHERMAL ENERGY." Boy, can't wait to see what's inside !

And now, a look inside the envelope.

1) First, the *"Steam Press,"* "The Journal of Geothermal Education." Go ahead; open it up. Hey, this is great! "Energy, Who uses it -- and how much?" "The Ring of Fire" and "Mighty Magma!" And look at "Hot Stuff" on the back. Wow! What a great way to teach kids -- and even grown-ups -- about geothermal energy, "the matchless energy source that doesn't pollute!"

"Steam Press" is a publication of our office, and we're very proud of it. And by the way, we welcome your ideas for our next issue. So don't be shy. Write a few simple, positive lines about what you do, and send it to us. Our next issue will include an article on "Careers in Geothermal," and your input will be greatly appreciated!

2) Now, pull out your little red book, *"About Geothermal Energy."* You may think you have seen it in years past, but this one is different. This one is updated. Last year, we were able to twist the publisher's arm to make the book right . (It helped a little that we were able to convince the Hawaii Dep't. of Business and Economic Development to hold their order of 10,000 booklets pending an update.) By the way, have a quick look at the back . If you have any of these booklets in your office already, and if they don't have this copy on the back ("Geothermal Education Office, 1-800-866-4GEO"), they are the old version . Please throw them away and order new ones from us.

As you look through this booklet, you'll see that, due to our efforts, it no longer tells the world that "geothermal smells disgusting," that the land often sinks under geothermal fields, or that the emissions are poisonous pollutants. This might look like just a comic book to you, but, like the *"Steam Press,"* it is a solid, yet easy-to-understand introduction of geothermal energy to people who've never heard of it. We encourage you all to order a few of both publications from us, so you'll have them around to give to your kids, to friends who ask about what you do, to visitors to your place of work, and to classes of students when you yourself visit schools.

3) Third item: a brochure about the Geothermal Education Office. Hmmm...

HOW CAN TODAY'S STUDENTS LEARN THE "REAL FACTS" ABOUT GEOTHERMAL ENERGY?

___ A. Magazines that omit geothermal in articles about alternative energy choices.

___ B. Fact sheets written and distributed by misinformed or self-serving energy organizations.

___ C. Propaganda distributed by radical environmental groups.

___ D. Biased and misleading newspaper headlines.

_X_ E. **Geothermal Education Office**

O.K. Now, let's look inside:

Notice, first, on the left, we have a great curricular advisory committee. These geothermal and education experts have been there when we've needed them -- when we helped rewrite fact sheets for the National Energy Education Development Project and for the Center for Renewable Energy Education; when we needed some good activities to contribute to curricular materials of the California Energy Extension Service and the Solar Energy Research Institute; when we needed reactions to a poster and to other graphics . We count on this committee -- and on others of you who periodically get calls from us -- who kindly contribute time and talent to help generate the best possible educational materials.

Now -- what *is* the Geothermal Education Office?

THE GEOTHERMAL EDUCATION OFFICE IS A NON-PROFIT ORGANIZATION WORKING TO ASCERTAIN THAT TODAY'S YOUTH UNDERSTAND:

1. the urgency of protecting our environment while providing needed energy;
2. the resultant need for the world to look to renewable energy sources as an important way to sustain our planet;

3. what geothermal energy is, what is does, and its growing place in providing necessary clean energy.

THE GOALS OF THE GEOTHERMAL EDUCATION OFFICE ARE:

1. to insure that geothermal energy is properly included in environmental and renewable energy education programs and materials;
2. to develop and distribute accurate and positive information to students;
3. to build relationships with the nation's energy educators, government agencies, utilities and environmental groups;
4. to continue to encourage industry involvement in the educational process.

Time is short, so I'll just briefly highlight a few of the Geothermal Education Office programs, publications and activities mentionned in this brochure:

1 . We have an 800 number for students and teachers to call for free information. Be sure you let people know about it!

2 . We network with other energy educators nationwide, and we carefully monitor materials that they produce. When they are unfair to geothermal, well . . . let's just say we offer to "help" them . We're tactful, but forceful.

3. You've seen our *Steam Press.* (Don't forget to send us ideas.) We are currently working on a sorely-needed, excellent fact sheet for broad distribution. Also on the horizon are posters, lesson plans and a dynamic audio-visual presentation which we hope to premier at the upcoming GRC annual meeting in October -- just in time for Energy Awareness Month!

4. By now you've probably read ahead and noticed that we also participate in energy curriculum contests, teacher conferences, environmental fairs and workshops.

5. We also get very involved with reviewing textbooks and making some not-so-subtle suggestions to the publishers, who all-too-frequently forget that over 30% of our country's air pollution comes from fossil-fuel-burning power plants.

Our message to anyone who will listen is: ***" A geothermal kilowatt is a great kilowatt!"***

So, the Geothermal Education Office is doing its part.

Now, here's how *you* can do *yours:*

1 . When you have a moment, read the letter on the back of our brochure.

It tells how you can become a *Friend of Geothermal Education.* Do it.

2. When you get home, read what your own encyclopedias or your kids' textbooks say about geothermal energy, about alternative energy, about renewable energy, about power production, about air pollution. Look for misinformation, omission, accusation about geothermal. You won't have to look very hard. Send copies of the culprits to the Geothermal Education Office, along with your suggestions for corrections. We'll follow up!

3. Another way you can help -- another big way -- is to help the Geothermal Education Office. Here's how:

a. Send us non-technical information that you already have or that you develop -- annual reports, brochures, explanations of what you do. Whatever *you* use to help the general public understand what you do, *we* can use.

b. Develop demonstration models of what you do in the industry, so we can use them in booths at major science teacher conferences. Show how you fit into the whole picture -- how you do your part to fulfill energy needs without harming the environment. Send us graphics and posters, too. We can find lots of ways to use them.

c. Send us ideas for activities and experiments that relate to what you and your organization do for the geothermal industry. We need them to include in curricular materials for all ages. We've got some, but we need more.

d. Send us referrals. When students, teachers or others ask you for information about geothermal energy, refer them to the Geothermal Education Office. That's what we're here for. Remember, we have an 800 number: 1-800-866-4GEO.

e. Join our support group, *Friends of Geothermal Education*. Your contribution makes it possible for us to send information to students and teachers at no charge.

4. And last, but not least, become a part of the Geothermal Education Office Speakers' Bureau. It works like this: If you are willing to speak to students, scouts or other community groups, sign up! -- and we'll call you if a speaker in your geographic area is requested. We do get requests from speakers from all over the country. It would be great to be able to "fill the orders." We'll be glad to help you figure out what to say, if you have questions -- how to make your presentation age appropriate, ideas on what to stress, etc. And, of course, we'll be happy to supply you with handouts and other ideas.

Coincidentally, there's a *Speakers' Bureau* form in your envelope. Please fill yours out and return it to me anytime.

In conclusion, I'd like to give a special thank you to Dr. Ted Mock for his enthusiasm, encouragement and support for what we are doing, and to Mary Condy, who originated the Geothermal Education Office. And, of course, many, many thanks to all of you who participate in our effort.

ENHANCED GEOTHERMAL DEVELOPMENT -- ITS ROLE IN INTEGRATED RESOURCE PLANNING

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

It is indeed a pleasure to join with the geothermal community to review the research and development program of the Department of Energy which I have been privileged to direct for some 10 years. Any technical successes achieved during my "watch" are directly attributable to the support we have received from this group and your predecessors. Industry has been candid and competent in its guidance in program planning and generous in its participation in program implementation. The scientists and engineers in the national laboratories, academic community, and other government agencies have provided the highest level of technical expertise that could be brought to bear on a technology development process as complex as the one involved in the extraction and use of geothermal energy. Further, the respect that all sectors of the geothermal community display for the talents and contributions of the others is especially noteworthy.

At last year's Program Review, an industry speaker noted the open spirit of inquiry and discussion at the sessions just concluded, the high technical level of the presentations, and the efforts of the presenters to make clear to the audience and to themselves the relevance of their work to the objectives of the Congress in funding geothermal technology R&D. I expect a similar performance this week and look forward to the reports and discussions to come.

FACTORS THAT WILL ENHANCE GEOTHERMAL DEVELOPMENT

I chose as my topic today the role of enhanced geothermal development in integrated resource planning, or IRP. I shall return to the elements of this concept later, but for now, I want to emphasize that integrated resource planning vis-a-vis geothermal energy is a two-way street -- that is, the use of this resource will increase the options available to this type of resource planning while, at the same time, implementation of the concept will enhance geothermal opportunities.

In fact, I think adoption of this concept is one of six major factors external to our program of technology development which will contribute to enhanced geothermal development over the next several years. One of the most important on my list is the healthy state of the geothermal industry. Just recently, Richard J. Stegemeier, Unocal Chairman and President, stated that geothermal continues to be "a good profit center for us." "It's also a clean and efficient energy resource, so it fits well with our domestic strategy of strengthening the company's position in environmentally preferred forms of energy," he added. Noting that his company's geothermal assets are not limited to U.S. holdings, he said that he anticipates "steady growth for Unocal's geothermal operations during the 1990's."

We are all familiar with the successes of the California Energy Co. at Coso and the strong support it has received from the financial community. Making believers of the investment industry was, not too long ago, seemingly one of the most formidable barriers to commercial geothermal development. Magma, too, has attracted the capital to develop its valuable properties in the Salton Sea area, and recently announced yet another quarter of record earnings, the thirteenth in a row, from these operations and royalty payments from other plants. And perhaps the best indicator of the attractiveness of geothermal operations as a healthy business enterprise is the number of substantial firms that have entered the industry in recent years -- some of them for their first energy venture.

Another on my list of factors that will serve to enhance geothermal development is the increased power demand in regions endowed with geothermal resources. According to the Energy Agenda of the California Energy Commission, the electricity demand in that state is expected to increase about 2.1 percent annually over the next decade, doubling the growth rate of the early 1980's. This growth coincides with a significant projected increase in the share of capacity provided by small power producers while the share owned by private utilities is expected to decline substantially, providing a market in which geothermal can successfully compete. In addition, the Commission is recommending that aging oil- and gas-fired power plants in the state representing almost 7,000 MWe of capacity be targeted for replacement or refurbishment. California's geothermal industry has sufficient resources proven to supply considerable new capacity and would likely be spurred to renewed exploration if market economics warrant it.

After a number of years of a substantial power surplus in the Pacific Northwest, at the lowest costs in the nation, a market for new capacity is opening. According to the 1990 Annual Report of the Northwest Power Planning Council, its joint interim forecast with the Bonneville Power Administration indicates that with very high economic growth in the area, the need for power could climb by 13,000 MWe by the year 2010, up from the 16,620 MWe consumed in 1988. A more likely medium-low to medium-high economic growth would translate into a 2,400 MWe to 7,800 MWe increase in regional demand compared with 1988.

The geothermal industry has been positioning itself to compete in the northwest power market with exploratory drilling in the promising areas of the Cascades -- an effort which DOE was pleased to share. The industry thus welcomes the call for development of this resource in a region virtually closed until now to new technologies. The confidence of the northwest planners and regulators in the reliability of geothermal energy is, I think, well placed.

Nationwide, according to William H. Clagett, DOE's Western Area Power Administrator, today only about 25,000 MWe of new generating capacity are under construction or committed in the form of large thermal plants. "That means that something like 70-75 percent -- three fourths -- of the load growth expected in this country in the next 10 years will be met with other than what the industry had considered 'conventional' generation (nuclear or fossil fuel power plants) for decades."

The environmental preference for geothermal energy and other renewable resources over fossil fuels, as noted by Mr. Stegemeier, is also becoming established with key decision-makers in key geothermal states. The California Energy Commission, for example, has found, after weighing the hidden costs of pollution, energy security, and waste disposal, that even with price weighted five times higher than other considerations, renewable energy and energy efficiency cost society only a fraction of other resources. In the case of geothermal energy costs in California, society does not have to pay a premium for the environmental and energy security benefits of this resource.

The Bonneville Power Administration is currently applying environmental cost estimates into its competitive pilot resource acquisition program -- which, as I have noted, solicits geothermal capacity, among others. This approach should favor geothermal since geothermal fluids in the northwest are very benign -- low both in salinity and gas concentrations -- and should incur very little environmental cost -- either through adverse impact or treatment requirements.

From an international standpoint, a new initiative is underway to reduce carbon dioxide levels worldwide. An intergovernmental negotiating committee charged with developing a framework convention on climate control was convened by the United Nations in the Washington area in February of this year. One hundred and thirty nations participated, with the White House Council on Environmental Quality serving as U.S. representative. A number of these countries have geothermal resources, and I believe that we can expect, as the committee focuses on "appropriate commitments" to reduce carbon dioxide emissions, that it will prioritize geothermal use in some areas. This international effort, combined with the limitations on carbon dioxide of the recent U.S. Clean Air Act revision, provides the incentive that has largely been lacking on the part of decision-makers and regulators to accept geothermal energy as a viable, cost-effective solution to their problems.

The joint efforts of the Department of Energy with the international geothermal community can only enhance technology achievement through broader experience with the resource. At Cerro Prieto in Mexico -- a field very similar to some in Imperial Valley -- discussions are underway on an injection system which are expected to lead to future chemical analysis of producing wells and design of a tracer test. At Los Azufres, Mexico, we are working with the International Atomic Energy Agency to design and implement a tracer test using its injection and production system. This effort will provide a basis for comparison with U.S. technology and broaden our experience with injection systems. In Italy, DOE is acting to facilitate an international conference in June of this year for a meeting of U.S. industry representatives from The Geysers and their counterparts in Ente Nazionale per l'Energia Elettrica (ENEL) with experience at the Larderello steam field. It is hoped that some of the data available from the long-term performance of that mature field will be transferable to problems at The Geysers.

Prospective areas of joint international projects include investigation of the potential of the moderate-temperature resources in Czechoslovakia, Hungary, and Poland for power generation. To this end, DOE has submitted a proposal to the AID Support for Eastern European Democratic (SEED) program for which Congress has authorized $370 million. It is our understanding that a large portion of this fund will be utilized by the Environmental Protection Agency, and we envision geothermal development work as an element in air quality improvement in this environmentally devastated region.

Other potential areas for overseas involvement are Saudi Arabia and the Soviet Union. The Saudis have requested assistance in identifying and assessing their geothermal resources with particular emphasis in an area along the Red Sea and recent volcanic fields. The Soviets have also expressed a general interest in receiving U.S. assistance to develop its geothermal resources. Although the Soviet Union is the world's largest oil producer, use of this fuel without adequate attention to pollution control has also reduced air quality in many of its industrial areas to a dangerously polluted level.

Next on my list of factors that will tend to enhance geothermal development is the recently enunciated National Energy Strategy (NES) which provides a supporting basis for renewable energy. I emphasize that the

NES represents a significant departure from past efforts in scope -- for the first time, an energy plan is integrated with environmental and economic policy options. As a result, the strategy is many things to many people. It is:

- an action plan to provide the nation with clean, competitively priced energy.
- a framework for informal debate and decision-making.
- a statement of future goals and a yardstick for measuring progress.
- a coherent rationale for advancing legislative and regulatory agendas.

Legislation has already been introduced to implement various facets of the NES, as Secretary Watkins has noted:

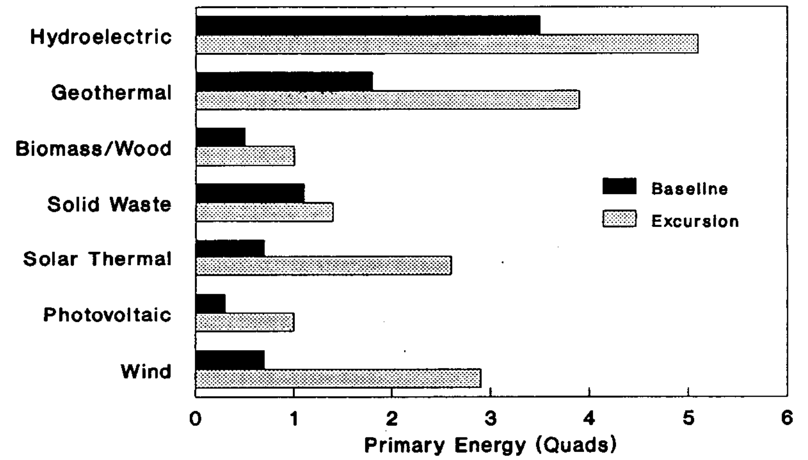
> "The National Energy Strategy Act, together with many NES items not requiring legislation, provides an extremely ambitious, balanced blueprint for a more secure, cleaner, and affordable energy future."

Finally, the strategy is not intended as a fixed, static strategy. "Our task," President Bush said in stating his charter for development of the strategy, "is... to make this strategy a living and dynamic document, responsive to new knowledge and new ideas, and to global, environmental, and international changes." This commitment, it seems to me, embraces the flexibility in which geothermal and other new, developing technologies can thrive.

Considerable information was developed in support of the NES and a large number of the analyses pertain to renewable energy. For example, Exhibit 1 shows the power production projections of the Energy Information Administration for renewable energy to the year 2030. The projection for geothermal is 23,000 MWe with high levels of R&D to 46,000 MWe with even more aggressive R&D programs.

Exhibit 1

Year 2030 EIA Projections
Renewable Energy



Source: EIA, 1990

RECENT CONTRIBUTIONS OF GEOTHERMAL RESEARCH

The above figures show that research is the key to geothermal's future, and is thus added to my list of factors that will enhance geothermal development. Lest we question the value of research, the accomplishments of research achieved in FY 1990 with limited funding are enumerated in Exhibit 2. An even better indication of the value of research is the technology transferred and the spinoffs achieved in just one funding year, as shown in Exhibit 3.

EXHIBIT 2
KEY FY 1990 ACCOMPLISHMENTS

- Assembled a team of Federal, state, utility, and industry interests to pursue a program of cost-shared research aimed at rejuvenating production at The Geysers steam field.
- Operated a first-of-a-kind, 1 MWe hybrid power system using geopressured brine from the Pleasant Bayou site in Texas.
- Used data from fluid inclusions to interpret the developmental history of The Geysers reservoir system in order to understand the distribution of fluids, including corrosive hydrogen chloride gas.
- Designed and filed patent applications for a drillable straddle packer assembly and a velocity-level flow meter in order to identify and characterize lost circulation zones in geothermal wells.
- Formed an industrial consortium to transfer geopressured technology and promote applications of the resource.
- Completed coring and analysis of well data from the first leg of the experimental well at Long Valley, California, in cooperation with other Federal agencies.
- Completed design of a laboratory bioreactor to test the efficiencies of various bacteria in removing heavy metals from geothermal waste sludges at high flow rates.

EXHIBIT 3
ENHANCED ENERGY USE THROUGH FY 1990
GEOTHERMAL TECHNOLOGY TRANSFER/SPINOFFS

- Oil industry adoption of methodology developed by Sandia National Laboratories for testing lost circulation materials for geothermal drilling -- test results were in excellent agreement with Sandia predictive equations.
- Oil industry consensus that lost circulation concepts being explored in the geothermal program may be especially useful in the completion of oil and gas wells as well as geothermal wells.
- Commercialization, under contract with the Geothermal Drilling Organization, of a revolutionary rotary head seal applicable for both oil and gas and geothermal wells.
- Use of high-temperature, corrosion-resistant polymer concrete, developed by Brookhaven National Laboratory for the geothermal industry, by Consolidated Edison of New York in prototype vaults for the steam district heating system in New York City. Use of this material will result in reductions in the required thickness of the vault walls, prevention of groundwater leakage, and elimination of corrosion in the reinforcing steel.
- Use of the brine chemistry model developed at the University of San Diego for geothermal applications by mining operations, especially potash mining.
- Extension by DOE fossil program of the BNL biochemical treatment developed for geothermal applications to enhanced oil recovery in stimulating flow and accelerating recovery as well as improving oil quality downstream.
- Use of the BNL process in high school science studies in which classes create their own wastes and use the technology for laboratory exercises.
- Negotiation by EPA to fund the biochemical process as an across-the-board waste treatment technique.
- Sufficient flexibility of Lawrence Berkeley Laboratory multi-phase, multi-component computer model (TOUGH) to allow its application to problems in nuclear waste isolation and hazardous waste management as well as geothermal reservoir studies.

ROLE OF ENHANCED GEOTHERMAL DEVELOPMENT IN INTEGRATED RESOURCE PLANNING

The definition of integrated resource planning is a utility planning process that considers both demand reduction and alternative energy sources in planning for the supply of future energy sources. The goals of this concept are to:

- increase efficiency of electric use
- reduce end-use electricity demand
- reduce need for new capacity
- increase utility system load factor and overall system efficiency.

As we will see, geothermal energy is uniquely able to satisfy each of these goals!

The activities of DOE's integrated resource planning will incorporate:

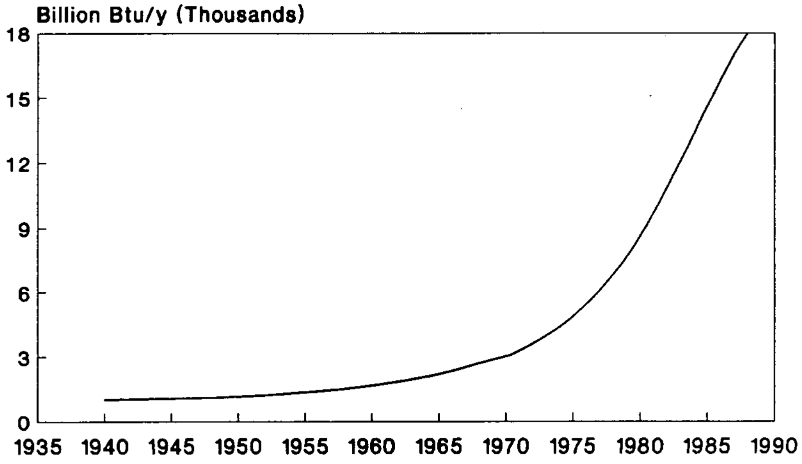
- utility regulations (consideration of demand reduction and alternative energy sources)
- total fuel-cycle analysis
- utility demand-side management
- planning processes.

In terms of the potential geothermal demand-side management and reduction of demand, let us look at the growth of geothermal direct use applications from 1935 to 1990. As shown in Exhibit 4, these uses now account for 18 trillion Btu's per year. They include:

- district heating systems
- space heating and cooling
- domestic hot water
- agriculture
- aquaculture
- industrial processing
- heat pumps
- enhanced oil recovery
- gold mining.

Exhibit 4

Growth of Geothermal Technology Direct Use



Source: Oregon Institute of Technology

Such growth does not take place without the hard work and motivation of a number of individuals. I would like to give credit to those who -- with limited funding and often *sub rosa* activities -- spearheaded these efforts!

- Paul Lienau and Gene Culver -- Geo-Heat Center, Oregon Institute of Technology
- Ben Lunis -- EG&G, INEL
- Gordon Bloomquist -- Washington State Energy Office
- Dennis Trexler -- University of Nevada at Las Vegas
- Jane Negus-de Wys -- EG&G, INEL

A growing success story in geothermal direct use is the market penetration of geothermal heat pumps. Over two years ago, the publication Geothermal Direct Use Engineering and Design Guidebook, edited by Paul Lienau and Ben Lunis with articles by many in this audience, summarized the growth and growth potential of geothermal heat pumps. The Electric Power Research Institute also conducted studies of this technology in 1987 and 1988. These and other studies concluded that:

- higher efficiency of geothermal heat pumps cuts energy use by:
    - 65% compared to oil
    - 50% compared to gas or electric
    - 33% compared to air source heat pumps.
- Their higher efficiency cuts energy costs by up to:
    - 40% for air conditioning
    - 70% for heating
    - 50% for water heating.

These attributes of geothermal heat pumps have resulted in major international growth in this technology. In Sweden, two nuclear plants were deferred by using GHP's; in Canada, growth in their use has exceeded 50 percent per year; and in the U.S., growth has exceeded 25 percent per year. In the service area of Public Service of Indiana alone, 10 percent of new homes are equipped with geothermal heat pumps.

Further, according to Bob Bergland, Executive Vice President of the National Rural Electric Cooperative Association:

> "Implementation of an aggressive geothermal heat pumps program can be used to defer the construction of baseload power generation."

This approach represents demand reduction and integrated resource planning at its best.

SUMMARY

In summary, geothermal energy faces an exciting period of growth -- both for power generation and direct heat applications -- aided and abetted by:

- a healthy industry
- increased power demand in the decade ahead
- favorable environmental factors
- joint international activities
- a supportive National Energy Policy
- utilities acceptance of integrated resource planning.

Thus, I conclude that geothermal energy is truly America's energy for a brighter tomorrow!

HYDROTHERMAL RESERVOIR TECHNOLOGY

Chairperson: Marshall J. Reed
Geothermal Division, U.S. Department of Energy

GEOTHERMAL RESERVOIR TECHNOLOGY RESEARCH

Marshall J. Reed, Program Manager
Geothermal Division
U.S. Department of Energy

INTRODUCTION

The Geothermal Reservoir Technology Research program has three major concerns which guide its activities: 1) to identify and address the problems faced by the geothermal industry, 2) to anticipate the future needs of the geothermal community, and 3) to transfer newly developed technologies to industry for rapid application. Reservoir technology research encompasses a variety of scientific and engineering investigations to support the utilization of geothermal resources through the development and verification of new methodologies for use in exploration, fluid production and injection, and prediction of reservoir capacity and commercial lifetime. This research program makes use of the technical fields of geology, geochemistry, geophysics, hydrology, and reservoir engineering to solve problems in reservoir analysis, brine injection, and geothermal exploration. A broad approach to reservoir research is taken in order to support the industrial, community, and private geothermal development activities in the United States. In order to attack so many diverse problems with the limited funding available, we try, whenever possible, to have DOE-funded researchers participate in cost-shared research with industry. A geothermal development company, which has people and equipment already dedicated to field operations, is in a good position to conduct scientific measurements or experiments and to work closely with a DOE-funded research group to test advanced equipment and to analyze and interpret the results. In this way we hope to gain the most from available funding.

INDUSTRY DIRECTION

The geothermal reservoir technology research is directed to investigate the major problems faced by geothermal developers, and we rely on the industry to identify these problems. Substantial input from the geothermal industry has been utilized in developing the research efforts included in this program. The Lawrence Berkeley Laboratory Industry Review Panel, The Geysers Research Steering Committee, the Geothermal Technology Organization, and other industry groups have identified priority research areas and continue to monitor and evaluate the research progress.

As an example of industry-directed research, we are involved in a major effort at The Geysers geothermal field in California. In 1988, The Geysers reached the peak electrical output of about 2000 megawatts. Steam production and electrical generation declined after that peak, and in April 1989, several industry leaders asked the Geothermal Division of the Department of Energy to assist the operating companies at The Geysers with a research program. In the summer of 1989, meetings were held with operators, research groups, and government agencies at county, state, and federal levels to identify the major problems at The Geysers and to outline possible research that could establish the causes and develop methods to mitigate the problems. Research projects with some built-in flexibility were directed toward these problems immediately, and, in the 1990 fiscal year, over $1,000,000 of DOE funding was directed toward research at The Geysers. The progress of this effort has been reported in several informal workshops to keep the operating companies apprised of new developments and to encourage interaction between researchers and operators.

In the 1991 fiscal year (the current year), over $2,500,000 of DOE funding will be directed to research at The Geysers. Even this substantial research funding would not be effective, were it not for the close cooperation and cost-sharing of the operating companies. Calpine Corporation, Coldwater Creek Operating Company, Northern California Power Agency, and Unocal have contributed money and manpower to this major research effort. The Geysers Research Steering Committee, made up of employees of these four companies, reviewed over forty proposals for research at The Geysers and suggested funding for those proposed projects which best met industry needs. The projects receiving DOE-funding this year will include investigations of polymer-concrete lined pipe for corrosion control, chemical-tracer tests to monitor the flow of injected water through the reservoir, analysis of microseismic signals to locate permeable fractures, computer modeling of injection and production to develop better knowledge of the reservoir parameters, and geological and geochemical studies to characterize the processes occurring in the reservoir. The close cooperation between researchers and operators and the frequent research reviews will help to rapidly transfer new techniques and innovations to the operating companies.

DEVELOPMENT OF NEW TECHNOLOGY

The geothermal industry has identified the need for reliable techniques to locate and characterize fractures, to define reservoir boundaries, to assess fluid recharge, and to understand fluid flow in complex reservoirs. In order to satisfy these needs, the reservoir technology research has looked first at related earth resource industries, petroleum, mining, and ground water, to adapt any usable technologies from these mature industries. Other techniques have been adapted from the chemical industry and from manufacturing processes dealing with hot water or steam. Many of the research organizations funded by this program have extensive experience in one or more of the related fields.

The research groups which have supported this program for many years offer many diverse strengths. The Stanford University Department of Petroleum Engineering provides the background and knowledge of thermal oil recovery and the understanding of the petroleum industry. The Lawrence Berkeley Laboratory (LBL) contributes an extensive background in hydrology and the physics of fluid flow. LBL also has a strength in geophysics, particularly in seismology research related to earthquake prediction, and the Lawrence Livermore National Laboratory contributes the expertise in seismic analysis of nuclear testing. Both seismic groups provide aspects of rock physics that are needed to locate and characterize the permeable fractures that are necessary for the commercial production of geothermal resources. The University of Utah Research Institute brings to this research program the experience and knowledge of the geophysics, geochemistry, and geology of the mining industry. This understanding of ore deposits is of great benefit because many of our geothermal systems are ore deposits in the making. The Idaho National Engineering Laboratory provides a strength in field engineering operations and in numerical simulation of reservoir processes. Oak Ridge National Laboratory gives us the benefit of an excellent laboratory for the measurement of chemical thermodynamic parameters for geothermal systems. Several additional university and industry research groups provide expertise in additional aspects of earth science research that are applicable to geothermal energy development. The U.S. Geological Survey has received partial funding from the DOE Geothermal Division for augmenting several ongoing Survey research projects.

EDUCATION FOR THE GEOTHERMAL INDUSTRY

One of the most important aspects of the Geothermal Reservoir Technology Research program is the education and training of students for the geothermal industry. In order to maintain a viable industry in the United States, we must assure a continued supply of well trained scientists and engineers to staff the operating companies. Our greatest success lies in the continuous DOE support over the last sixteen years of the Stanford Geothermal Program. Many of the reservoir engineers in the geothermal industry were trained at Stanford. Also of great importance, are the student training programs at other universities and the national laboratories. These geothermal programs supply the industry with individuals who have participated in the latest research and can transfer their knowledge to the companies. Many of the former students maintain a strong tie to their professors and research colleagues which facilitates the productivity of the ongoing, joint, cost-shared research.

Expected advances in the geothermal industry over the next few years will require an even better trained supply of students. To aid in this training, it is important that the geothermal industry make an effort to provide lecturers and workshop participants to visit the universities and discuss the current activities and problems in geothermal operations. The geothermal operating companies have been generous with financial support and with data for student research topics, and the benefits to the companies have been substantial.

GEOTHERMAL EXPLORATION

A major period of geothermal exploration culminated in 1979 and 1980, with the DOE cost-shared program for Industry-Coupled Drilling. In that program, DOE used federal funds to share the risk of exploratory drilling in fifteen prospect areas in Utah and Nevada. The program was highly successful, and seven of those geothermal prospects are now producing electricity. The advent of Standard Offer 4 from the California utilities provided the needed incentive for development of many of these sites. Unfortunately, geothermal exploration has not kept pace with development, and there are now very few geothermal sites that are available for future development. A major exploration effort is needed to build the inventory of geothermal areas for another period of rapid development. We anticipate a strong market for geothermal electrical generation as a result of the Clean Air Act of 1990 and the need for energy sources with low atmospheric emissions and proven environmental safety.

Most of the easily located geothermal systems, those with hot springs, fumaroles, and geysers, are already known and many are developed. A new generation of tools is needed to locate and characterize the hidden geothermal systems that do not reach the surface. To participate with the geothermal industry in development of the necessary exploration tools, the President's budget request for fiscal year 1992 includes a DOE initiative for $1,500,000 for improved exploration technology. If approved by Congress, we expect this to be a productive, cost-shared effort of industry and government.

In addition to new geophysical and geochemical methods, we hope to provide a procedure for reservoir testing and evaluation which is compatible with core drilling. Core drilling has become an important method of geothermal exploration, but it is still necessary to drill a more expensive large-diameter well for reservoir testing. We hope also to improve the methods of reservoir testing and evaluation through research to develop new instruments and new methods of interpretation. Development of new technologies to address these needs will increase drilling success rates, and consequently, decrease the overall drilling costs for a given project. When geothermal reservoirs can be fully characterized to allow development of effective exploitation strategies, they can reach their full production potential. Developers need the ability to predict the total available energy and the useful productive lifetime for a geothermal reservoir at the earliest possible stage of development in order to maximize the benefit from this attractive energy resource.

INTERNATIONAL COOPERATION

Cooperative geothermal research projects with Italy and Mexico began in the mid-1970s, largely motivated by the difficulty at that time in obtaining proprietary data from U.S. geothermal companies. These international research efforts have provided several new techniques and significant operational information for the U.S. geothermal industry. Our joint research with U.S. companies has greatly expanded over the last several years, and the industry has provided access to important operational data. Continued cooperative research with foreign geothermal developments still has a value in bringing to the U.S. geothermal operators a greater understanding of the long-term changes in reservoir conditions due to production. The Larderello geothermal field in Italy has been generating electricity since 1904 and has continuous field data since 1945. The similarities between Larderello and The Geysers are numerous, and we feel there is much U.S. operators can learn from the Italian development. As part of the present research effort on The Geysers, we hope to gain a great deal of applicable knowledge from Larderello.

FUTURE INDUSTRY NEEDS

Part of the reservoir technology research is designed to anticipate future industry needs. Our emphasis for the future is in the area of reservoir operations. We expect that geothermal operating companies will need real-time monitoring of changes in reservoir conditions in order to extract the maximum useful energy from their systems. The development and testing of a cryogenic, superconducting gravimeter is designed to provide an operational monitor of mass changes in a geothermal reservoir in response to production and injection of steam and water. Such a monitor of mass changes would allow the field operator to vary the rates of production and injection to control fluid residence time in the reservoir. The down-hole, high-precision measurement of pressure, temperature, flow rate, and fluid chemistry would be valuable for reservoir testing and evaluation. The capability now exists for only some of these measurements at temperatures up to 300°C, and our suspended research in fiber-optic systems has the possibility of providing all of these parameters at temperatures of 400°C. The accurate numerical modeling of reservoir geochemical processes would make possible the prediction of increases or decreases in permeability, the precipitation of scale, and the effects of corrosion. Present thermodynamic data are inadequate to predict reactions in complex geothermal solutions, but laboratory measurements of thermodynamic variables are underway to characterize the aluminosilicate minerals and their solution products. Other research funded by the Geothermal Division includes developing the geochemical models to use these new data when they become available.

SUMMARY

In the following papers, you will read about a diverse collection of research projects designed to better understand geothermal reservoir processes and responses to production. Each of these projects uses the specialties developed by an experienced research group. The projects are designed to investigate current problems facing the geothermal operators and to anticipate future needs of industry. Many students are involved in these research projects, and their training is important for the future health of the geothermal industry.

OPTIMIZING REINJECTION STRATEGY AT PALINPINON, PHILIPPINES BASED ON CHLORIDE DATA

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ABSTRACT

One of the guidelines established for the safe and efficient management of the Palinpinon Geothermal Field is to adopt a production and well utilization strategy such that the rapid rate and magnitude of reinjection fluid returns leading to premature thermal breakthrough would be minimized. To help achieve this goal, sodium fluorescein and radioactive tracer tests have been conducted to determine the rate and extent of communication between the reinjection and producing sectors of the field. The first objective of this paper is to show how the results of these tests, together with information on field geometry and operating conditions were used in algorithms developed in Operations Research to allocate production and reinjection rates among the different Palinpinon wells.

Due to operational and economic constraints, such tracer tests were very limited in number and scope. This prevents obtaining information on the explicit interaction between each reinjection well and the producing wells. Hence, the chloride value of the producing well, was tested to determine if use of this parameter would enable identifying fast reinjection paths among different production/reinjection well pairs. The second aim, therefore, of this paper is to show the different methods of using the chloride data of the producing wells and the injection flow rates of the reinjection wells to provide a ranking of the pair of wells and, thereby, optimize the reinjection strategy of the field.

INTRODUCTION

The Palinpinon Geothermal Field (Figure 1) is one of two producing steamfields currently operated by the Philippine National Oil Company (PNOC). The steam requirement of the 112.5 MWe commercial plant, known as Palinpinon 1 has been met by 21 production wells and 10 reinjection wells which accept wastewater by gravity flow. Figure 2 shows the surface reticulation system, the production and reinjection multi-wells pads, as well as the well tracks. The need to reinject waste liquid effluent has been primarily dictated by environmental constraint, which in the Philippines prohibit full disposal into the rivers that are used for field irrigation. In addition to this, the other benefits of injection, such as maintaining reservoir pressures and increasing thermal recovery from rocks have been recognized.

Although injection wells have been drilled at the periphery of the field, preferably at the identified outflows, initial chemical monitoring of the produced fluids showed increases in well reservoir chloride values (Figure 3). This has been interpreted as evidence of the return of reinjected fluids to the production sector. To maximize productivity of the reservoir and prolong the economic life of the field, guidelines for the safe and efficient management of the Palinpinon reservoir have been established. These include the requirements of:

1) minimizing fluid residence times in the surface and downhole piping while operating reinjection wells to prevent or minimize silica deposition of injected fluid that is supersaturated with respect to amorphous silica.

2) minimizing steam wastage due to varying steam demand and supply by prioritizing high enthalpy production wells during peak steam requirements and choosing injection wells with additional capacity.

3) adopting a production and reinjection well utilization strategy such that the rapid rate and magnitude of reinjection fluids returns leading to premature thermal breakthrough would be minimized, if not avoided.

Towards this objective, a comprehensive testing and monitoring programme was instituted. This programme includes fluorescein and radioactive tracer testing to determine interaction between the injecting and producing blocks.

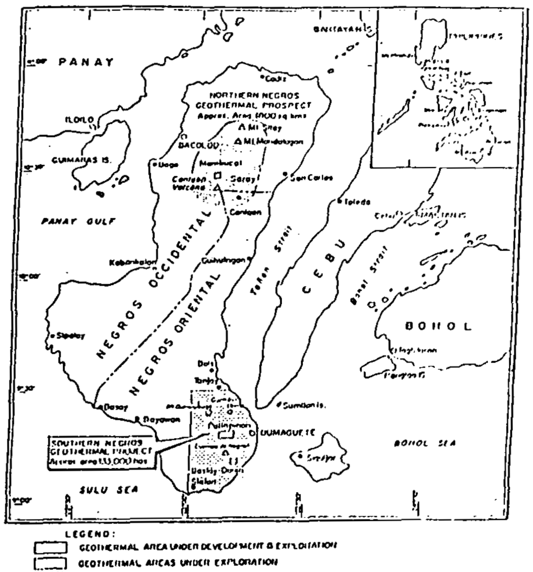

Figure 1 Location Map of Palinpinon Geothermal Field Southern Negros Geothermal Project

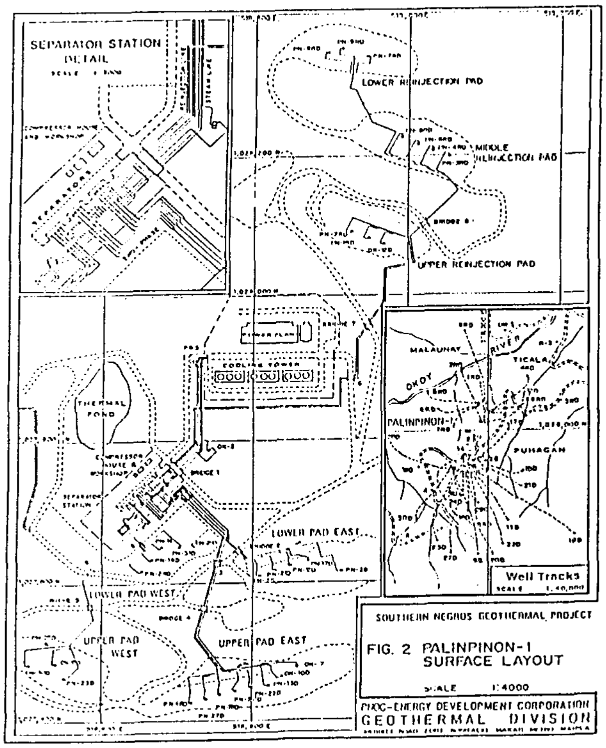

Figure 2 Palinpinon-1 Surface Layout

It is one aim of this paper to use the results of these tracer tests in algorithms of Operations Research to determine optimal production and reinjection rates among the different Palinpinon wells. However, since these tracer tests are limited, the other objective is to find another parameter that could be used in place of tracer return data in the optimization of production and reinjection strategy.

TRACER TESTS AT THE PALINPINON GEOTHERMAL FIELD

Table 1 shows the results of conducting fluorescein and radioactive tracer testing at Palinpinon 1. Sodium fluorescein dye was injected into OK-12RD, PN-1RD, and PN-9RD while radioactive Iodine-131 was injected into OK-12RD and PN-9RD. Amounts of the dye and radioactive tracer were increased with succeeding tests to expand the scope of the tests and overcome the limitations imposed by degradation of the tracers.

The results from Table 1 show that the eastern injection wells (OK-12RD, PN-1RD, and PN-6RD) communicate strongly with the eastern and central Puhagan wells such as PN-15D, PN-17D, PN-21D, PN-26, PN-28, and OK-7. The western injection well PN-9RD, likewise, interact with the western, southwestern, and central Puhagan wells such as PN-14, PN-19D, OK-9D, PN-23, PN-24D, PN-29D, PN-30D, PN-31D, OK-7, PN-26, PN-28, PN-16D, and PN-18D. Figure 4 shows the tracer breakthrough curve for OK-7 which had the earliest and strongest return during the PN-9RD tracer test. Coupled with interference testing and chemistry

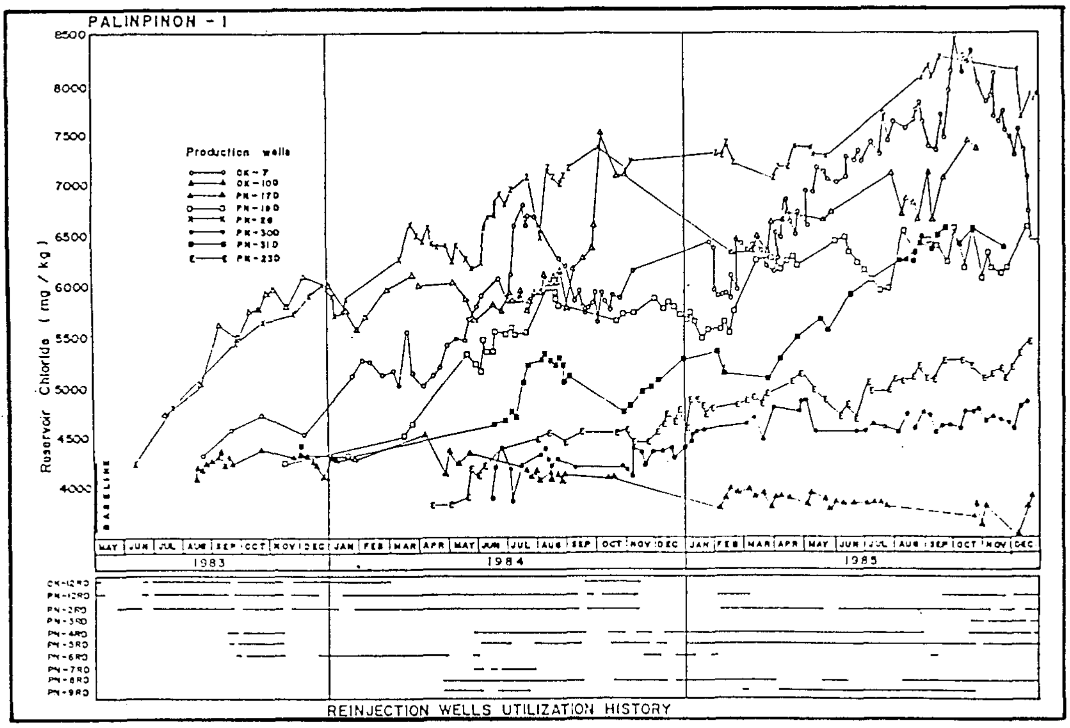

Figure 3 Reservoir Chloride vs Time

Table I

Tracer Tests at the Palinpinon Geothermal Field

TRACER AMOUNT	RECIPIENT WELL (Inclusive Dates)	MONITORING WELLS, SPRINGS, RIVERS	RESULTS		
			Positive Return	Transit Time	% Return
Iodine-131, 18.5 GBq (0.50 Ci)	OK-2 (15 Aug - 06 Sept 81)	OK-7, OK-12D, PN-13D PN-16D, OK-9D, OK-10D Ticala and Buhayan Springs	OK-7	16.0 days	0.23
			OK-12D	16.4 days	0.05
			PN-13D	16.2 days	0.10
Sodium Fluorescein 0.5 kg/test	OK-12RD (30 July - 02 Aug 83)	PN-6RD at different operating conditions	PN-6RD	.75-2.1 hours	8 - 55
Iodine-131, 20.2 GBq (0.545 Ci)	OK-12RD (03 Aug - 29 Aug 83)	OK-7; OK-10D, PN-15D, PN-17D, PN-21D, PN-26, PN-28, PN-29D, PN-3RD, PN-4RD, PN-6RD	OK-7	14.6 days	1.28
			OK-10D	13.8 days	1.35
			PN-15D	7.3 days	0.35
			PN-17D	3.9 days	8.22
				7.5 days	2.32
				10.5 days	2.52
			PN-28	6.0 days	0.58
			PN-21D	Traces on 4th and 9th day afte tracer injection	
			PN-26	Traces on 5th and 7th day afte tracer injection	
			PN-3RD	Very low traces	
			PN-4RD	Very low traces	
Sodium Fluorescein 2.0 kg	PN-1RD (28 Aug - 21 Sept 84)	OK-7, OK-9D, OK-10D, PN-15D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-24D, PN-29D, PN-30D, PN-31D, N-3, OK-2, RI 317/318, PN-3RD, PN-6RD, PN-9RD	PN-26	40.0 hours	
			PN-28	60.0 hours	
			OK-7	80.0 hours	
			OK-2	90.0 hours	
			PN-3RD	On downhole sample 27 hours after tracer injection	
			PN-6RD	On down hole sample 94 and 146 hours after injection	
			PN-9RD	On down hole sample 168 hours after injection	
Sodium fluorescein 10 kg Iodine-131, 67 GBq (1.81 Ci)	PN-9RD (26 Sept - 20 Oct 85)	OK-7, OK-9D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-26, PN-28, PN-29D, PN-30D, PN-31D RI 317/318	OK-7	5.7 days	29.20, 21.7*
			PN-29D	14.0 days	6.80, 4.6
			PN-26	11.0 days	3.90, 0.5
			PN-28	10.3 days	1.10, 0.3
			PN-18D	15.6 days	0.80, 1.6
			PN-30D	15.7 days	0.80, 1.6
			PN-23D	15.8 days	0.40, 1.6
			PN-31D	16.0 days	0.40, 1.6
			PN-16D	Tracer found in samples after 8-19 days	
			PN-19D	Tracer found in samples after 15-19 days	

*PNOC-EDC recalculated returns are in second column. Previous values for PN-26 and PN-28 believed to be erroneous due to innacurate flowrates used.

monitoring, results indicate fast interaction, too, of western injection wells PN-7RD and PN-8RD with the western and central Puhagan wells. Additional studies (PNOC-EDC, 1986) indicate that geological structures or faults are the preferred flowpaths of the reinjected fluids back to the producing wells.

From radioactive tracer testing, one can obtain the tracer breakthrough time, the peak tracer recovery time, the peak tracer concentration, and the fraction of tracer recovered. This presents an advantage over fluorescein testing where only breakthrough times and the quality (intensity) of the return were established during the test. This is why only the results of the radioactive tracer test were used for the algorithms in the optimization study as discussed later in this report.

Through this intensive chemical monitoring, tracer testing, as well as interference testing, injection and production wells with strong interactions have been identified; knowledge of which was employed to optimize the well utilization scheme. As an example, the northern and northeastern injection wells PN-2RD, PN-3RD, PN-4RD, and PN-5RD are considered "priority" in that they have exhibited minimal communications so far with the production wells. It is acknowledged that though almost all production wells produce reinjected fluid in varying proportions, the rate and magnitude of reinjection fluid returns are dependent on the combination of wells used for injection and production at any given time. It would be an advantage, therefore, to find a tool that would demonstrate or assess the interaction of a given injector/producer pair with time.

OPTIMIZATION STRATEGY

The results of the tracer tests, information on field geometry together with operating conditions were used to test algorithms in Operations Research to allocate reinjection and production rates in Palinpinon wells. These algorithms were modified by Lovekin (1987) to optimize injection scheduling in a geothermal field.

Essentially, under this strategy, the reservoir is idealized as a network of channels or arcs connecting each pair of wells in the field. The arc cost, c_{ij}, expresses the likelihood of thermal breakthrough resulting from the movement of a unit fluid from injection i to producer j. It consists of weighting factors which are taken from tracer return data, field geometry and field operating conditions as shown by Equation 1.

$$c_{ij} = \frac{1}{t_i}\,\frac{1}{t_p}\,C_p \cdot f \cdot \frac{1}{L^2}\,e\,s\,h \cdot \frac{q_p}{q_{pt}}\,\frac{1}{q_{rt}} \qquad (1)$$

where

t_i = initial tracer response, days
t_p = peak tracer response, days
C_p = peak tracer concentration, t^{-1}
f = fractional tracer recovery
L = horizontal distance between wells, meters
h = elevation difference between production and injection zones, meters
s = scaling factor
q_p = producing rate under operating conditions
q_{rt} = injection rate during tracer testing

The results of the tracer tests demonstrate that the earlier the breakthrough or initial tracer response, the greater the tracer return, and the greater the likelihood for thermal breakthrough. Hence, the times of initial (t_i) and peak (t_p)tracer response are made to be inversely related to the arc cost c_{ij}. In contrast, the fraction of tracer recovered (f) and the peak tracer concentration (Cp) are made linear to the arc cost.

For a porous-media type of reservoir, the thermal recovery of injected fluid depends on the heat exchanged between the fluid and the rocks. Since this rock surface heat area is proportional to L^2, then the probability of thermal breakthrough is greater for smaller surface area. This means an inverse relationship between L^2 and the arc cost. The elevation difference (h) between the producing and injecting zone is made linear to the arc cost due to the fact that injected fluid, being cooler and denser would tend to sink down the reservoir. Hence, it is intuitive that a deep producing well would have a higher chance of communicating with an injection well, than a shallow producing well would. Since h could be positive (producing zone below the injection zone) or negative, it appears in the equation as an exponential term e^{sh}, with a scaling factor s to keep it from dominating the rest of the weighting factors.

In a similar manner, producing and injecting rates during the tracer tests (q_{pt} and q_{rt}), can also be made as weighting factors. A well which produces at a small rate and manifests positive tracer return would have a higher likelihood of being affected by injection returns than another well which is producing at a higher rate with similar returns. Therefore, q_{pt}, and with the same logic, q_{rt}, are inversely related to the arc cost.

It is to be emphasized that all the factors need not be used to get the arc costs. Some factors could be deleted, and others weighed or included depending on which ones the developer deem to be important on the basis of reservoir behavior and information.

The sum of the arc costs from a particular injection well to all the producing wells is its cost coefficient. The unknown or decision variable is the reinjection rate, q_{ri}, into injection well i. The product of the injection rate and the arc cost is the breakthrough index for the specific arc or injection/production pair of wells as expressed by Equation 2.

$$b_{ij} = c_{ij} q_{ri} \qquad (2)$$

The summation of breakthrough indices for all arcs is then the fieldwide breakthrough index B. Under the optimization strategy, it is this index which is the objective function that has to be minimized subject to well capacities and field operating constraints.

Two algorithms were used for optimization strategy:
1) linear programming which employs the simplex method, and
2) quadratic programming

Linear Programming

In the linear programming algorithm, the objective functions to be minimized are shown by Eqs. 3 and 4.

Minimize:

$$B_1 = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} q_{ri} \qquad (3)$$

subject to

$$q_{ri} \leq q_{rimax}$$
$$\sum q_{ri} = Q_{rtot}$$
$$q_{ri} \geq 0 \qquad i = 1, N_1$$

Minimize:

$$B_2 = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} q_{pj} \qquad (4)$$

subject to

$$q_{pj} \leq q_{pjmax}$$
$$\sum q_{pj} = Q_{ptot}$$
$$q_{pj} \geq 0 \qquad j = 1, N_2$$

where N_1 = number of injectors
N_2 = number of producers
q_{ri} = injection rate into well i
q_{pj} = producing rate from well j
q_{rimax} = maximum permissible rate into well i
q_{pjmax} = maximum permissible rate from well j
Q_{rtot} = total required injection rate
Q_{ptot} = total required producing rate

In this algorithm, the mutual dependence of injection and production rates is accounted for by alternately exchanging their roles as decision variables and weighting factors.

Quadratic Programming:

On the other hand, the formulation for the second algorithm is shown by Equation 5.

Minimize:

$$B = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} q_{ri} q_{pj} \qquad (5)$$

where the variables and constraints are the same and combined as in the first formulation. In this approach, the interdependence of injection and production rates is explicitly acknowledged by treating both as decision variables and including them in the objective function as a product. Hence, the objective function becomes a quadratic and the problem is solved by a quadratic programming (QP) solver.

Preliminary Results Using Tracer Return Data

The results of the two radioactive tracer tests shown in Table 1 were used in the above algorithms. Specifically, the mean transit recovery time, the fraction recovered, the aerial and vertical separation between the injection and production pair of wells, the flowrates during the tracer tests, as well as the maximum flowrates of all the wells were used as input in the algorithms. In this test, it was assumed that only OK-12RD and PN-9RD are the reinjection wells. The problem calls for allocating the

Table 2

Allocation of Production Rates Among Palinpinon Wells Using Linear (LPAL) and Quadratic Programming (QPAL)

Qrtotal = 260 kg/s; Qptotal varies

	LPAL3					QPAL		
Qptotal kg/s	Injectors	Qrinjected kg/s	Curtailed Producers	Qpcurtailed kg/s	Cost Coefficients	Injectors	Curtailed Producers	Qpcurtailed kg/s
930	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	3	0.003200		PN-18D	3
900	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	33	0.003200		PN-18D	33
850	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	19	0.001000		OK-10D	19
800	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	17	0.000640		PN-31D	17
750	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	Total	0.000640		PN-31D	Total
			PN-15D	2	0.000300		PN-15D	2
700	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	Total	0.000640		PN-31D	Total
			PN-15D	52	0.000300		PN-15D	52
650	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	Total	0.000640		PN-31D	Total
			PN-15D	Total	0.000300		PN-15D	Total
			PN-30D	30	0.000095		PN-30D	30

production rates among the different wells as the required total production rate decreases from 930 kg/s.

The results as shown by Table 2 indicate that the two approaches or algorithms give similar results. As the required total field load decreased, the producing rates was reduced and production wells were shut in one-by-one depending on its potential damage to the field as manifested by the injector/producer cost coefficient. The higher the cost coefficient, the more serious is the potential for thermal breakthrough. However, these cost coefficients which enable the explicit ranking of the wells are present only in the linear programming algorithm. Nevertheless, as seen from Table 2, the actual allocations provided by quadratic programming duplicate those of linear programming.

It can be concluded, therefore, that by knowing the arc costs, the programs obtain the optimal rate allocation for both injection and production wells.

USE OF CHLORIDE DATA

Due to economic and operational constraints, radioactive tracer cannot be injected into every reinjection well. Similarly, not all the production wells can be monitored during a tracer test. To find another parameter which can be used to optimize reinjection strategy, attention was turned to the reservoir chloride measurement of the production wells as shown by Figure 3. It has been established by the PNOC geochemists that the chloride values of a producing well can be used as an indication of the extent of reinjection returns to this well. The correlation or strength of the relationship between the chloride of a producing well and the flowrate of an injecting well was obtained in four different ways. Figure 4 shows in graphical form the different methods used to correlate the chloride values of a production well with the injection flowrates of an injection well. It should be remembered when comparing, that these numbers represent a relative assessment of the producer/injector pair potential for thermal breakthrough.

1. First, the correlation between the chloride value with time of a production well and the mass flowrate with time of an injection well was obtained (Figure 4a).

2. Second, the correlation between the chloride value with time of a production well and the total mass flowrate with time of an injection well was calculated (Figure 4b).

3. Third, the correlation between the deviation of the chloride value of a production well from the best fit line and the flowrate rate of an injection well was computed (Figure 4c).

4. Lastly, the chloride value with time of a production well was expressed as a linear combination of the mass flowrates of the injection wells.

The first method (Figure 4a) of chloride-flowrate correlation stems from the observation that the chloride values of a production well are affected when particular injection wells are disconnected from or hooked on line. If an injection well communicates strongly with a production well, then putting this injection well on line is usually followed by a substantial increase in the chloride measurements of the affected well. Once it is removed from service, there is an accompanying decrease in the chloride data of the producing well.

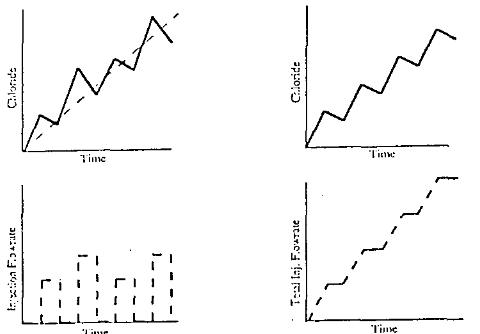

Figure 4a. Chloride vs Flowrate

Figure 4b. Chloride vs Total Flowrate

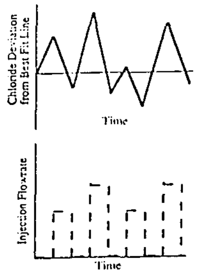

Figure 4c. Chloride deviation vs Flowrate

Figure 4 Chloride vs Flowrate Correlation Methods

In the second method (Figure 4b), what is examined is the relationship between chloride and the total flowrate. Since the chloride value of a production well at a particular time is the cumulative effect, it is reasonable to see the relationship between this chloride value and the total flowrate of the injection well. Given the hypothetical case of an injection well affecting strongly a production well, the plots of the two variables with time would be similar to Figure 4b.

On the other hand, it is also desirable to examine the relationship between the magnitude of the increases in chloride value of a production well with the flowrate of an injection well. Going back to the hypothetical case, it would be logical to expect that the effect of a high injection rate would be a greater step change in the chloride value of the production well. The magnitude of this change is measured by the deviation of the chloride value from the best fit line and this deviation is then correlated with the injection flowrate at that time (Figure 4c).

The effect of a particular injection well on a certain production well can be concluded unambiguously only when all other factors are held constant (such as injection flowrates of other injection wells and producing rates of all other wells are unchanged). This is complicated by the fact that a single injection well could interact with more than one production well. As a consequence, the net effect on a production well at a particular time interval would be due to the effects of the particular injection wells which were active in the same time interval. To take this into account, the last method seeks to express the chloride value of the production well as a linear combination of the injection flowrates of all the active reinjection wells at the concerned time. This is illustrated by Equation 6.

$$Cl_i = a_o + \sum_{j=1}^{n} a_j q_j \qquad (6)$$

where Cl_i = chloride value of well i at time t
a_o = initial chloride value at time t
a_j = correlation coefficient between production well i and injection well j
q_j = mass flowrate of injection well j
n = number of injection wells

The system of linear equations is put in matrix form and then solved simultaneously by a matrix solver like the Gauss-Jordan method of elimination.

Results of the Chloride Data Methods

The plots of the first three chloride methods are shown in Figures 5 to 12 using the wells OK-7, PN-9RD, PN-28 and PN-2RD. The first method is demonstrated by Figures 5 and 6, the second by Figures 7 and 8, and the third by Figures 9 and 10. Figures 11 and 12 have been included for comparison.

Figure 5a reflects the increase in monthly chloride values of well OK-7 and Figure 5b shows the monthly injection flowrates of PN-9RD. For an injector/producer pair with strong communication, it has been observed that the crests and troughs of the injection plot usually coincide with those of the producing well. This is reflected in high correlation coefficients during these times as demonstrated by Figure 6a. In this case, this would infer and confirm that there is good communication between OK-7 and PN-9RD. Figure 6b exhibits the effect if the correlation is calculated with a shift in time of the chloride values of OK-7. This was done to accommodate the reasoning that the increase in chloride value is an effect, and that there could be a lag or delay in the response of the producing well. In spite of the shift, the general trend of the correlation plot remains the same.

Figure 7b shows the plot of the cumulative flowrate with time of PN-9RD. The correlation with time of the chloride data with total rate shown in Figure 8 remain remarkably high throughout. The same pattern has been demonstrated by the rest of the OK-7/injection well pairs. The other plots of producing/injecting pairs show that the general trend for a particular production well remains the same with almost all the injection wells. This would indicate that this method can not be used to assess and differentiate the relationship between a producer and an injector.

Figure 9a is the same plot of OK-7 monthly chloride but with the dashed line representing the linearly regressed line to this curve. The deviations from this best fit line are plotted in Figure 9b and the correlation between the deviation and injection rate is shown in Figure 10. It can be seen that this plot of Figure 10 (Cldev-flowrate) and that of Figure 6 (Cl-flowrate) are similar.

Figures 11a and 11b show the chloride values of PN-28 and the flowrates of PN-2RD. These are correlated and the results plotted in Figure 12. One would note that the correlation values remain negative implying a lesser degree of interaction or communication between PN-28 and PN-2RD. When Figure 12 is compared with that of Figure 6, both being chloride-flowrate correlation, the immediate disparity in the relationship between OK-7/PN-9RD and PN-28/PN-2RD can be concluded.

Table 3 gives a tentative summary of the coefficients obtained from the four chloride methods. The method of chloride-total rate correlation (the second method) has been disregarded and, therefore, not included in this tabulation. For the linear combination method, the table only shows the correlation taken for the whole data set. For the chloride-rate correlations, the numbers chosen were either the average or those taken at the time the injection well has stopped injecting. The table shows:

1) In slightly more than half of the tabulated results, the calculated chloride-flowrate correlation is similar and very close to that of the chloride deviation-flowrate correlation. When only the signs of the correlation are compared, this increases to about 70%.

2) In general, the relationship shown by the linear combination coefficients agree with the observed relationships. For example, there is a high coefficient of correlation of OK-7 and PN-26 with PN-9RD, PN-8RD, and PN-1RD.

The limitation imposed by the two chloride-rate correlation methods (first and third) as shown by the dashed line is due to the fact that during the time considered the reinjection well was not injecting. Similarly, the linear combination method fails when the matrix is singular and no solution to the system of linear equations can be found.

A detailed study is ongoing and there is a need to examine the criteria for choosing which numbers best represent the relationship of injector/producer pair.

SUMMARY AND CONCLUSIONS

The tracer return data, together with field geometry and operating conditions have been used to allocate production and injection rates among the Palinpinon wells using algorithms in Operations Research.

The theory behind the optimization strategy is that the reservoir can be visualized as a network of arcs connecting injector to producer. Each arc has a potential for thermal breakthrough caused by fluid flow from injector to producer and this potential is measured by the arc cost. The methods for optimization make use of linear programming and quadratic programming where the objective function to be minimized is the fieldwide breakthrough index defined to be the product of the arc cost and the flowrate.

The results of allocation are the same for both linear and quadratic programming. However, cost coefficients which provide a ranking of the injector/producer pair according to the potential for thermal breakthrough is provided only in linear programming.

Chloride was examined as another parameter for optimization since it has been observed to be an indicator of the extent of reinjection returns to a producing well. Four different methods of finding the correlation between the chloride value and the flowrate were examined. In general, there has been agreement between the chloride-rate correlation and the chloride deviation-rate correlation. The linear combination method also shows encouraging signs. However, there is a need to examine the factors behind the disparities in the results. Nevertheless, the initial results of the study have been encouraging and points out that the correlation between chloride and flowrate can be used as arc costs in optimizing production and reinjection strategy.

REFERENCES

1. Lovekin, J., and Horne, R.N.: "Optimization of Injection Scheduling in Geothermal Fields," G.R.C. Transactions, 11, 1987.

Figure 5a OK-7 Average Monthly Res Chloride With Time

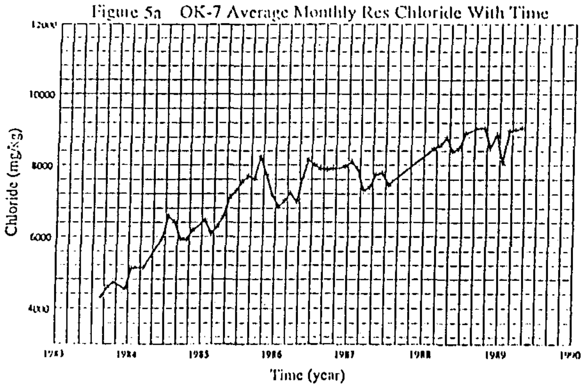

Figure 5b PN-9RD Monthly Average Injection With Time

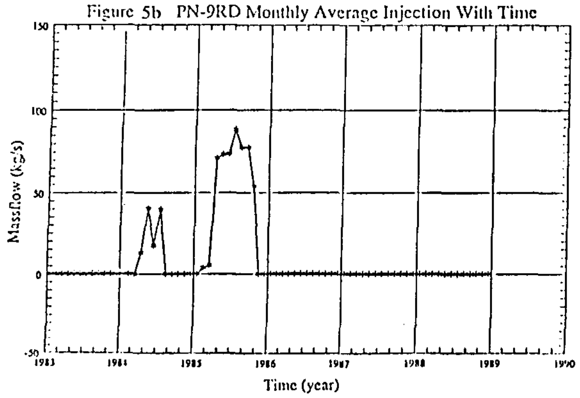

Figure 5 OK-7 Chloride and PN-9RD Flowrate

Figure 6a OK-7/PN-9RD Correlation With Time

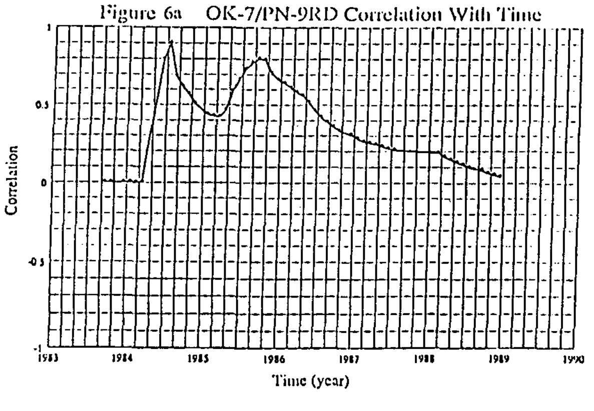

Figure 6b OK-7/PN-9RD Correlation (Chloride Shift of 1 Month)

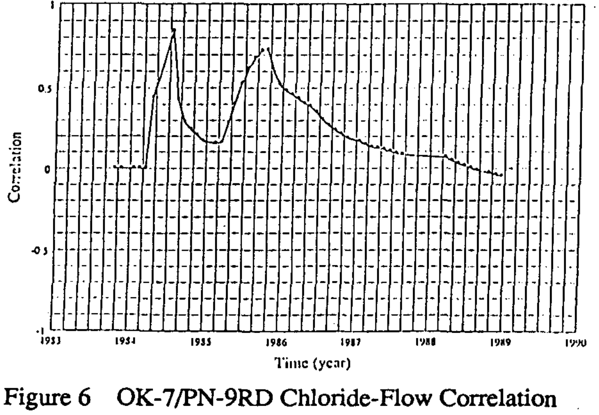

Figure 6 OK-7/PN-9RD Chloride-Flow Correlation

Figure 7a OK-7 Average Monthly Res Chloride With Time

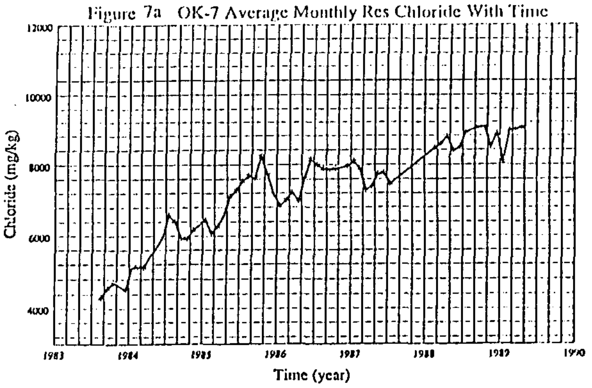

Figure 7b PN-9RD Total Flowrate With Time

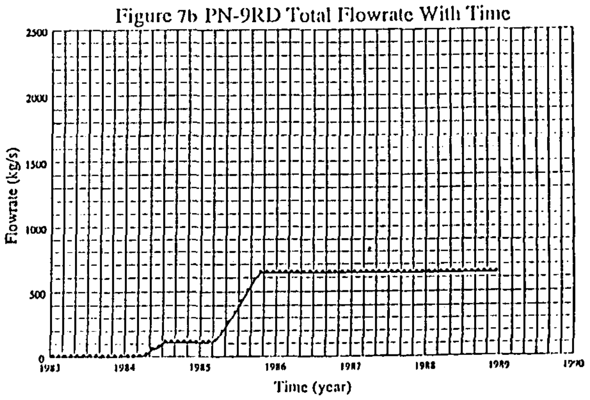

Figure 7 OK-7 Chloride and PN-9RD Total Flowrate

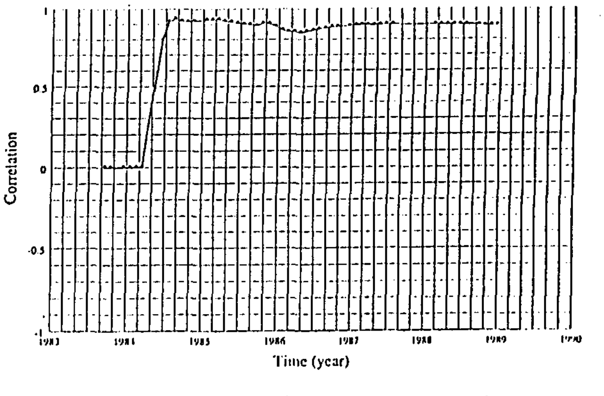

Figure 8 OK-7/PN-9RD Cl-Total Fow Correlation

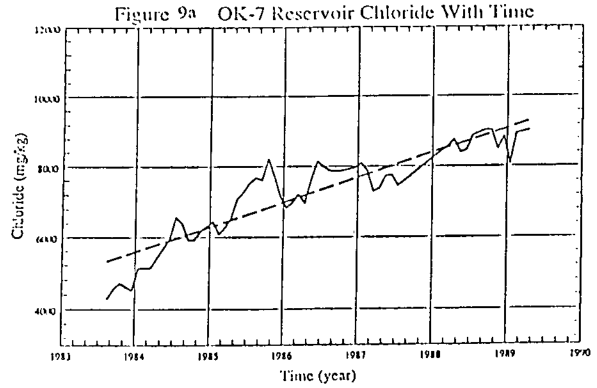
Figure 9a OK-7 Reservoir Chloride With Time

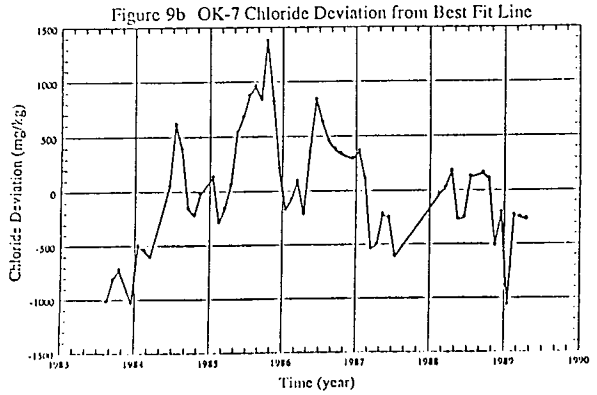
Figure 9b OK-7 Chloride Deviation from Best Fit Line

Figure 9 OK-7 Chloride and Deviation

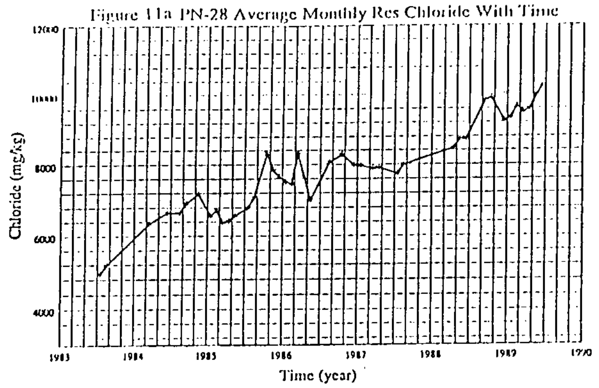
Figure 11a PN-28 Average Monthly Res Chloride With Time

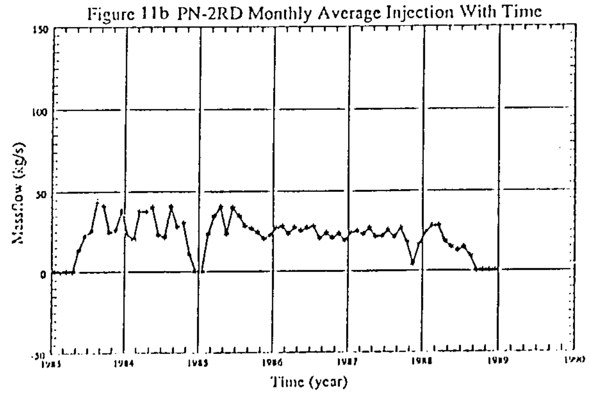
Figure 11b PN-2RD Monthly Average Injection With Time

Figure 11 PN-28 Chloride and PN-2RD Flowrate

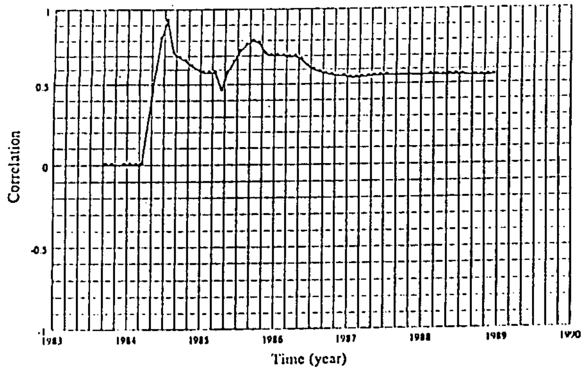

Figure 10 OK-7/PN-9RD Cldeviation-Flow Correlation

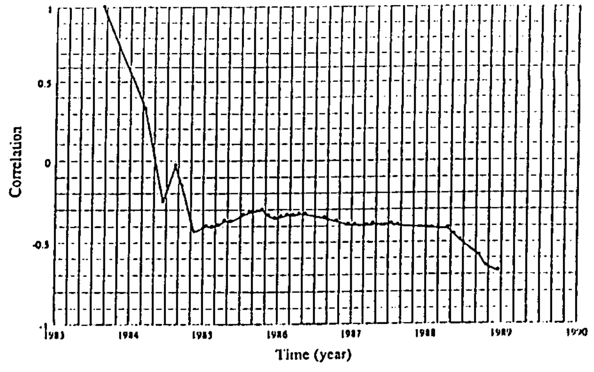

Figure 12 PN-28/PN-2RD Chloride-Flow Correlation

Table 3
Summary of Chloride - Flowrate Correlation

		REINJECTION WELLS								
PRODUCTION WELL	METHOD	PN-1RD	PN-2RD	PN-3RD	PN-4RD	PN-5RD	PN-6RD	PN-7RD	PN-8RD	PN-9RD
OK-10D	Cldev-Flow Corr	0.4320	-0.1310	-0.2740	-0.3800	-0.5690	0.3240	0.3590	-0.0330	-0.3910
	Cl-Flow Corr	0.3420	-0.2850	-0.0600	-0.3520	-0.4560	0.3320	0.4190	-0.0400	-0.3890
	Linear Comb Coeff	4.0440	-11.5100	1.7370	2.8710	-7.6590	4.1940	5.2960	2.6470	1.8320
OK-7	Cldev-Flow Corr	-0.1650	-0.1580	0.0270	0.4680	0.6140	-0.5050	0.9300	0.8160	0.9260
	Cl-Flow Corr	-0.4840	-0.4110	0.6370	0.4600	0.7790	-0.1310	0.9050	0.3730	0.9000
	Linear Comb Coeff	11.9300	-21.9200	28.5600	5.0000	11.2100	8.1530	-6.8300	20.9400	29.3800
PN-15D	Cldev-Flow Corr	0.2420	0.1510	-0.4720	-0.6670	-0.5340	0.3950	-0.4150	-0.5100	-0.7190
	Cl-Flow Corr	-0.2660	-0.5452	0.6250	0.5820	0.7840	0.3470	0.2620	0.5110	0.3040
	Linear Comb Coeff	12.9800	-19.0200	37.1400	-1.5330	-6.5890	5.3900	-0.2979	11.0600	0.2206
PN-26	Cldev-Flow Corr	0.0910	-0.1440	0.3050	0.3010	0.5460	-0.2830	0.7950	0.4000	0.5000
	Cl-Flow Corr	0.1150	-0.1260	0.7550	0.4520	0.5380	-0.3860	0.8010	0.1910	0.4730
	Linear Comb Coeff	9.4090	-14.7200	25.2200	5.4490	5.4950	7.6020	-6.2060	21.3000	17.0900
PN-28	Cldev-Flow Corr	0.4480	-0.1720	-0.0130	-0.0590	-0.0640	0.2230	0.5000	-0.2130	-
	Cl-Flow Corr	-0.0190	-0.4050	0.6790	0.5600	0.5320	0.2670	0.7470	-0.2010	-
	Linear Comb Coeff	9.7210	-8.9670	22.6100	-4.6030	15.1300	8.7520	-1.4170	-0.3865	-
PN-30D	Cldev-Flow Corr	-0.0840	-0.2100	-0.1630	0.0040	-0.1020	0.1720	-	-0.2130	-
	Cl-Flow Corr	-0.0900	-0.2470	-0.1620	-0.0640	-0.1020	0.1950	-	-0.2010	-
	Linear Comb Coeff	1.0040	-7.3590	4.7760	7.5970	-5.4280	1.7240	-	-0.3865	-

The LBL Geothermal Reservoir Technology Program

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Abstract

The main objective of the DOE/GD-funded Geothermal Reservoir Technology Program at Lawrence Berkeley Laboratory is the development and testing of new and improved methods and tools needed by industry in its effort to delineate, characterize, evaluate, and exploit hydrothermal systems for geothermal energy. This paper summarizes the recent and ongoing field, laboratory, and theoretical research activities being conducted as part of the Geothermal Reservoir Technology Program.

Introduction

Many U.S. and foreign areas with potential geothermal resources have yet to be thoroughly explored and evaluated, and other geothermal areas have not been fully developed or optimally exploited because they have never been properly characterized. We believe that the lessons learned from reservoir engineering studies of developed geothermal fields have applicability to the initial characterization of a field in the exploration and early development stages. By incorporating the knowledge of fluid flow in developed geothermal reservoirs, the evaluation and early operating strategy for geothermal fields can be optimized and the possibility of overdevelopment can be avoided. The Reservoir Technology research is designed to identify and test reservoir management practices that could reduce the rate of reservoir pressure drawdown and the impact of some of the deleterious effects associated with pressure decline: mineral precipitation which decreases reservoir permeability, and changes in the composition of the produced fluids.

The Geothermal Reservoir Technology Program at the Lawrence Berkeley Laboratory (LBL) is funded by the Geothermal Division (GD) of the U.S. Department of Energy (DOE). Our basic mission is the development, demonstration, and transfer to industry of improved methods for defining, characterizing, evaluating, and exploiting hydrothermal resources. Field investigations are carried out jointly with geothermal development companies on a cost-shared basis. The joint research is more effective in transferring new technologies and the cost sharing augments limited federal funding. A good example of present activities that benefit from joint research with industry and cost sharing is The Geysers Research project.

Geysers Research Activities

Research activities on The Geysers are directed toward the mitigation of several problems that have appeared recently because of the intense exploitation of the field. The goal of this work is to identify and determine the impact of reservoir management practices that might be implemented to (1) increase the extraction of the heat stored in the subsurface, (2) reduce the corrosiveness of the steam, (3) decrease the amount of noncondensible gases in the steam produced and (4) lengthen the commercial life of the field.

As a first step to understanding the processes taking place, LBL researchers are developing and testing conceptual models of The Geysers system to provide a frame of reference for predicting the effects of changes in the field development strategy. LBL seismologists are working with the Coldwater Creek Operating Company to monitor the microseismic activity associated with water injection and are analyzing and interpreting the data that is being collected to develop a velocity model of the area (Fig. 1) needed to trace the flow of injected water in the subsurface. The analysis of seismic activity will also provide a greater understanding of the stress system in The Geysers and will help map out the distribution of productive fractures.

Geysers Vp/Vs Ratio (top 1.5 km) Ref

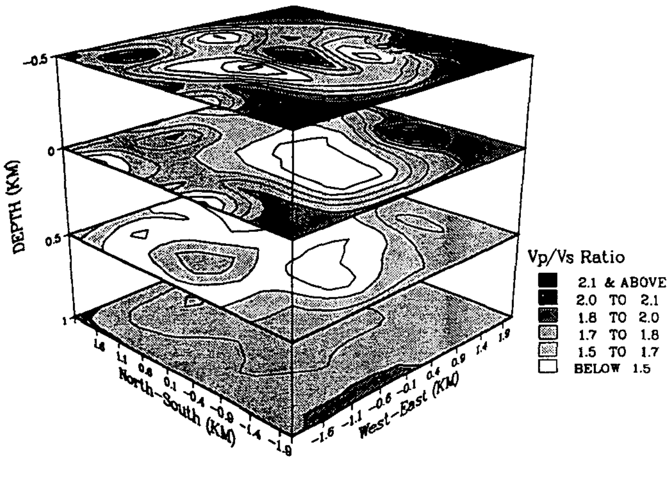

Figure 1. Three-dimensional distribution of the seismic velocity ratio (Vp/Vs) in the Northwest Geysers. One hundred master seismic events were used to develop the velocity model for this area (A. Schultz and E. Majer, pers. comm., 1991).

A multi-disciplinary team of LBL researchers are working with most of the operating companies to analyze the pressure and geochemical changes measured during well tests and long-term production and injection operations at The Geysers in order to trace the growth of low-pressure regions in the field. The analysis of this data is important in reconstructing operating practices which had a deleterious effect on energy production. With the information produced by this study, the operators can be sure of the ramifications of changes to production and injection. LBL engineers are developing equipment and procedures to sample corrosive gases as they enter the well from reservoir fractures. The occurrence of hydrogen chloride gas in the steam from wells in the northern area of The Geysers leads to a concern about corrosion of metal surfaces wherever steam condensate forms. By locating the reservoir source for the hydrogen chloride, it may be possible to prevent its entering the wells or to control its release from the reservoir.

Laboratory Research

In laboratory research, LBL scientists are investigating some fundamental reservoir characteristics and processes. Research has found that complex, coupled physical and chemical processes control the short- and long-term response of geothermal wells and reservoirs to production. For example, well productivities and injectivities are largely controlled by the permeability of the reservoir, and this permeability tends to vary with changes in the proportion of water and steam present (relative permeability effects) and with the precipitation or dissolution of minerals in the fractures and pore spaces (chemical effects). The high flow rates necessary for commercial production of geothermal energy depend on high permeabilities in the reservoir rocks, and any changes which decrease permeability can adversely effect production.

Laboratory experiments at LBL, under controlled conditions, allow researchers to study the flow of single- and multi-phase fluids through natural or man-made fractures. The purpose of these studies is to determine the interaction between geometric properties (aperture and roughness) and hydraulic properties (absolute and relative permeability) of fractures (Fig. 2). The results from these experiments will be combined with other investigations to identify and quantify the physical and chemical processes controlling the mass and heat transport in fractures. This information will expand our understanding of actual geothermal fields.

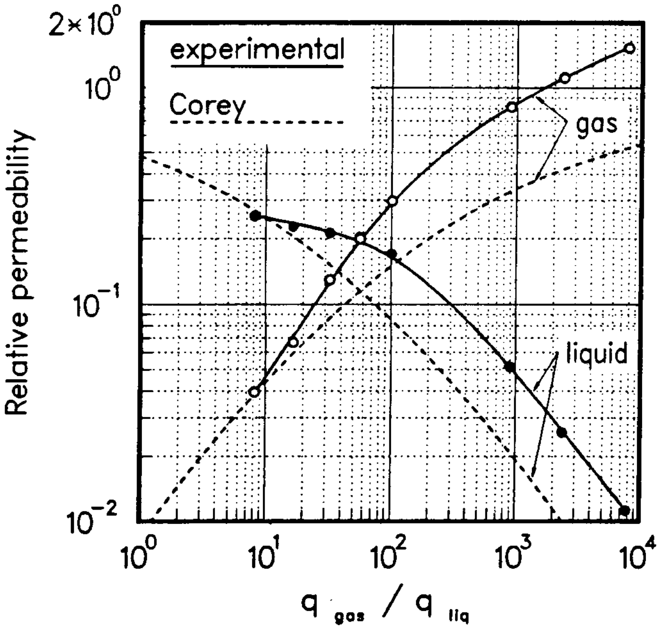

Figure 2. Relative permeabilities for rough-walled fractures measured with the LBL two-phase flow visualization apparatus. The experimental relative permeabilities are plotted against the ratio of gas and liquid flow rates. For comparison, Corey-type curves, typical of porous media, are also shown (from Persoff *et al.*, 1991).

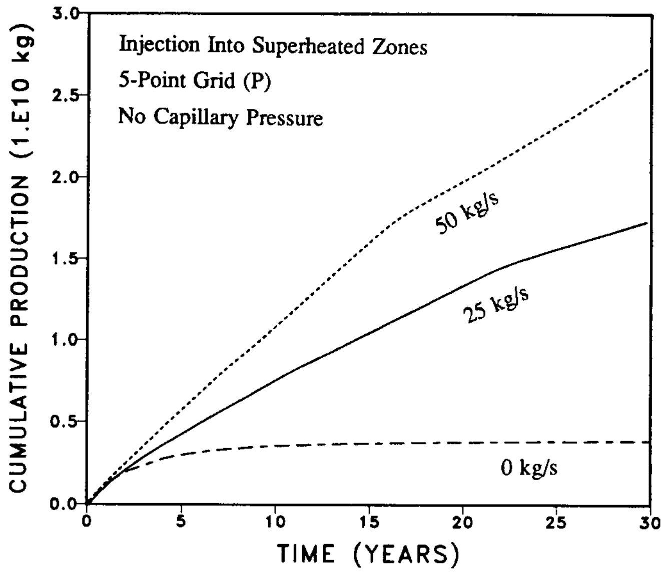

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Figure 3. Modeling results showing enhanced cumulative steam production in response to water injection into superheated vapor-dominated zones; the assumed injection rates are indicated on the curves (after Lai and Bodvarsson, 1991).

Theoretical and numerical studies have been focussed toward the fundamental understanding of geothermal reservoir processes, especially those occurring in vapor-dominated systems. For example, computer calculations have shown that injection into superheated zones yields much greater recovery of the injected fluid (Fig. 3) than injection into two-phase vapor-dominated regions. The studies also showed the importance of grid refinement and orientation effects on these calculations. Possible means of overcoming them are being evaluated. The analysis of thermodynamic and transport aspects of vapor pressure lowering due to capillary and phase adsorption effects have been initiated with the purpose of evaluating their significance on production and injection operations in vapor-dominated reservoirs. Very preliminary results so far indicate that depletion behavior is not strongly affected by pressure lowering effects.

Upgrade of Reservoir Engineering Codes

Since the mid-1970s, LBL has been developing computer programs used in the simulation of the transport of heat, mass and chemical species in porous and fractured geothermal systems. Codes for modeling transport in wellbores and for interpreting geothermal well test data have also been produced. Among these programs are CCC, SHAFT79, TOUGH, ANALYZE, WELBORE, all of which are available to industry through DOE's National Energy Software Center.

Because of a better understanding of the behavior of geothermal reservoirs and wells, as well as the availability of new and faster numerical algorithms to solve mathematical equations, LBL continues to develop new geothermal reservoir engineering computer programs and to upgrade existing ones. A similar effort in geophysical codes is being carried out by other LBL scientists, but is being funded by other DOE programs.

Recently LBL's multi-feedzone geothermal wellbore model was expanded to include CO_2-water mixtures. Also, a major subset of MULKOM modules have been prepared for release under the name TOUGH2 and an expert system for well test analysis has been modified to interpret data from geothermal wells.

Field Case Studies

A significant amount of information on the characteristics and operational history of U.S. and foreign geothermal fields is becoming available in the open technical literature. However, there is a wealth of data that can only be acquired through joint projects with the organizations operating the fields. This has led to (formal and informal) agreements between these organizations and DOE (or the groups funded by GD's Reservoir Technology Program) to jointly analyze existing data sets and to carry out field activities to obtain a new understanding of reservoir processes and behavior.

As part of this activity LBL continues its joint projects with U.S. and foreign organizations (such as CFE of Mexico) to collect and analyze exploration and developmental data from fields under evaluation or production. The goals of this work are: (1) to document the experiences learned by the field developers and operators during the different phases of a geothermal project, (2) to obtain actual field data that can be used in fundamental studies of geothermal systems and (3) to evaluate existing, and design new exploration and reservoir management methodologies for geothermal areas with given physical and geochemical characteristics (see Table 1).

For example, at Long Valley, CA, LBL operated and maintained a high-resolution seismic borehole array and acquired microearthquake data which was used to image the resurgent dome area. The P- and S-velocity structure of the caldera was investigated to determine the presence of hydrothermal activity and/or shallow magma bodies. The analysis of the behavior of the Cerro Prieto, Mexico, field continues, and production and well information is regularly updated and studied (Fig. 4). A two- and three-dimensional gravity study of the Coso, CA, geothermal area was completed. It revealed the presence of a large, deep low-density region underlying the area.

Technology Transfer Activities

The methodologies and instrumentation being developed by LBL with GD funding are made available to industry by way of collaborative efforts, workshops, publications and by distribution through DOE's National Energy Software Center.

Last September, a workshop on the TOUGH/MULKOM program, attended by more that 60 scientists from geothermal and other technical areas, was held at LBL. The assistance to the Geothermal Resources Council in planning courses devoted to technology transfer to industry continues. Several lectures during the October 1990 workshop on "Assessment of geothermal reservoirs and estimation of reserves" were presented by LBL scientists. Starting in April 1, 1991, the Secretariat of the International Geothermal Association (IGA) will be located at LBL. This will enhance the interaction between DOE-funded researchers and the IGA and its visitors.

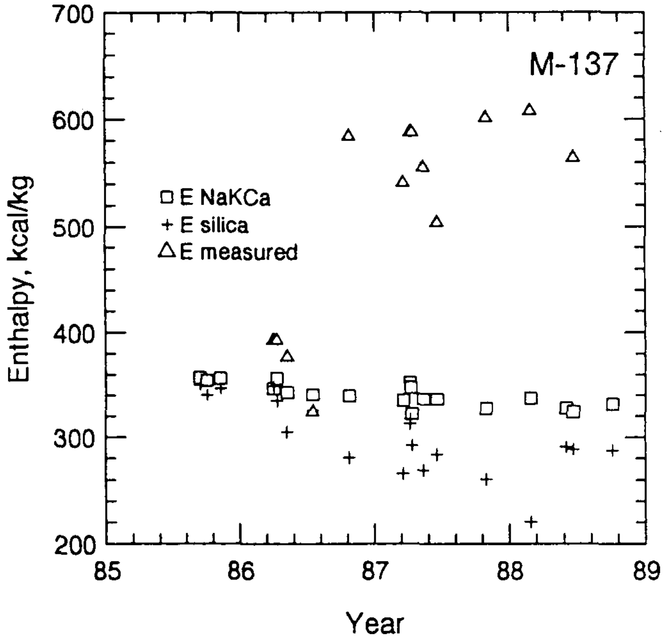

Figure 4. Enthalpy history of a well in the northeastern part of the Cerro Prieto field showing increasing reservoir boiling. E NaKCa is the enthalpy of liquid calculated from the Na-K-Ca geothermometer temperature; E silica is the enthalpy of liquid calculated from the quartz saturation geothermometer temperature; E measured is the measured wellhead total fluid enthalpy (from Truesdell and Lippmann, 1990).

A strong emphasis is placed on the publication of results obtained from this program. During 1990 and 1991, 28 papers and reports have been completed, so far. Twelve of them have been submitted to or published in referred journals (see List of Publications below).

Acknowledgements

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HYDROTHERMAL OPPORTUNITIES AND CHALLENGES IN THE BASIN AND RANGE

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ABSTRACT

A review of resource plans for the next decade of several western utilities indicates a growing power deficit occurring over the 1991-2000 time period. Utility preference over the past decade has been to purchase electricity rather than build new facilities to supply incremental power. This trend is expected to continue and result in a growing market for wholesale electric power. Thus, the question arises, where is the new power going to come from?

Geothermal development in the Basin and Range is a viable alternative for a portion of the new power. The existing fields in operation, short development lead times, ability to add incremental power generation, and the favorable environmental aspects all bode well for the industry. The Basin and Range province has a large inventory of both developed and undeveloped prospects. Currently, there are 434 MW_e (gross) of installed generating capacity, which has been added at an average rate 67 MW_e per year. Additional areas can be considered as maturing exploration prospects.

An improved exploration and development approach would rely on a multi-disciplinary team of geologists, geochemists, geophysicists, and reservoir engineers. An exploration model would be developed by the team and continually reevaluated as exploration and development progressed. The role of the reservoir engineer would be the ongoing incorporation of geologic and engineering data into a reservoir model, providing a reality check on the exploration team. At each stage, the model is available to management for the latest estimates of reservoir deliverability, project economics, a reservoir management plan, and be used for well site selection. This approach could be used to provide investors and utilities with greater confidence in reservoir deliverability and longevity estimates.

The cooperative study of geothermal reservoirs by industry and the U.S. Department of Energy national laboratories can identify reservoir performance issues. Industry can identify those resource issues that directly impact profitability. The national laboratories can gain a "big picture" viewpoint by working with the industry and can assist with technology transfer.

INTRODUCTION

The power glut of the 1980's is rapidly giving way to a power shortfall for the 1990's. Population growth in 1988 for the sunbelt states of California and Nevada was 2.2% and 3.8%, respectively, and is estimated to account for 70% of the future demand increases (U.S. Department of the Interior, 1990). Other factors are also at work, such as the retirement of old power plants, increasingly restrictive air quality regulations, and the decreasing availability of hydropower. The recent salmon summit highlighted the issues needed to avoid the extinction of the native salmon runs in the Columbia River basin. Larger spring streamflows are required to flush the smolts to the ocean, leaving less water available for hydropower. These combined factors will require new sources of electricity. The estimated combined shortfall for Nevada Power Company, Sierra Pacific Power Company, Los Angles Department of Water and Power, and Pacific Gas & Electric may exceed 1500 MW_e by the year 2000 (U.S. Department of the Interior, 1990; Sierra Pacific Power Company,1991; Department of Water and Power of the City of Los Angeles, 1990; Pacific Gas & Electric, 1991). A yearly breakdown of the combined shortfall is shown in Figure 1.

Clearly, there is an opportunity for geothermal power to provide a portion of this needed energy.

OPPORTUNITIES

The utilities are increasingly risk adverse and would rather employ demand side management (DSM), purchase surplus power on the spot market, or enter into long term purchase agreements from independent power producers (IPP). The demand forecasting errors in the 1970's have discouraged the utilities from investing in additional capacity and have provided an incentive to purchase power from other sources. Diversified fuel choices reduce risks by including fuels whose future prices are not highly correlated with inflation (Sutherland, 1989).

The additional capacity required by the utilities thus presents an opportunity for the geothermal industry to supply a portion of this need. However, the question arises, where are the resources to supply the new power? Exploration in the Cascades has yet to discover and delineate a commercial reservoir. Furthermore, exploration drilling in this area has only been active in the last five years or so, with the exception of Newberry Crater. Clearly, there is a large resource base present, however commercial reserves have yet to be identified. The lack of a pilot or demonstration power plant in the Cascades province is cited as one of the reasons the Northwest Power Planning Council considers geothermal to be a high risk source of electricity for the northwest due to lack of proven reservoirs and local operating

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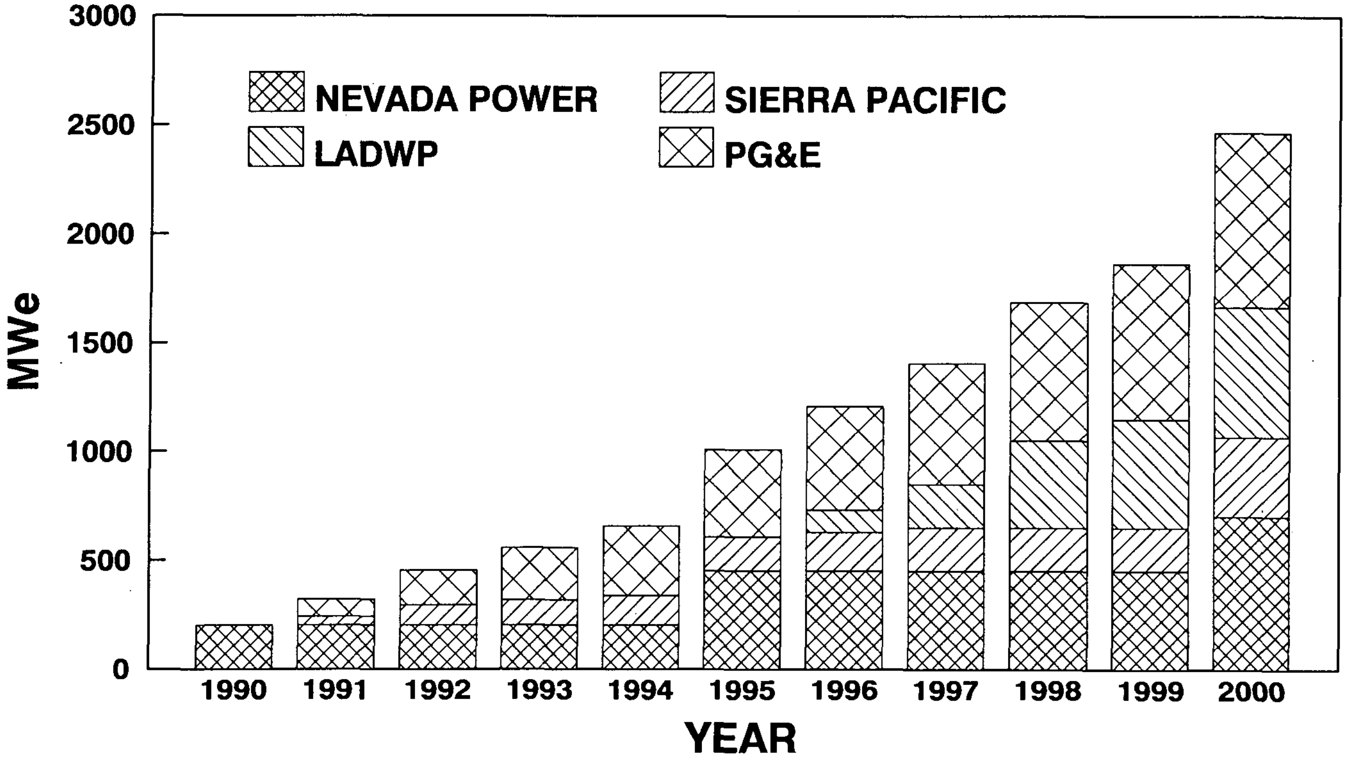
FIGURE 1 PROJECTED POWER SHORTFALL FOR FOUR UTILITIES



experience. Despite this drawback, the NPPC is proposing to reserve 400 MW$_e$ for geothermal resources for the 1990s, relying on 10 to 25 MW$_e$ pilot plants to demonstrate resource reliability (Northwest Power Planning Council,1989). This caution is in marked contrast to the situation in the Basin and Range.

Fifteen years of exploration in the Basin and Range province has lead to the commercial development and installation of over 434 MW$_e$ of capacity at twelve sites. The location of these field and prospects is shown in Figure 2. The installed capacity in the Basin and Range is tabulated below:

Table 1

FIELD	INSTALLED CAPACITY (GROSS)
Beowawe, NV	17 MW$_e$
Coso Hot Springs, CA	236
Cove Fort, UT	13.5
Desert Peak, NV	9
Dixie Valley, NV	62
Long Valley, CA	19
Roosevelt Hot Springs, UT	20
San Emidio Desert, NV	3
Soda Lake, NV	18.5
Stillwater, NV	17
Steamboat Springs, NV	18
Wabuska, NV	1
TOTAL	**434 MW$_e$**

Many of the operating fields have potential beyond the currently installed capacity. Several years of production at these levels of installed capacity provides the operating company with reservoir engineering information necessary to assess additional development potential. This in turn reduces resource risks and allows the next increments of capacity to be installed with short construction times. This advantage is illustrated by recent announcements of firm contracts signed by Sierra Pacific Power Company (SPPC,1991) or intent to add capacity at Coso by Los Angeles Department of Water and Power (Geothermal Resources Council, 1991). This information is presented in Table 2.

Table 2

FIELD	ANNOUNCED CAPACITY	COMPLETION DATE
Coso Hot Springs, CA	140 MW$_e$	mid-1994
San Emidio Desert, NV	5.4	11/1992
	21.6	11/1995
Steamboat Springs, NV	13.4	11/1992
	13.4	11/1993
Stillwater/Soda Lake, NV	14.3	11/1992
	14.3	11/1993
TOTAL	**222.4 MW$_e$**	

Past growth in installed capacity in the Basin and Range has occurred at an average rate of about 67 MW$_e$/year. With the above announced plans to add capacity, the historical trend provides an estimate of future growth. This is presented in Figure 3.

There are other areas that can be considered as maturing exploration prospects that were investigated under the DOE/Industry Coupled Program (DOE/ICP) or are recent discoveries. It should be noted that this list has changed very little in the last 10 years. Essentially we enter the 1990's with the same resource inventory with which we entered the 1980's. These areas are:

The **Alvord Desert** area has a recent confirmed discovery with a 460 m small diameter well which was flow tested at 18.5 kg/sec for 22 hours. A two-phase wellhead temperature of 152°C was measured.

Baltazor Hot Springs has had geophysical and geochemical surveys and exploration drilling performed. A deep test hole measured a maximum temperature of 119°C at 1109 m.

At **Coloda**, eighteen shallow temperature gradient wells were drilled under the DOE/ICP, with a maximum temperature of 113°C measured at a depth of 76 m. A 2438 m well recorded a maximum temperature of 149° C.

Humboldt House, with the Campbell E-1 capable of producing 126 kg/sec of 183°C fluid. This well has a shut-in wellhead pressure of 10 bars, with fluid present at the wellhead. This prospect also has at 260°C the highest indicated subsurface temperature from geochemistry in Nevada. The Campbell E-2 was drilled to 2456 m under the DOE/ICP and recorded a maximum temperature of 193°C.

McCoy has had geophysical, geochemical, and drilling exploration performed, in part under the DOE/ICP. Temperatures of 102°C have been measured at 500 m. Geothermometers indicate a maximum temperature of 120°C.

Raft River is being revisited and is currently under evaluation for a small binary plant. This reservoir has a maximum measured temperature of 146°C. Power plant technology has advanced sufficiently in the past decade to allow use of the lower enthalpy fluids. The DOE had an active drilling and evaluation program in the late 1970s and early 1980s, focusing on reservoir analysis and demonstration binary plant technology.

The **Tuscarora** area has an area with high heat flow (450 mW/m_2), measured temperatures of 147°C (geothermometers indicate a maximum of 200°C), and siliceous and calcareous sinter along a 1.4 km section of Hot Creek. Several exploration wells have been drilled, including one with DOE funding from the Industry Coupled Program.

The past cooperation of the DOE/Industry Coupled Program in identifying, testing, and making the data publicly available has assisted the development of geothermal resources in the Basin and Range. This assistance has given the industry and utilities greater confidence in using this resource. This is evidenced by the success and increasing acceptance of geothermal energy as a viable alternative to fossil fuels.

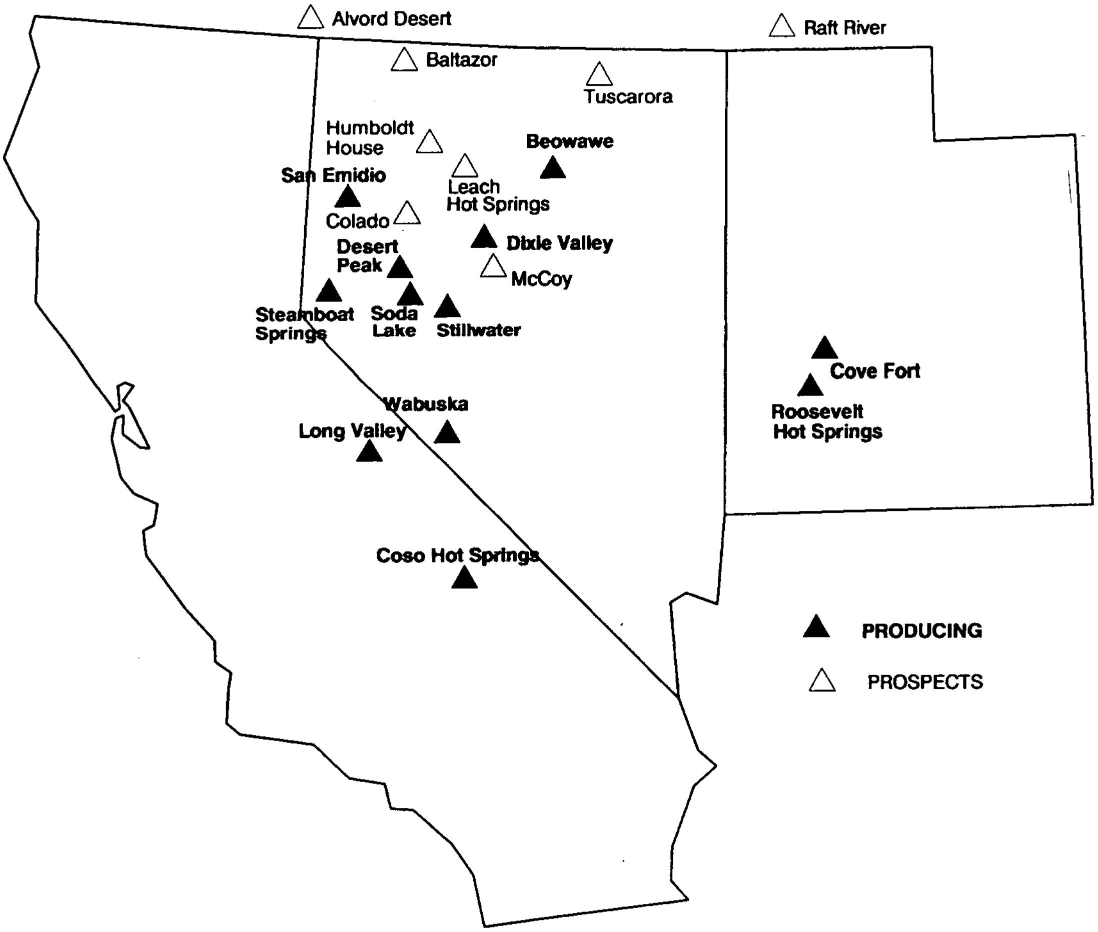
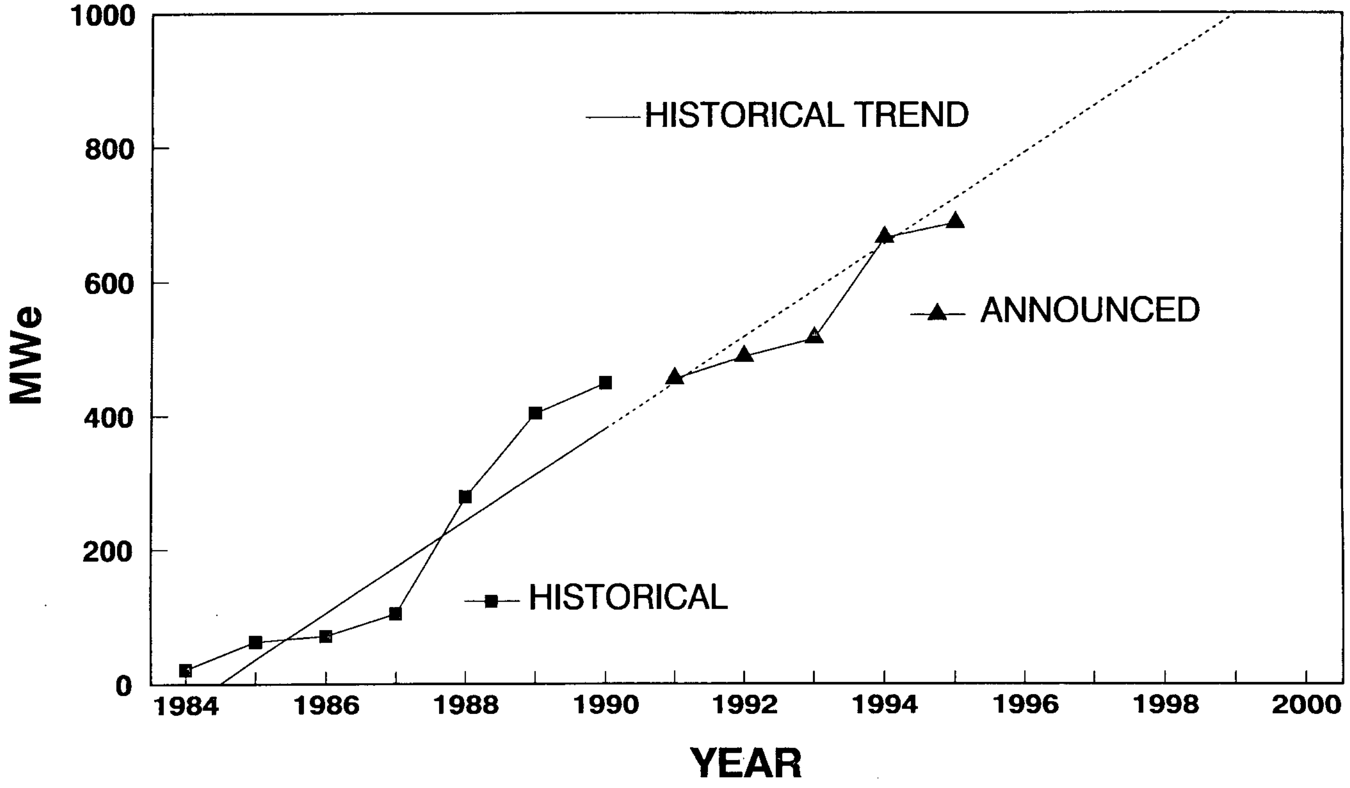


FIGURE 2 GEOTHERMAL FIELDS IN THE BASIN & RANGE

FIGURE 3 BASIN & RANGE INSTALLED CAPACITY



CHALLENGES

A review of past exploration, testing, evaluation, development, and reservoir management is helpful to identify topics for further research. Exploration practice has been as simple as to drill next to known hot springs. This practice is analogous to oil industry practice of drilling next to oil seeps over a hundred years ago. Ward et al. (1981) discussed an exploration strategy for high-temperature hydrothermal systems in the basin and range province. They proposed the formulation of exploration models and the constant updating of these models as the exploration proceeded. An operating sequence was suggested which consisted of 25 steps. Steps 1 through 24 of the evaluation phase are performed by geologists, geochemists, and geophysicists, while the last step required input from reservoir engineering for a reservoir model study.

This approach ignores the contribution a reservoir engineer can make in the exploration phase and reflects a strong geologic bias. An improved approach to exploration and reservoir testing would rely on a multi-disciplinary team of geologists, geochemists, geophysicists and reservoir engineers. An exploration model would be developed by the team and be continually reevaluated as the exploration progressed. The role of the reservoir engineer would be the ongoing incorporation of geologic and engineering data into a reservoir model. This model could be used to test various exploration ideas and distinguish between what is possible, probable, or unlikely. Thus, the role of the reservoir engineer at each stage is to provide a reality check on the geologic team. As the project matures the reservoir model would be continually updated with the latest drilling, geologic and well test information. At each stage, the model is available to management to provide the latest estimates of ultimate reservoir deliverability, project economics, an outline of a reservoir management plan, and be used to select well locations.

The last step in this process could include the installation of a small pilot plant to provide crucial reservoir performance data. This data would then be evaluated with the model to verify reservoir predictions and provide firm estimates of development potential. This process would speed the evaluation and development times and provide a real cost benefit to the industry. As shown above in Table 2, fields that initially had small pilot plants are now securing contracts for additional capacity.

Once a resource is identified, large diameter production wells are necessary to test the reservoir deliverability. Typically, high sustained flow rates for a short period of time (hours to days) are sufficient to confirm a productivity. A more detailed program might entail a longer term flow test with the well instrumented for pressure transient analysis and the use of available observation wells to measure reservoir response over a large portion of the reservoir.

Development well siting is based on geologic information or may be chosen rather haphazardly or as a matter of convenience. Typically, at this stage there is little input from the reservoir engineer or concern for long term reservoir management. Production and injection wells may be chosen on the basis of well productivity, with injection wells selected on the basis of poorer production characteristics . These wells may be drilled on the same fault system, leading to potential problems once full production begins. Rapid tracer breakthrough has been documented at Dixie Valley and noted at Beowawe and Coso. Production well testing is typically conducted one at a time, thus minimizing potential interference effects. Thus, the sum of individual well deliverabilities may be much greater than total reservoir deliverability with all wells on production simultaneously. This can and has lead to the installation of more generating capacity than the reservoir can sustain. The presence of an updated reservoir model during development would reduce these risks.

Obviously, this type of exploration and development approach requires a team of professionals that understand and appreciates their individual and collective roles in the process, and requires reservoir simulation tools that are both user friendly and powerful. It is this last point that I want to stress. A simulation code that is labor intensive for preparation of each input deck, must be run on a large computer, and lacks a graphical pre- and post- processor interface greatly hinders engineering productivity. This is probably the reason that in 1981 the role of the reservoir engineer was left to the last step in the exploration process. What is needed are simulation tools that can keep up with the changing information during rapid development. Witness the rapid development of 240 MW_e in three years at Coso Hot Springs. Only now an operational reservoir model is being developed. It is highly likely an approach an outlined above could have easily provided cost savings, provided a comprehensive reservoir management plan, and avoided some of the problems that have developed.

The role of the national laboratories in this process is to cooperatively study with industry those issues that impact resource performance. One important issue is the native state of the geothermal reservoir? This issue is more important than first appears. A hydrothermal system is dynamic flow process and adjusts to changes in boundary conditions such as recharge, heat flow, and discharge. Exploitation response is controlled by these factors and an inadequate understanding and quantification of the native state can result in a less than optimum reservoir management plan. The process outlined above would implicitly involve native state studies.

One of the largest uncertainties still present is how to reinject fluid to provide pressure support without premature thermal breakthrough. While generic parametric simulation studies are useful, the real world is always more complex and surprising than a laboratory or research setting. The continual evaluation and inclusion of real field data in a reservoir model can provide insight to the reservoir processes involved.

The researchers in the national laboratories have access to the big picture by careful observation of what the various operators are doing and how their fields are responding to exploitation. Open communications and cooperative research with the industry can identify common problems and solutions. This obviously requires greater openness by industry and more sensitivity by the researcher to industry's concerns. The experience gained and the technology used can be transferred to the various participants.

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SUPPORTING RESERVOIR TECHNOLOGY RESEARCH

J. L. Renner
Idaho National Engineering Laboratory

In addition to the Reservoir Technology Research described in other papers of this volume (Faulder; Horne; Lippmann; Moore, Adams and Wannamaker; Reed), researchers at Lawrence Livermore (LLNL) and Oak Ridge (ORNL) National Laboratories, University of Maryland and the University of California, San Diego conduct research in support of the objectives of the program. The geothermal program, and in particular the reservoir technology program, also conduct cooperative geothermal research with the geothermal industry through the Geothermal Technology Organization with the assistance of the Idaho National Engineering Laboratory (INEL). Work at Lawrence Livermore is centered on analysis of the seismicity associated with production and injection at geothermal systems and the effects of geothermal systems on seismic signal from beyond the fields. LLNL is continuing studies of seismic attenuation related to the presence of steam at The Geysers. ORNL investigators conduct research to obtain thermodynamic and kinetic data needed as input into geochemical models of geothermal systems. The current program at ORNL is placing emphasis on the distribution of HCl in steam at The Geysers. Philip Candela at the University of Maryland is studying the partitioning of elements between melt, aqueous liquid phase and vapor to predict transfer of elements to hydrothermal systems overlying magmatic systems. John Goodkind of the University of California, San Diego is developing highly sensitive and accurate gravimeters to determine fluid movement within geothermal systems.

Lawrence Livermore National Laboratory

Geophysicists at Lawrence Livermore National Laboratory are testing use of attenuation of seismic signals as a means of determining the presence of steam in a geothermal reservoir. LLNL and Lawrence Berkeley Laboratory are planning a joint deployment of seismic instruments in the southeast Geysers to test the method. The scientists are also initiating a study of the mechanism responsible for the velocity attenuation.

In geothermal fields studied to date, low attenuation and low velocity are associated in seismic signals passing through portions of the reservoir. The usual geologic relationship is that high attenuation is paired with low velocity. LLNL is initiating an effort to understand the mechanisms that cause the unusual observations in geothermal systems.

(Contact: Paul Kasameyer, 415/422-6487)

Oak Ridge National Laboratory

Researchers at ORNL are performing experiments to obtain needed thermodynamic and kinetic data for input into geochemical models which predict the phase behavior and corrosion characteristics of geothermal fluids. 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 major concerns of this program.

Previous work on the speciation of aluminum and the solubility of hydroxide/oxide phases to 100 ^{o} C aqueous solution is being readied for publication. Two papers, "The Solubility of Gibbsite in the System Na-K-Cl-OH-$Al(OH)_4$ from 0 to 100 ^{o} C" and "The Solubility of Gibbsite in Acidic Sodium Chloride Solutions from 30 to 70^{o} C" have been prepared for submission to Geochimica et Cosmochimica Acta. Studies of aluminum speciation will be conducted at higher temperatures during this year.

The principal effort of the ORNL researchers addresses physical chemical measurements relative to understanding the origin and transport of chloride in vapor dominated geothermal systems such as The Geysers and Larderello, Italy. 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. 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.

Measurements of the distribution of HCl between liquid and vapor phases have been completed at 50 ^{o} C intervals from 50 to 350^{o} C. All results have been expressed in terms of the equilibrium constant K for the reaction HCl (liquid phase) = HCl (vapor phase), using published values for liquid-phase activity coefficients for HCl. 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.

It is anticipated that a draft manuscript reporting experimental details and results of this study will be submitted for publication in early 1991. Further modeling of these results will focus on the correct separation of the observed volatilities into the component reactions; i.e., the formation of liquid-phase ion pairs, followed by partitioning of neutral HCl molecules to the vapor phase.

(Contact: Robert Mesmer, 615/574-4958)

University of Maryland

Philip Candela and his students at the University of Maryland are performing experimental and theoretical studies of the production of HCl and some metal chlorides in magmatic/hydrothermal systems. The experimental studies are performed by loading platinum capsules with Bishop Tuff and chloride solutions. The starting solutions range from 0.68 to 3.36 molal total chloride with the nominal ratio of NaCl to HCl to KCl being 1:1:1. The samples are loaded into a two-zone furnace that produces very small temperature gradients across the sample. The experimental charge reaches equilibrium after several days at a temperature of 800° C and pressures of 1 and 0.48 kbars. At the end of an experimental run the sample is rapidly quenched preserving the equilibrium compositions at the experimental temperature and pressure.

Candela is modelling the evolution of the aqueous phase in conjunction with the experimental study. The model enables calculation of HCl and other elements in successive separations of supercritical magmatic aqueous phase during the polybaric rise of a water saturated magma and during the isobaric devolatilization of magma during cooling. Results of the studies may help understand the generation of HCl in geothermal systems.

(Contact: Philip Candela, 301/405-2783)

University of California, San Diego

John Goodkind at the University of California, San Diego is developing a high-precision cryogenic gravimeter to monitor subsurface fluid movement through changes in mass distribution. These instruments have been used to monitor rainfall and subsequent changes in gravity signal due to groundwater movement.

The geothermal research project has deployed one gravimeter since December 1989 and the instrument has operated successfully during that period. A second instrument is scheduled to be deployed soon to the same site in order to determine the relative response functions of the two instruments and establish a quantitative determination of the drift function. After this period the second instrument will be moved to a nearby location and long-term records will be obtained with the pair of instruments. The United States Geological Survey is assisting in this through the independent and accurate monitoring of mass changes intrusion. If this new gravimeter proves to be reliable and accurate in its test, it will be deployed in a developing geothermal field to examine the usefulness of monitoring mass changes as a tool for reservoir management.

(Contact: John Goodkind, 619/534-2716)

Cooperative Research With Industry

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

- conducting cooperative research under the "National Cooperative Research Act of 1984,
- sharing research costs with the DOE,
- facilitating the industrial development of basic research results, and
- 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):

- funds research in reservoir performance and energy conversion technology,
- seeks research with high probability of short term benefits, and
- 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 are currently cooperating in the interpretation of tracer return data from an industry tracer-injection test in the southeast Geysers.

Industry suggestions for GTO research or requests for additional information concerning GTO can be made to Mohinder Gulati, Chairman of the GTO or to Joel Renner, DOE Liaison to GTO.

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PROGRESS IN HYDROTHERMAL RESERVOIR RESEARCH AT UURI

by

Joseph N. Moore, Michael C. Adams and Philip E. Wannamaker

ABSTRACT

During the past year, research at UURI has focused on techniques for evaluating the physical and chemical conditions within geothermal systems and in monitoring the effects of production. Because of the production declines that have occurred at The Geysers, California, the greatest emphasis has been placed on solving problems identified by the operators of this field. These investigations have included work on the chemical and thermal evolution of the steam reservoir and on the development of vapor-phase tracers.

Petrographic and fluid inclusion studies of core and cuttings from The Geysers are being used to track the evolution of the geothermal system that produced the present steam reservoir. The data show that near the felsite, both temperatures and salinities decreased over time as meteoric fluids were superimposed on older magmatically derived brines. The steam reservoir may have formed recently when temperatures were near 240°C.

The tracer studies have been directed at an evaluation of the halogenated alkanes (HFCs), which appear to be excellent candidates for tracing the movement of steam. We have compiled the available thermodynamic data on these compounds and have predicted their stabilities at geothermal temperatures. The stabilities of these compounds are currently being determined experimentally in a laboratory specifically designed for this purpose. A field test of two of these tracers was initiated at the end of January, 1991 and is currently in progress.

A magnetotelluric study of the Long Valley caldera, California was completed. The project resolved several important caldera structures and detected a mid-crustal low resistivity zone that correlates with regions of low velocities and low densities defined by teleseismic and gravity data. Ongoing studies include a profile across the eastern Great Basin and a shallow controlled source audiomagnetotelluric survey in the vicinity of drill hole CSDP VC-2B in the Valles Caldera, New Mexico.

INTRODUCTION

During 1990, the emphasis of UURI's investigations shifted from liquid-dominated geothermal systems to The Geysers. Programs were developed in cooperation with Calpine Corp., Coldwater Creek Operator Corp., NCPA, and Unocal Geothermal Division to evaluate the chemical and thermal characteristics of the steam reservoir and to develop and test new tracers for monitoring the effects of injection-production strategies.

Work on liquid-dominated systems has nevertheless continued. Hydrogeochemical and geologic studies were conducted at Coso, California (Moore et al., 1990), Zunil and Tecuamburro, Guatemala, (Moore et al., in press; Musgrave and Moore, in press), Los Azufres, Mexico, Steamboat Hot Springs, Nevada, and at Valles, New Mexico. Good progress has also been made on the application of geophysical techniques to geothermal problems. Self-potential investigations were conducted at Rincon, Radium Springs, and Las Cruces-East Mesa, New Mexico (Ross and Witcher, unpub. data) and in the Escalante Desert, Utah (Ross and Blackett unpub. data). Magnetotelluric investigations have been conducted at Long Valley, California (Wannamaker, 1991), the Valles caldera, New Mexico, and in parts of Utah and Nevada (Johnston and Wannamaker, 1991).

This paper is divided into three parts. In the first two sections we discuss the results of our work at The Geysers. The third section describes the magnetotelluric research being conducted at UURI.

RESEARCH AT THE GEYSERS

PETROLOGIC AND FLUID INCLUSION INVESTIGATIONS

Although the general framework of The Geysers geothermal system was established more than 20 years ago in a classic paper by White et al., (1971), a number of important questions regarding the evolution of this system remain to be answered. In 1988, UURI initiated studies to 1) better characterize the thermal and chemical evolution of this system, 2) constrain various hypotheses on the origin of the HCl-bearing steam, and 3) develop a structural model of the field. The initial studies were conducted on cuttings from depths above the present steam reservoir in the Northwest Geysers (Moore et al., 1989). Subsequent fluid inclusion and petrographic studies have included samples from both the normal and high-temperature reservoirs. These samples were provided by Calpine Corp., Coldwater Creek Operator Corp., and Unocal Geothermal Division.

Several periods of veining can be recognized in the rocks. The oldest assemblage is characterized by discontinuous veins of quartz and calcite. This mineral assemblage is typical of Franciscan veins that occur outside The Geysers (Lambert, 1976). The remaining vein assemblages display consistent spatial and thermal relationships to the felsite intrusion beneath The Geysers. These veins, in order of decreasing temperature, are characterized by tourmaline + biotite + actinolite + potassium feldspar + quartz, epidote + actinolite + ferroaxinite + quartz, and epidote + potassium feldspar + quartz ± calcite.

Fluid inclusions suitable for heating and freezing measurements have been found in several of the vein minerals including quartz, epidote, actinolite, ferroaxinite, and calcite. The inclusions can be grouped into several types on the basis of their phase relationships at room temperature. These types include liquid-rich inclusions with 2, 3, or 4 phases and vapor-rich inclusions. The most common liquid-rich inclusions consist of liquid and vapor at room temperature. These inclusions have salinities ranging up to approximately 20 equivalent weight percent NaCl, although the majority are in the range of 0 to 8 weight percent NaCl. Liquid-rich fluid inclusions containing one or more solid phases are present mainly near or within the felsite. These inclusions generally contain halite or halite + sylvite. The presence of halite is significant because it indicates salinities exceeding 26 weight percent NaCl. In addition, inclusions containing a variety of accidentally trapped solids such as iron oxides and micas have been observed.

Vapor-rich inclusions are common in metamorphosed quartz veins of Franciscan age. These inclusions may have formed from liquid-rich inclusions by necking or leaking.

Fluid inclusion data from samples of the reservoir rocks, plotted with respect to the approximate top of the felsite (Thompson, 1989), are shown in Figures 1 and 2. The data show several interesting features. First, they show a general trend of increasing temperature with decreasing distance to the felsite (Fig. 1). These temperatures however, show only a weak correlation with the actual elevation of the sample points. In addition, there are no systematic differences between conditions displayed by rocks from the high-temperature and normal reservoirs. In a similar manner, the maximum salinities of the fluid inclusions also generally increase as the felsite is approached (Fig. 2). Together, these relationships suggest that the high salinity, high temperature inclusions formed in response to intrusion of the felsite. Thus, they record an early stage in the evolution of The Geysers field. Furthermore, most samples have similar minimum fluid inclusion temperatures and salinities. The correspondence between the temperatures of the liquid-rich inclusions and the measured temperature of 240°C suggest that temperatures have never been much lower than they are today and that development of the steam reservoir may be a relatively recent feature of the system. The data however, indicate no simple pattern of heating and cooling. While the general trend is one of cooling with time, some of the fluid inclusions from samples of the high-temperature reservoir record temperatures as low as 240°C. Thus, these rocks appear to have undergone multiple periods of heating and cooling.

Finally, the relationships between the salinities and temperatures of the fluid inclusions cannot be explained simply in terms of the boiling down of a brine. In general, there is a correlation between temperature and salinity, with the lower temperature inclusions having lower salinities. This implies that the hydrothermal system developed around the felsite may have first collapsed downward before development of the steam reservoir.

VAPOR-PHASE TRACER DEVELOPMENT

As a result of the pressure declines in the production wells at The Geysers, our emphasis in the tracer development program has shifted from liquid- to vapor-phase tracers. Last year we initiated investigations of a class of compounds, the halogenated alkanes (HCFCs), that appear to be suitable as tracers in vapor-phase geothermal systems. A comprehensive literature search was performed to evaluate what is known about the stabilities and solubilities of these potential tracers. Because all of the data tabulated are for low-temperature conditions, they were extrapolated to geothermal temperatures (Adams et al., 1991).

Although there is a broad base of thermodynamic data for the HCFCs, these data primarily relate to refrigerant conditions. Thus, the data base is restricted to the pressure-temperature-volume relationships and heat capacities of the anhydrous liquid or gas (Martin, 1959). However, the critical constants for a majority of the compounds are known, allowing the estimation of compressibility factors and fugacity coefficients. Because of the corrosion potential of water in a refrigeration system, some data also exist on the solubilities of the HCFs in water to temperatures of 100°C. The solubility data were extrapolated to higher temperatures by transforming the Henry's Law constants (Kh) to volatility ratios (VR), which represent the ratio of the molal concentration in the gas to that in the liquid. It has been shown empirically that log(VR) is an approximately linear function of temperature (Drummond, 1981). The compressibility factors required for the transformation of Kh to VR were calculated from the critical constants using the three-parameter corresponding states correlation of Lee and Kesler (1975).

The solubilities of HCFCs in water, extrapolated to geothermal conditions, are shown in Figure 3. The measured solubilities of hydrogen and carbon dioxide, which are common geothermal gases, are shown for reference. The solubility behavior of the HCFCs follow a consistent trend with composition. Those containing hydrogen (R-22, -23, and -31) are the most soluble. Compounds that contain only chlorine and fluorine (i.e., R-12 and -13) are intermediate in solubility, with the solubility being proportional to the number of chlorine atoms in the molecule. Gases that contain only fluorine (i.e., R-14, R-116, R-218, R-C318, and SF_6) are sparingly soluble, with the solubility decreasing as the molecular weight increases.

The stabilities of HCFCs have been tested under various conditions, some of which were similar to ethose found in geothermal environments. The test conditions ranged from repeated flow cycles through a high-temperature (up to 700°C) compartment (Snider, 1967; Callighan, 1969) to static experiments in sealed quartz vials containing oils, metals, metal oxides, water, or oxygen (Norton, 1957; Parmelee, 1965; Kvalnes and Parmelee, 1957). The experiments with oxygen and water are particularly pertinent because oxygen is absorbed from the atmosphere in the cooling tower and has the potential to degrade many organic compounds.

The stabilities of HCFCs also vary as a function of their compositions. In general, the stability of these compounds is directly proportional to fluorine saturation and inversely proportional to hydrogen saturation. For example, temperatures that will induce 1% decay per year in substituted methanes with one, two, and three fluorines are 298°, 498°, and 538°C, respectively. In contrast, a compound that contains two fluorines but also one hydrogen will decay 1% per year at 250°C. These decay rates are based on the experimental data of Norton (1957).

During 1990, a laboratory was set up at UURI to test and analyze these compounds. The laboratory consists of an hydrothermal autoclave designed for liquid-vapor equilibria studies and a gas chromatograph with flame ionization and electron-capture detectors for quantification of a broad range of concentrations. We have begun our testing program on the potential tracers in pure water. These experiments will be extended to include gas compositions and minerals similar to these found in the reservoir.

We have also continued our effort to develop more liquid-phase tracers. These efforts primarily consist of testing fluorescent groundwater tracers for their thermal stabilities. To this end, we have obtained a luminescence spectrometer, which is capable of screening out background fluorescence to a larger degree than a standard filter fluorometer. This will enable us to determine which wavelengths are appropriate for a geothermal tracer, and to only test fluorescent compounds that are sensitive in those ranges.

THE GEYSERS TRACER TEST

A tracer test using the halogenated alkanes R-12 and R-13 is currently underway in the Low Pressure Region of the Southeast Geysers. These tracers were chosen on the basis of their cost and their expected solubilities and stabilities. Two tracers were injected in order to check for unexpected results. The test was designed by UURI, performed by Thermochem, Inc. and UURI, and jointly

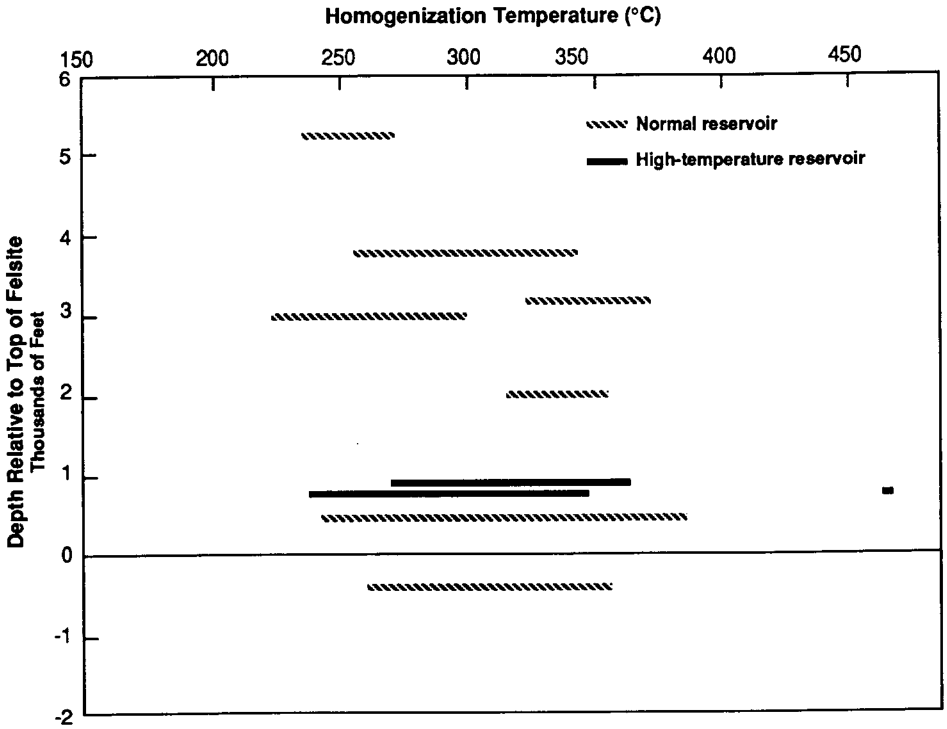

Fig. 1. Range of homogenization temperatures of fluid inclusions measured in samples of the reservoir rocks. The data are plotted with respect to the top of the felsite.

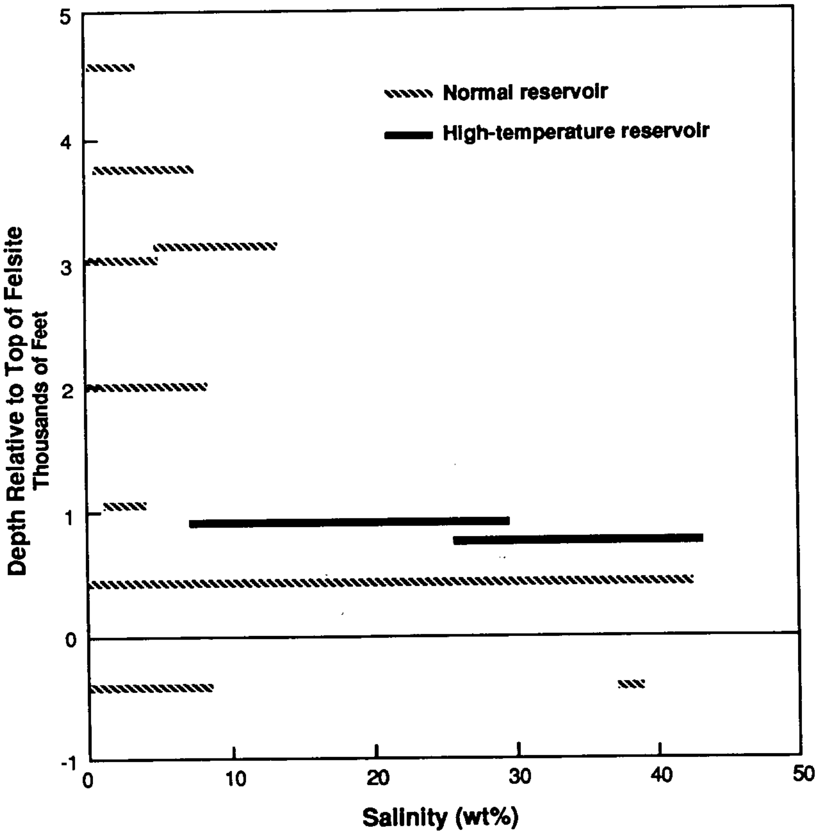

Fig. 2. Range of salinities of fluid inclusions shown in Fig. 1.

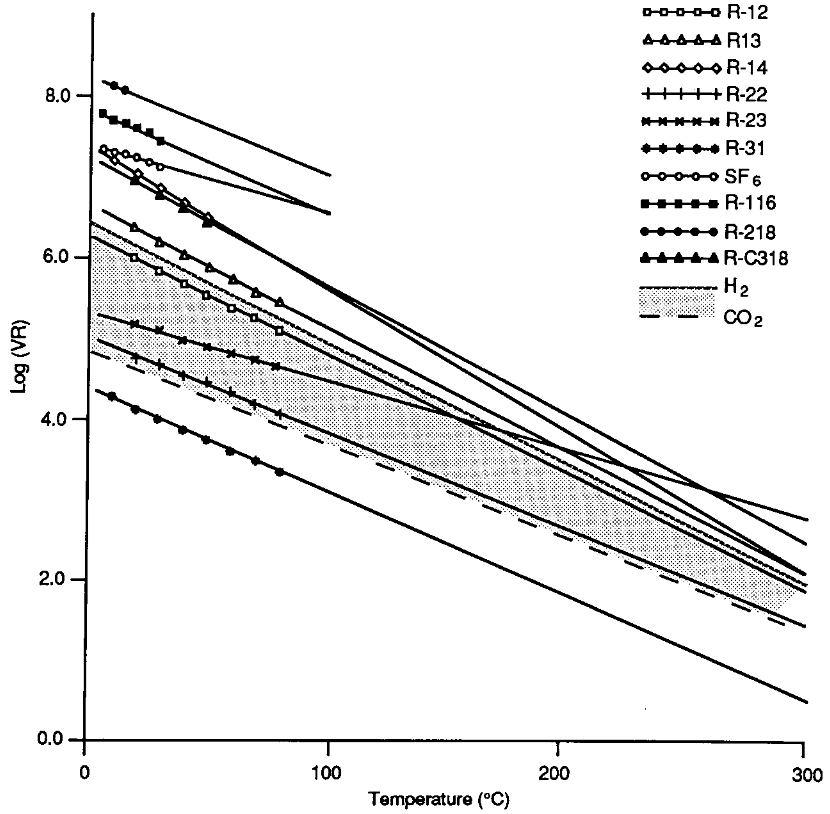

Fig. 3 Temperature variations of the volatility ratio (VR) of the HCFCs. VR is defined as the ratio of the molal concentrations in the steam and liquid phases. The shaded area represents the VR region of common geothermal gases (Drummond, 1981). The data sources for the HCFCs are listed in Adams et al., 1991. The symbols represent measured values, while the solid lines are extrapolations. The lines for H_2 and CO_2 lines represent measured values throughout the temperature range.

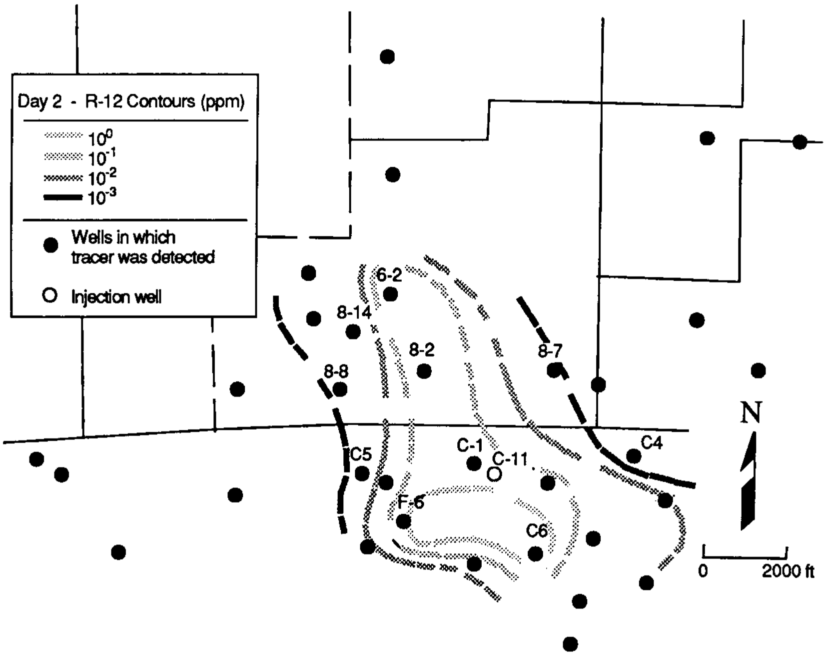

Fig. 4. Distribution of R-12 in the production wells on the second day after injection. The solid dots show the locations of all but two of the wells that have produced measurable quantities of R-12 since the test began. Contours are in parts per million in steam. Data from J. Beall (pers. communication, 1991).

funded by the Geothermal Technology Organization and the Geysers operator companies Calpine Corp., NCPA, and Unocal Geothermal Division.

The tracers were injected into well NCPA C-11, which lies in a region that has developed superheat and low reservoir pressures due to a lack of pressure support from injected fluid (Enedy, 1989). Injection into C-11 began in October, 1989, and has continued to the present, with the exception of a two month shutdown for casing repair. A 1991 study by Enedy et al. (1991) demonstrated that injection in this region has successfully increased the pressures and steam output in the production wells. In addition, comparison of stable isotope data from wells in the Low Pressure Area before and after injection began demonstrated that there were definite and strong fluid pathways between the injection and production wells in this region (Beall et al., 1989; Beall and Enedy, personal communication).

Approximately 300 kg of R-12 and 100 kg of R-13 were injected simultaneously into C-11 over a four hour period. Forty production wells are being monitored for tracer returns. Of these, 10 are being monitored under the GTO agreement. The remainder are being sampled by the operators themselves. To date, tracers has been detected in 36 of these wells. A contour map of the R-12 concentrations in steam from the production wells is shown in Figure 4 for the second day of monitoring.

R-13 was monitored in three wells. These return curves revealed some unexpected relationships between the two tracer returns. Because R-13 was injected at one third of the concentration of R-12, it was expected that they would arrive at the production wells in the same ratio. In fact, the ratio of R-12 to R-13 increased from 1/3 to more than 100 by day 20. In addition, the logarithm of the ratio was approximately linear with time. These observations are consistent with a fairly rapid pseudo-first-order decay of R-12. The decay constant computed for the data from the three wells is 0.3 ± 0.04 day^{-1}. The decay constant derived in this manner is intended only for investigating the hypothesis of decay. It should not be taken as final because of the many variables involved in the return curves. We will attempt to refine the decay rate in our laboratory experiments by reproducing the reservoir environment. By reproducing the magnitude of the field test results, we will be able to show which laboratory conditions are most similar to field conditions, and then test more stable tracers under these conditions. The laboratory experiments will be the focus of our research in the coming year.

MAGNETOTELLURIC (MT) RESEARCH AND DEVELOPMENT

Electrical resistivity provides a window on Earth structure and processes unlike that of any other geophysical technique (Wannamaker, 1990; 1991; Wannamaker and Hohmann, 1991). The potential of the MT methods in the exploration of deep geothermal resources has been well demonstrated by the results of a detailed MT transect of the Long Valley caldera (Fig. 5). Several important structural components were resolved in conjunction with other geoscientific

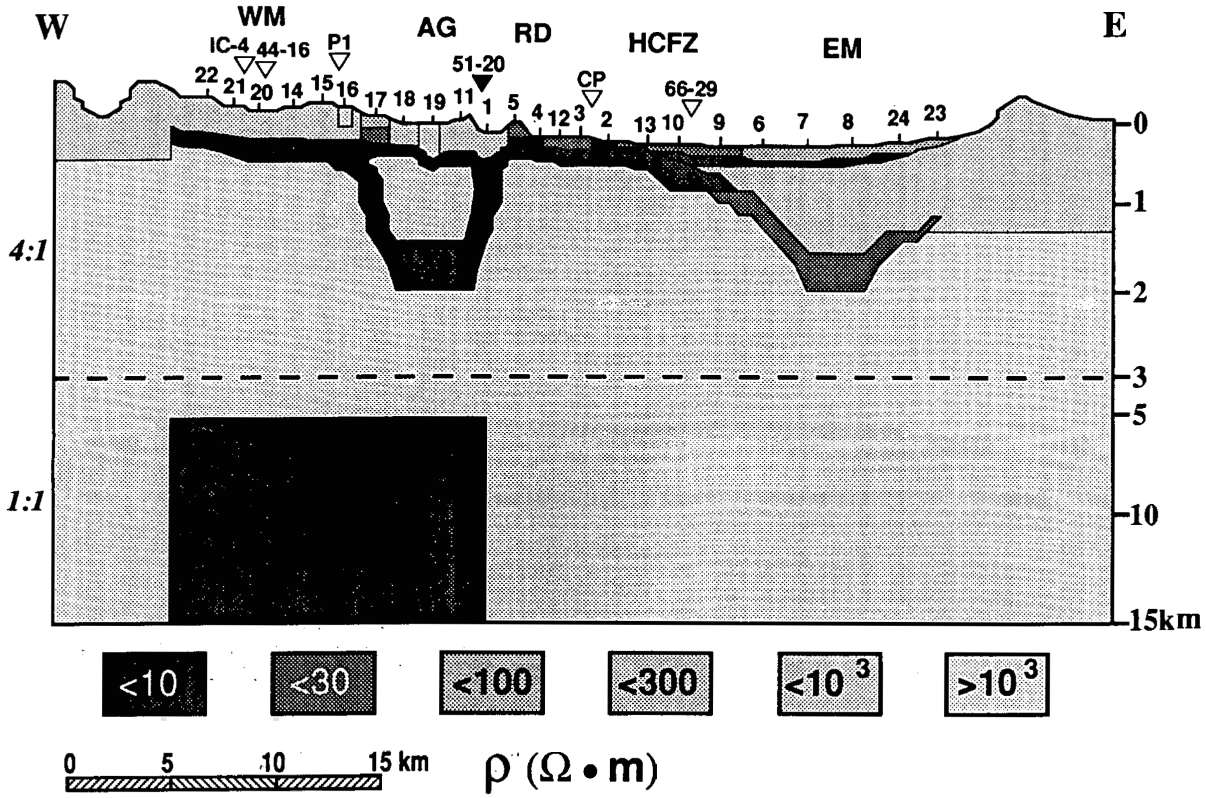

Fig. 5. Model resistivity cross section for the MT results at Long Valley obtained by trial-and-error fitting using a finite element forward algorithm and emphasizing the nominally TM mode data. Details for the finite element geometry have been preserved but the model resistivities have been grouped into ranges of one-half decade for display. Important geologic features include the west moat (WM), axial graben (AG), central resurgent dome (RD), Hilton Creek fault zone (HCFZ), and the east moat (EM). The projected locations of the drill holes are shown as triangles Note the change in vertical exaggeration from 4:1 to 1:1 at a depth of 3 km.

constraints. These include low-resistivity layers 0.5 to 1.5 km deep under the eastern half of the caldera, beneath the axial graben of the resurgent dome, and under the west caldera moat. Most of this layering appears to lie in post-caldera Early Rhyolite tuffs and the uppermost unwelded Bishop Tuff which, at least in the west moat, comprise the primary hydrothermal fluid aquifer. A low-resistivity layer has also been discovered at somewhat greater depths below the axial graben near the base of the Bishop Tuff. Low resistivities are modeled at a depth of about 5 km below the entire west moat and central graben. These may represent a zone of hydrothermal fluids released from magma crystallization, with potential magma contributions at greater depths. There is a striking correspondence between this region of low resistivity, and teleseismic delays and low density zones found in other studies. We received a great deal of cooperation from the Unocal Geothermal Division who contributed large sets of time-domain EM and MT data. The time-domain EM data were incorporated in our modeling for control on the shallowest levels of structure.

Development continued on our remote-reference MT instrumentation for geothermal and basic earth science research. In this system, five channels of EM time series (Ex,Ey,Hx,Hy,Hz) are observed at a base site and two channels of magnetic field time series (Rx,Ry) are observed at a reference site. The data are transmitted via digital FM telemetry to the recording truck and processed in real time. At the recording truck, an IBM PC with an 80386 processor and a multi-tasking control program prioritize individual jobs that are each running under MS-DOS. Time- series processing is based on cascade decimation, allowing real-time data quality assessment and a virtually finished MT sounding on-site. The time series are archived together with the MT spectra and impedance functions for further processing, if desired. To increase portability, we have recently purchased three Model BF-4 light-weight coils from EMI, Ltd., and are incorporating them into the base setup. The complex base software for real-time processing and archiving has been completed and verified using example time-series recorded with an independent apparatus. The principal task remaining is to complete software for synchronizing sensor data acquisition and assembling data packets for transmission to the truck. The majority of our MT field instrumentation development has been funded by the DOE. However, our accomplishments to date have resulted in recent support from the NSF. Under this award, we will be incorporating into the present system an E-field profiling capability that is back-packable. The University of Utah and UURI together comprise the only research entity in the U. S. receiving federal support for MT instrumentation.

We have also been conducting an ambitious transect of MT soundings in the eastern Great Basin and Colorado Platau of Nevada and Utah under DOE and NSF support. The most intriguing outcome of the analysis so far are low resistivity structures that may be related to Sevier age overthrust tectonics (Johnston and Wannamaker, 1991). These subhorizontal layer segments are about 2 and 4 km deep below the Wah Wah Mountains and the Mountain Home Range in Utah. They are tentatively suggested to represent Late Paleozoic or younger sedimentary rocks below the regional Wah Wah-Pavant thrust system. Important hydrocarbon source and reservoir rocks are contained in the younger interval. Thus, our model may warrant consideration for petroleum exploration. No anomalously low resistivities at lower crust and upper mantle depths were found in the region of Roosevelt Hot Springs in southwestern Utah.

MT research sponsored by the DOE/BES will provide additional information on the structure of geothermal systems. At the Valles caldera, New Mexico, the relatively shallow (<2 km) hydrothermal regime in the vicinity of CSDP corehole VC-2B is being investigated by an extensive controlled-source audiomagnetotelluric (CSAMT) survey. These are fully tensor data to provide control for lateral heterogeneity in structure. The purposes of the CSAMT survey include: establishing basement relief, mapping stratigraphy, estimating relative fluid content or alteration, inferring relative permeability, and delineating possible vapor regimes. Unocal Geothermal Division is providing existing natural-field MT data from the Valles caldera for comparison with the controlled source data we are generating.

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HYDROTHERMAL ENERGY CONVERSION TECHNOLOGY

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

PROGRESS IN HYDROTHERMAL ENERGY CONVERSION TECHNOLOGY

Ken Taylor
U.S. Department of Energy - Idaho Operation Office

The goal of the Hydrothermal Program is to reduce the cost to produce from the geothermal resource to 3 - 10 cents per kilowatt-hour. One of the approaches being taken to obtain this goal is to reduce the costs associated with binary and flash plants by increasing plant efficiencies and reducing operational and maintenance costs.

The Geothermal Conversion Technology Program is investigating ways to increase plant efficiencies and reduce operational and maintenance costs. During this session the activities taking place in this program were discussed.

Lawrence Kukacka, Brookhaven National Laboratory, discussed efforts to develop advanced materials for use in geothermal applications. This work has resulted in a large number of materials ranging from pipe liners that inhibit scale buildup to advanced drilling fluids.

Eugene Premuzic, Brookhaven National Laboratory, presented advances that he has made in utilizing biotechnology to treat Geothermal waste. This is an extremely important aspect of the program because the geothermal sludge produced from certain geothermal reservoirs is considered hazardous waste by RCRA, and thus, must be treated, stored, or disposed of in a manner that is often expensive.

Greg Mines, Idaho National Engineering Laboratory, provided an overview of the Heat Cycle Research Project. This project evaluates new power cycles through paper studies and experiments at the Heat Cycle Research Facility located in East Mesa, CA.

Finally, John Weare, University of California at San Diego, presented the results generated from a brine chemistry model he has developed. This model among other things determines at what conditions scaling takes place. This very useful model is being made available to industry.

The accomplishments from the research projects presented in this session have been many. It is hoped that these accomplishments can be integrated into industrial geothermal power plants to assist in realizing the goal of reducing the cost of energy produced from the geothermal resource.

GEOTHERMAL MATERIALS DEVELOPMENT
FY 1990 ACCOMPLISHMENTS AND CURRENT ACTIVITIES

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ABSTRACT

Advances in the development of hydrothermally stable materials, the commercial availabilities of which are considered essential for the attainment of the Geothermal Division's (GD) Hydrothermal Category Objectives, continue to be made. Fiscal year 1990 R&D was focused on reducing well drilling and completion costs, energy conversion costs, and on mitigating corrosion in well casing. Activities on lost circulation control materials, CO_2-resistant lightweight cements and thermally conductive corrosion and scale-resistant liner systems have reached the final development stages. In addition, field tests to determine the feasibility for the use of polymer cement liners to mitigate HCl-induced corrosion at the Geysers were performed. Technology transfer efforts on high temperature elastomers for use in drilling tools such as drillpipe protectors and rotating head seals were continued under Geothermal Drilling Organization sponsorship.

Phosphate-modified calcium aluminate cements containing hollow silliminite spheres and retarded using inorganic acids show promise as CO_2-resistant well cements. Promise is also being shown with chemical systems for lost circulation control. Depending upon the placement method chosen, materials should be ready for field testing in FY 1991. Field testing of thermally conductive corrosion protective composite coating systems in binary heat exchangers will also take place this year. Initial test results from the Geysers indicated that increases in casing life can be obtained by the use of polymer cement liners in regions where low pH steam condensate is formed. Larger-scale tests are scheduled for this year. Recent accomplishments and ongoing work on each of these activities are described 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 Division's (GD) Level III Program Objectives is to reduce the cost of deep wells and directionally drilled wells by 10 percent in the near-term. 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 GD-sponsored R&D and a successful technology transfer program, the lack of suitable hydrothermally stable chemical coupling systems needed to bond the elastomers to steel reinforcement is preventing the successful development of a drillpipe protector. The attainment of other GD Level III Program Objectives such as 1) reducing the costs associated with lost circulation episodes by 30 percent, 2) reducing well cementing problems for typical hydrothermal wells by 20 percent, 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, are similarly dependent upon successful materials development. Specific material needs 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 composites which can be used as protective liners on fluid transport and heat exchange equipment.

The GD-sponsored Geothermal Materials Project being performed at Brookhaven National Laboratory (BNL) has resulted in many material advances which are now routinely used by the geothermal industry. These include high temperature elastomers,[1-3] polymer cement corrosion protective liners,[4], and well cements.[5,6]

Results from the Geothermal Drilling Organization's (GDO) efforts on drillpipe protectors have resulted in increases in the operating capability of the tool for oil and gas applications and the improved tool is being commercialized. Additional work is needed to meet geothermal needs. Ongoing work on rotating head seals, CO_2-resistant cements, lost circulation control materials and corrosion protective liners are expected to be successfully completed within the FY 1991-92 time frame when field demonstrations are performed. The project is coordinated with the Conversion Technology Task at the Idaho National Engineering Laboratory (INEL) and the Hard Rock Penetration Task at Sandia National Laboratories (SNL), and is the subject of cost-shared activities with U. S. industrial firms and the New Zealand Department of Scientific and Industrial Research (DSIR).

Major findings during FY 1990 and the thrust of the current efforts are summarized below.

1. Advanced Lightweight Cements

   o Phosphate-bonded calcium aluminate cements show promise as a CO_2-resistant binder for lightweight cementitious-matrix composites.

   o The inclusion of conventional organic-type retarders results in pumpable slurries, but the retarders undergo carbonation reactions.

- o Inorganic acid retarders are not as effective for extending pumpability, but they are not susceptible to carbonation.
- o Initial data from autoclave and field testing obtained.

2. Chemical Systems for Lost Circulation Control

- o Identification of possible placement methods.
- o Verification of pumpability
- o Optimization of formulations with respect to placement method and operating environment.

3. Thermally Conductive Heat Exchanger Materials

- o Durability verified after 24 month laboratory laboratory test in brine at 150°C and 6 months at 175°C.
- o Tests performed in low pH condensing fluids.
- o Base-line field data from flowing low salinity brine obtained.
- o Field site selected for FY 1991 test in hypersaline brine.

4. Corrosion Mitigation at the Geysers

- o BNL/industry cooperative program established.
- o Field tests performed at the Geysers in well-head environments established technical feasibility of process.
- o Laboratory optimization studies performed in low pH condensing steam environments.

5. GDO Elastomer Activities

- o Commercial availability of improved drillpipe protector for oil and gas drilling operations.
- o Elastomer and bonding system selected for use in completely redesigned rotating head seal.
- o Field testing planned for FY 1991.

Detailed descriptions of the work accomplished in each of these project activities are given below:

RESULTS

1. Advanced Lightweight Cements

In order to meet the GD Programmatic Objectives of reducing well cementing problems for typical hydrothermal wells by 20 percent, 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 DSIR. BNL develops the cement formulations and performs physical, chemical and mechanical evaluations. DSIR is conducting downhole tests in wells at their Mokai and Rotokowa geothermal fields.

During FY 1990, work to formulate and test lightweight CO_2-resistant cements continued. In addition to resistance to CO_2 attack at high temperature, other property criteria are as follows: slurry density <10 lb/gal, pumpable for a minimum of 4 hr at 150°C, compressive strength >1000 psi at an age of 24 hr, water permeability <0.1 m Darcy, and a bulk density <62.4 lb/ft^3.

The results from the laboratory studies performed during the year first confirmed that all calcium silicate hydrate-based well cements undergo carbonation reactions when exposed to hydrothermal fluids containing CO_2. The carbonation rates are strongly dependent on CO_2 concentration, temperature and pressure. The presence of sodium cations in the fluid was found to result in alkali metal - catalyzed hydrolysis of the cement hydrates, thereby increasing the carbonation and subsequent deterioration rate.

The most promising CO_2-resistant formulation identified at BNL is a phosphate modified calcium aluminate cement. The cements yield compressive strengths far in excess of the criterion. For example, curing in air for 24 hr produces a strength of 4000 psi. Curing in hydrothermal environments at 150°C and 200°C for 20 hr yields strengths of 4740 and 10500 psi, respectively.

The formulation can meet API pumpability standards by the incorporation of conventional organic-type retarders such as gluconic acid or glucuronic-6,3 lactone. Unfortunately, these retarding materials undergo reactions with CO_2 leading to carbonation. Inorganic acid-type additives such as boric acid and sodium tetraborate decahydrate are not as effective in retarding the curing rate, but they are not susceptible to carbonation. Studies to explore other methods for extending the pumpability are planned for FY 1991.

The cost-shared cooperative program with the DSIR is continuing. Series of calcium aluminate cements were sent to DSIR who installed them in a well where they are being exposed to CO_2-containing brine at 320°C and pH ~2.2. After only 3 months in this environment, conventional well cements had volume reductions of up to 20% and were completely carbonated. To date, none of the BNL-supplied samples have been removed for evaluation.

The results from the FY 1990 studies can be summarized as follows:

1. Phosphate-bonded calcium aluminate cement showed great promise as a CO_2-resistant binder.
2. Calcium aluminate cements are not pumpable without the addition of retarders.

3. Conventional organic-type retarders yield pumpable slurries but are susceptible to carbonation.

4. Inorganic acid additives (boric acid, borax) are not as effective retarders, but they are not subject to carbonation.

5. Initial data from downhole testing at DSIR received.

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 GD Level III Objective is to reduce well drilling costs for typical hydrothermal wells by 10 percent in the near term. A significant cost reduction can be accrued if an advanced high temperature chemical system that can be introduced through the drill bit into the lost circulation zones is developed. Elimination of the need to remove the drillstring will not only greatly reduce down time, but it will also aid in the location of fractured zones.

During FY 1990, R&D work was continued as a cooperative effort with SNL. Experiments were performed with a previously identified bentonite-ammonium polyphosphate-borax-magnesium oxide system to determine methods for controlling the curing rates and, therefore, pumpability. Microencapsulation of the magnesium oxide in organics was determined to be an effective method for controlling pumpability. The formulations were then optimized with respect to placement and formation temperatures and the resultant mechanical properties of the cured cements.

Six potential methods for placement of the advanced chemical systems into fractured zones were identified by SNL. These are listed below: (1) pumped through open drill pipe, (2) pumped through drillable straddle packer, (3) pumped through bit using encapsulated accelerator, (4) pumped through bit using downhole injector, (5) pumped through wireline-deployed porous packer, and (6) pumped through drillstring - deployed porous packer. For each of these methods the pumpability requirements, material quantitites, setting times, and operating temperatures were estimated, and these needs were then matched with the laboratory identified materials characteristics. Advanced high temperature rapid setting materials suitable for placement using methods 1 and 2 appear to be available today, and they will be tested on a larger scale by SNL in prototype placement equipment in FY 1991. Materials for use with methods 3-6 require additional optimization in FY 1991, but they should be ready for prototype testing in FY 1992, in time to meet the Level III Objective.

3. Thermally Conductive Heat Exchanger Materials

One of the Level III Goals of the Conversion Technology Task is to reduce the cost of binary power cycles by development of low cost corrosion and scale resistant materials of construction for heat exchanger tubing. This activity 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 could possibly be solved with the development of thermally conductive corrosion and scale resistant polymer cement liners for steel tubing. The work consists of determinations of the effects of composition 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 under laboratory and field conditions.

Due to problems encountered in selecting a site for the field testing of a prototype shell and tube heat exchanger containing 80 feet of carbon steel tubing lined with a thermally conductive polymer cement, start-up of the test was delayed until this year.

Prior to installing the unit at the test site where it will be exposed to a 275,000 ppm TDS brine at 180°C, "base-line" fluid flow and heat transfer data were obtained using a "non-scaling" brine. These tests which were conducted at a brine inlet temperature of 170°C indicated that when compared with similar data from a AL-29-4C tube, the pressure drop was higher and the heat transfer coefficient was lower. Both characteristics would be expected to improve when industrial-scale fabrication methods are utilized. Similar tests will be conducted with the higher salinity fluid.

Laboratory evaluations of small pieces of tubing lined with the protective coating were continued. After 24 mo in brine at 150°C and 6 mo at 175°C, liners with a thickness of 0.02-in. provided excellent corrosion protection for the steel substrate. No disbondment or deterioration of the liner were apparent.

Corrosion tests were also performed as a cost-shared effort with the Gas Research Institute (GRI). The purpose of the tests which were performed at temperatures up to 200°C in condensing flue gas environments with the pH ranging from 0.5 to 2, was to determine the technical feasibility of using the material for protective liners in condensors. Based upon the results from these tests which were performed at Battelle Columbus Laboratories, GRI has selected the material for further R&D.[7]

Basic research studies focused on obtaining the information necessary to modify the surface characteristics of thermally conductive composite liners to make them less susceptible to scale deposition are underway at BNL. 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.

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

4. Corrosion Mitigation at the Geysers

Increased HCl concentrations in the steam produced from geothermal wells at the Geysers have resulted in severe corrosion problems in the upper regions of the well casing where some condensation occurs, and in the steam collection piping. In some cases this has resulted in the shutdown of wells causing reduced steam supply and, therefore, decreases in electric power generation. Increased operating costs and safety and environmental concerns have also resulted.

Based upon an industrial request to DOE/GD, BNL initiated cost-shared work with the Coldwater Creek Operator Company in mid FY 1990 to determine the technical feasibility for the use of previously developed polymer cement composites for corrosion protection. Two BNL-supplied test sections were installed at the Geysers at locations where failure of 0.5 in. thick wall steel casing generally occurs within 5 weeks. Neither test section failed during a five week test, but some chemical attack was apparent. The probable cause of this attack was the presence of an excessive amount of portland cement in the formulation and the presence of a significant amount of laitance on the liner surface. Normally, the hydrothermal stability of polymer cements is improved by the addition of insoluble forms of calcium-containing compounds found in portland cement, but acid resistance is decreased. Therefore, for use in a high temperature (170° to 200°C) highly acidic (pH 2-4) environment, an optimization of the formulation with respect to fluid temperature and pH is required. This study is scheduled to be made early in FY 1991 and it will be followed by the field testing of coated test coupons and lined 8-in. diameter x 12-in. long wellhead sections.

5. Geothermal Drilling Organization Elastomers Activities

BNL provides liaison services to SNL and the GDO in order to enhance the transfer of completed GD-sponsored high temperature elastomer technology to industry so that it can be utilized in equipment needed by the GDO. Such needs include drillpipe protectors, rotary head seals, blow-out protectors, and Moineau stators for downhole drillmotors.

In FY 1990, work on the development of advanced high temperature drillpipe protectors was essentially completed by the GDO selected contractor, Regal International. Based upon laboratory and field testing conducted in FY 1989 and FY 1990, it was concluded that the unavailability of a hydrothermally stable chemical coupling system needed to bond the elastomers to steel reinforcement, prevented the development of a tool which met the GDO requirements. However, the program increased the operating capability for oil and gas applications, and the tool is being commercialized for those uses.

Development of advanced rotary head seals was continued by A-Z Grant International under contract with GDO. Two promising elastomers and a bonding system were identified and laboratory tested, a sealing configuration designed, and full-scale seal units fabricated. Field testing will commence in FY 1991.

CONCLUSIONS

The DOE/GD-sponsored Materials Development Project continues to make major contributions to GD's programmatic goals. Many successes have already been accrued and the results transferred to industry.[8]

In FY 1990, the R&D efforts were focused on reducing well drilling and completion costs and on mitigating corrosion in well casing. Activities on lost circulation control materials, CO_2-resistant lightweight cements, and thermally conductive corrosion and scale-resistant protective liner systems have reached the final development stages, and cost-shared field tests are planned for the FY 1991-92 time frame. Technology transfer efforts on high temperature elastomers for use in drilling tools are continuing under GDO sponsorship. In the case of drillpipe protectors, increases in the operating capability for oil and gas applications have been achieved and the tool is being commercialized for those markets. Unfortunately, until suitable high temperature hydrolytically stable chemical bonding systems, needed to bond the elastomers to steel reinforcement, are developed, the tool will not meet geothermal requirements. Development of advanced bonding systems is a high priority activity in the 1991 Materials Project.

Development of advanced rotary head seals needed for geothermal drilling operations should be successfully completed in FY 1991. This device will also strongly impact oil and gas drilling.

Laboratory results indicate that mixtures of phosphate-modified calcium aluminate cements and hollow silliminite spheres produce promising CO_2-resistant well cementing materials. Retarders which result in the cement slurries meeting API pumpability standards have been identified, and downhole testing of cured samples in CO_2 containing brine at 320°C and pH ~2.2 was started as a cost-shared program with DSIR in New Zealand. If tests scheduled for FY 1992 are successful, the Level III Objective of reducing well cement problems by 20% should be met.

Similar promise is being shown with chemical systems for lost circulation control. Depending upon the placement method selected, materials will be ready for field testing in late FY 1991. If successful, a major advance towards meeting Level III Objectives for reducing lost circulation episodes will have been made.

Work on thermally conductive polymer cement liners for the corrosion protection of heat exchange tubing in binary plants has been slowed by delays in obtaining a field test site. This problem was solved late in FY 1990 and the program should be completed in FY 1991.

Preliminary cost-shared field tests performed at the Geysers with private sector steam producers established the technical feasibility for the use of polymer cement liners to provide corrosion protection for the upper portions of well casing and steam collection piping. Larger-scale tests are scheduled for FY 1991. If successful, wells that are being considered for shut-in due to unfavorable economics resulting from corrosion problems will continue to be operated, thereby helping to maintain electric generating capacity at the Geysers.

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Advances in Geothermal Waste Treatment Biotechnology

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ABSTRACT

Biotechnology based on microbial biochemical processes by which geothermal wastes are converted from hazardous to nonhazardous depends on a number of process variables. These include (a) reactor size, (b) effects of agitation, (c) the efficiency of single and mixed cultures, (d) the effect of biomass, (e) pH and dissolved oxygen, (f) cell growth, (g) concentration of residual sludge, (h) metal salts and, (i) temperature. The effects of these parameters will be discussed in terms of two bioreactor designs, one based on a fluidized bed and the other on an agitated tank. The comparative analyses are relative and represent laboratory data with different sludge loading capacities, residence time, and bioreactor type. In this paper particular attention will also be given to the effects of temperature on the rates of detoxification and materials balance. Preliminary results dealing with recovery of toxic metals will also be briefly addressed.

INTRODUCTION

Work in this laboratory has shown that a low-cost environmentally acceptable biotechnology for detoxification of geothermal residual sludges is economically and technically feasible.[1,2] The emerging biotechnology is programmatically consistent with the goals and objectives of DOE's Geothermal Research Programs. The experimental strategy used at Brookhaven National Laboratory (BNL) for the development of detoxification biotechnology for geothermal waste is based on the use of biochemical methods for dissolution of toxic elements found in geothermal residues. Produced solutions containing toxic and valuable metals can be reinjected or used for concentration and recovery of metals. In the recovery mode, both chemical and biochemical methods are being developed. The R&D effort at BNL has identified several variable parameters essential to the development of the new biotechnology for the biochemical treatment of residual geothermal sludges. Thus, for the purposes of process design and optimization, reactor size, agitation, mixed microbial cultures and their delivery must be considered simultaneously with the management of temperature, pH, dissolved oxygen, concentration of residual sludge and residence time. The effects of these variables will be discussed in the light of most recent studies.

EXPERIMENTAL

Comparative studies of fluidized bed and agitated tank type bioreactors have been carried out in 30 gallon plastic reactors already described.[4] These experiments have been conducted at ambient temperatures ranging from 20-21°C.

Kinetic experiments at elevated temperatures have been carried out in specially constructed three liter all glass bioreactors equipped with sampling ports as shown in Figures 1 and 2. Chemical analyses have been carried out by atomic adsorption using analytical procedures reported previously.[1,5,6]

RESULTS AND DISCUSSION

Preliminary Economic comparison of Two Types of Bioreactors

In this study two processes have been considered, one based on a fluidized bed and the other on an agitated tank bioreactor. It is to be understood that in the analysis of the two processes only relative qualitative estimates have been used based on laboratory data at ambient temperatures. The purpose of this study was to gain comparative information rather than an optimum state-of-the-art design/cost estimate.

The proposed biochemical waste treatment process is based on 80,000 lb/day of dry geothermal waste contained in a 65% filter press cake from a 50-MW double flash plant. The process flow diagram for the proposed biochemical waste treatment facility using either a fluidized bed or agitated tank bioreactor is given in Figure 3. The filter press cake (65% of solid) from a brine-solids separation plant is sent to the fluidized bed bioreactor by a conveyor belt at an average rate of 123,000 lb/day. An agitated tank biotreatment process is very similar to the fluidized bed bioreactor process except that the fluidized bed bioreactor is replaced by an agitated tank bioreactor and a much smaller air supply is necessary. The main difference between a fluidized bed reactor and an agitated tank bioreactor is the source of the driving force for mixing of solids and liquid, i.e., a large air compressor is used in a fluidized bed whereas a motor-driven stirrer is used in the agitated tank. The details of each are discussed elsewhere.[7,8] The streams of biochemical waste treatment plant for the fluidized bed bioreactor and the agitated tank bioreactor are summarized in Table 1 for various solid loadings. For these experiments, calculations were based on the production of geothermal sludge (5130 lb/hr) in a 50-MW power plant. Further the volume of the reactor depends on the process design, the residence time and solid loading. In either process

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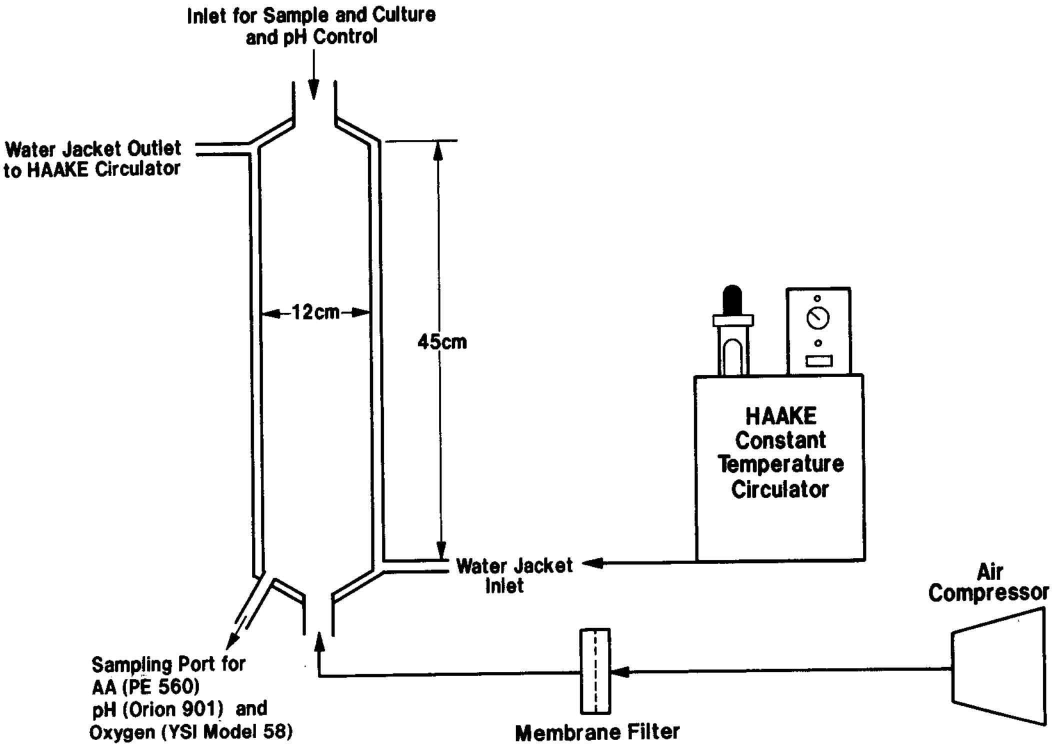

Figure 1. All Glass Fluidized Bed Bioreactor

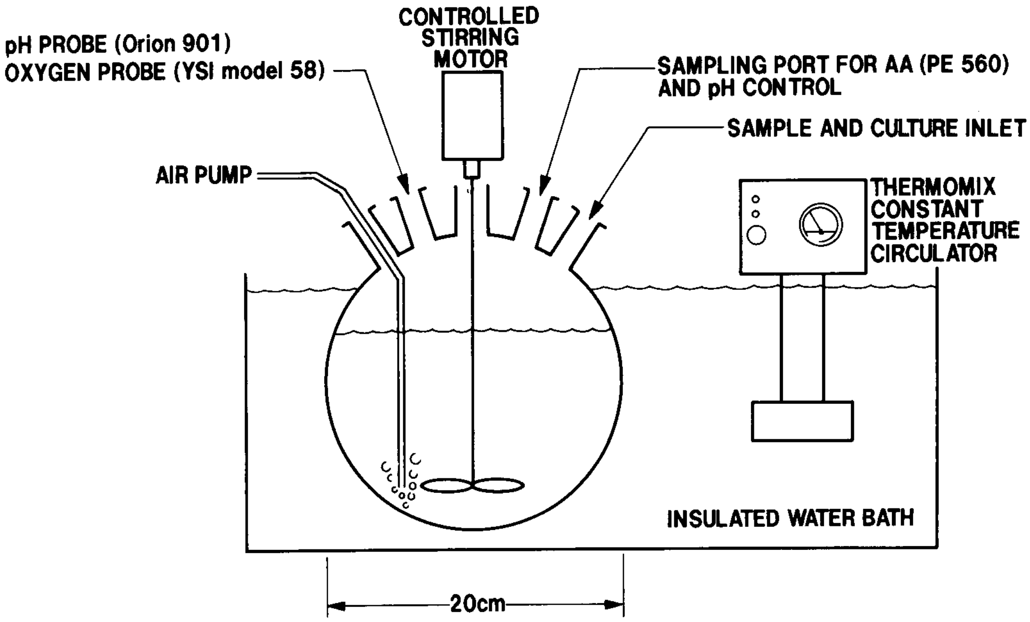

Figure 2. All Glass Agitated Tank Bioreactor

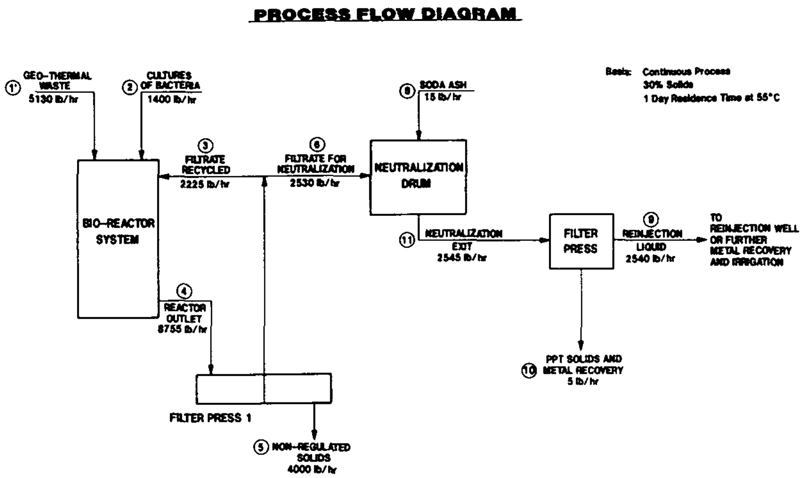

Figure 3. Process Flow Diagram

configuration bacteria are continuously added to keep as high a cell concentration and as low a medium pH as possible in the reactor. The fermenter and storage tank of bacterial cultures are connected to the biological waste treatment plant. Fully grown mixed cultures are stored in a tank until they are needed.

Interaction between microbial biomass and geothermal sludge takes place in the bioreactor where the solid and liquid components are well mixed at the same residence time. The bioreactor outflow (stream 4) containing a certain solids loading, is sent to filter press 1 where it is concentrated to a 65% solid cake, which is the nonhazardous solid waste product. In the event that the solid product is still hazardous (e.g., during start-up), the filter press cake can be recycled to geothermal sludge holding tank (stream 5) and reprocessed. The liquid which passes through the filter press can also be recycled back to the bioreactor (stream 3), or (stream 6) it can be sent to a neutralization drum where the pH is raised to at least 4. It is then pumped through a filter in order to collect any washed out bacteria and precipitated solids from the neutralization process. The filter leachate from filter press 2 is then pumped down a reinjection well (stream 9). Any precipitated solids which were collected by filter press 2 may be sent to the metal recovery plant as another alternative process which may be considered in the future.

For the purpose of a preliminary economic comparison of the proposed process the two bioreactor types, i.e., fluidized bed and agitated tank, have been taken into consideration and the total capital cost of each treatment plant was a mortized over a 10-year plant life at an interest rate of 10%, to be paid in ten equal end-of-year payments. Further, in the calculations[7,8] several reactor volumes, solid loadings and residence times have also been included. The results of these analyses are given in Table 2.

The annual operating cost of each process, which includes nutrients costs for the bacterial culture, disposal costs of solids, electric power, irrigation water, insurance, labor, and pH control, ranged from $710,000 to $930,000. This cost analysis does not include quality control and flexibility in recycling and therefore represents only relative and qualitative estimates. For example, disposal cost of non-regulated waste should in practice be lower, because such detoxified material may be used as a land filler and/or as a nontoxic additive in the production of concrete. Further, different materials should also be considered for the construction of a waste treatment plant. However, this analysis clearly illustrates the importance of optimization and the significant influence of variables such as, for example, aeration/ agitation costs which vary from process A to E.

Temperature, Sludge Loading and Residence Time Studies

Preliminary studies with temperature adapted acidophilic microorganisms have shown that fast, highly efficient rates of removal of toxic metals from geothermal brines can be achieved at elevated temperatures (>50°C).[2] The temperatures can easily be maintained by using the residue waste heat from the power plant. In order to gain further knowledge about the rates, efficiency, and reproducibility of the biochemical process for detoxification of geothermal sludges at elevated temperatures, the existing bioreactors had to be modified. Two key experimental parameters had to be considered: temperature (>50°C) and acidity, i.e., corrosion potential (pH 1-2). In order to keep within budget, this phase of R&D has been carried out in smaller, all glass bioreactors as shown in Figures 1 and 2. Both reactors are based on a three liter capacity. The fluidized bed bioreactor (Figure 1) was heated by a hot water jacket, while the agitated tank bioreactor (Figure 5) was heated by means of a water bath. In temperature was controlled and maintained at 55°C, with temperature and pressure monitored during the course of reactions.

All the analyses reported here have been carried out in triplicate, both in solid and liquid phases.

Table 1. Biological Waste Treatment Plant Stream Summary

BIOLOGICAL WASTE TREATMENT PLANT STREAM SUMMARY

Stream Number	Description	Flow Rate			Amount of Solids
		10% (W/V)	20% (W/V)	30% (W/V)	
1'	Filter Press Cake from Brine-Solid Separation	5130 lb/hr	5130 lb/hr	5130 lb/hr	65%
1	Filter Press Cake from Geothermal Sludge Holding Tank	5130 lb/hr	5130 lb/hr	5130 lb/hr	65%
2	Bacteria Culture	2000 gal/hr	1000 gal/hr	615 gal/hr	0
3	Filter Press Recycle	1785 gal/hr	785 gal/hr	450 gal/hr	0
4	Reactor Outlet	4060 gal/hr	2080 gal/hr	1360 gal/hr	
5	Filter Press Cake	5130 lb/hr	5130 lb/hr	5130 lb/hr	~65%
5'	Filter Press Cake Recycle	5130 lb/hr	5130 lb/hr	5130 lb/hr	65%
6	Filter Press Cake Recycle (Neutralization)	3685 gal/hr	1705 gal/hr	985 gal/hr	0
7	Water and Nutrients	2000 gal/hr	1000 gal/hr	615 gal/hr	0
8	Soda Ash	400 lb/hr	400 lb/hr	400 lb/hr	100%
9	Reinjection Liquid	3730 gal/hr	1740 gal/hr	1020 gal/hr	0
10	Precipitation Solid	<100 lb/hr	<100 lb/hr	<100 lb/hr	65%
11	Neutralization Exit	3730 gal/hr	1750 gal/hr	1030 gal/hr	0

Table 2. Economic Analysis of Biochemical Processes for Geothermal Sludge Treatment (10 Year Plant Life, 10% Interest Rate)

ECONOMIC ANALYSIS OF BIOCHEMICAL PROCESSES FOR GEOTHERMAL SLUDGE TREATMENT

(10 YEAR PLANT LIFE, 10% INTEREST RATE)

Case	A	B	C	D	E
Reactor System	Fluidized Bed	Fluidized Bed	Fluidized Bed	Fluidized Bed	Agitated Tank
Solids Loading (%W/V)	10	20	30	10	10
Residence Time (day)	2	2	2	1	2
Reactor Volume (gal)	230,000	120,000	80,000	120,000	230,000
Purchased Equipment Cost	$1.31M	$0.97M	$0.84M	$0.95M	$1.25M
Annual Operating Cost	$0.89M	$0.80M	$0.93M	$0.71M	$0.88M
Total Annual Cost	$1.63M	$1.37M	$1.44M	$1.27M	$1.59M

For sake of expedience, four metals, copper, zinc, manganese, and lead have been used as representative constituents of the geothermal residual brine sludge used in these experiments. In each case the data are presented for 0-80 h and a 0-25 h time interval. The both systems experiments have been carried out with mixed cultures of temperature adapted <u>Thiobacillus thiooxidans</u> and <u>T</u>. <u>ferroxidans</u> at 55°C and a pH range of 1-2.[9] Analyses have been carried out on samples obtained from the solid and liquid phases in each bioreactor, viz., tank or fluidized bed used. Analysis of both the solid and liquid phase is a necessary step for the determination of material balance. Typical results for a single metal, e.g., copper and different bioreactor loadings, e.g., 10%, 20%, 30% and 40% are shown for solid and liquid phases in Figures 4-7. Figures 8 and 9 represent a summary of all the analyses at 40% loading with corresponding error bars as shown in the figures. There is an excellent agreement in the rate curves between the solid and liquid phases. High metal removal efficiency in time intervals of 25 hours are evident.

Except for lead, after a 25 hour interval a steady state is reached. Because of solubility of lead sulfate formed, the initial and final concentrations of lead and sulfate ions are process limiting steps. However, the initial concentration of lead in the samples of geothermal residual sludge (2050μg/g) used is such that even at a rate of 1% removal per hour over a period of twenty five hours, the concentration of lead remaining in the solid is below the total threshold limiting concentration (TTLC) as defined by regulatory agencies.[10] The removal of other metals is also consistent with TTLC. The results also show that there is an initial rapid removal of metals, followed by a considerable drop in the rate of metals removal. These experimental observations indicate that several biochemical mechanisms are involved in the solubilization of metals from residual geothermal brines. Although these mechanisms have not been studied, their practical utility is obvious. From the data presented, a fast rate of metal removal in most cases so far studied can be achieved at elevated temperatures

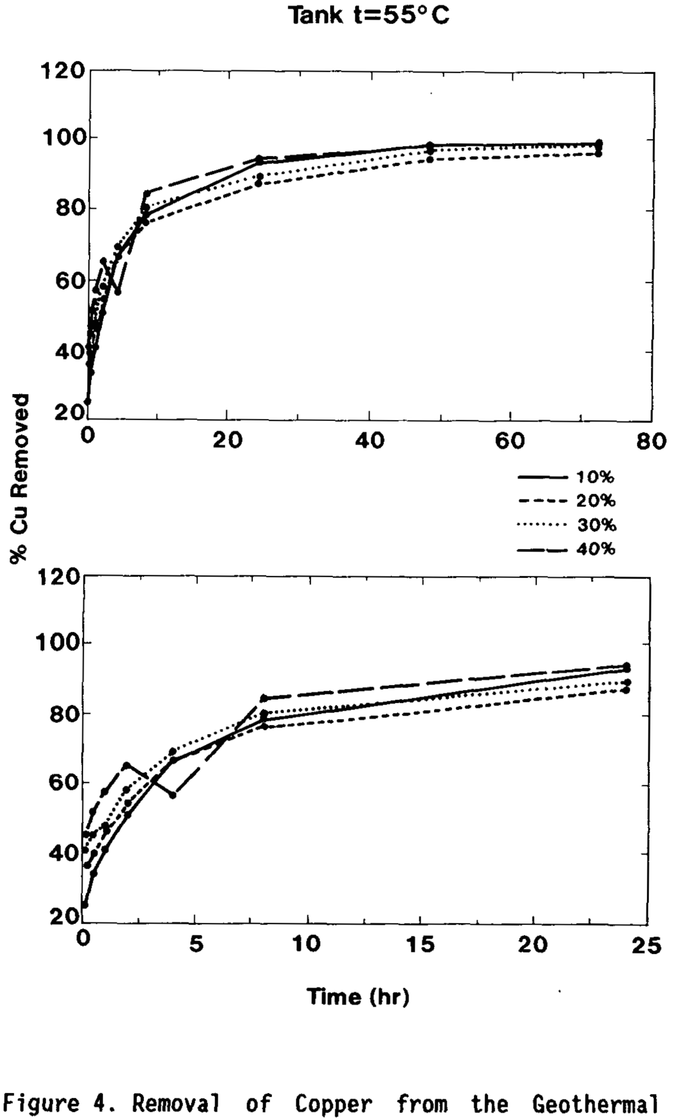

Figure 4. Removal of Copper from the Geothermal Residual Sludge Solid Phase. Agitated Tank Bioreactor at 53°C.

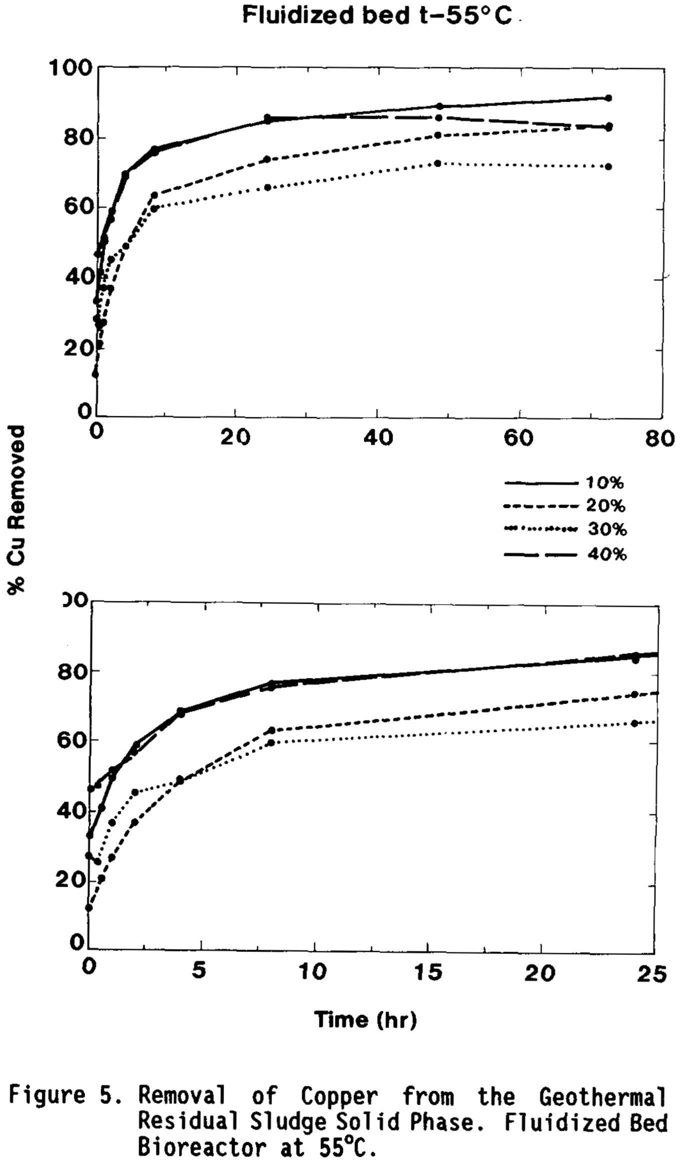

Figure 5. Removal of Copper from the Geothermal Residual Sludge Solid Phase. Fluidized Bed Bioreactor at 55°C.

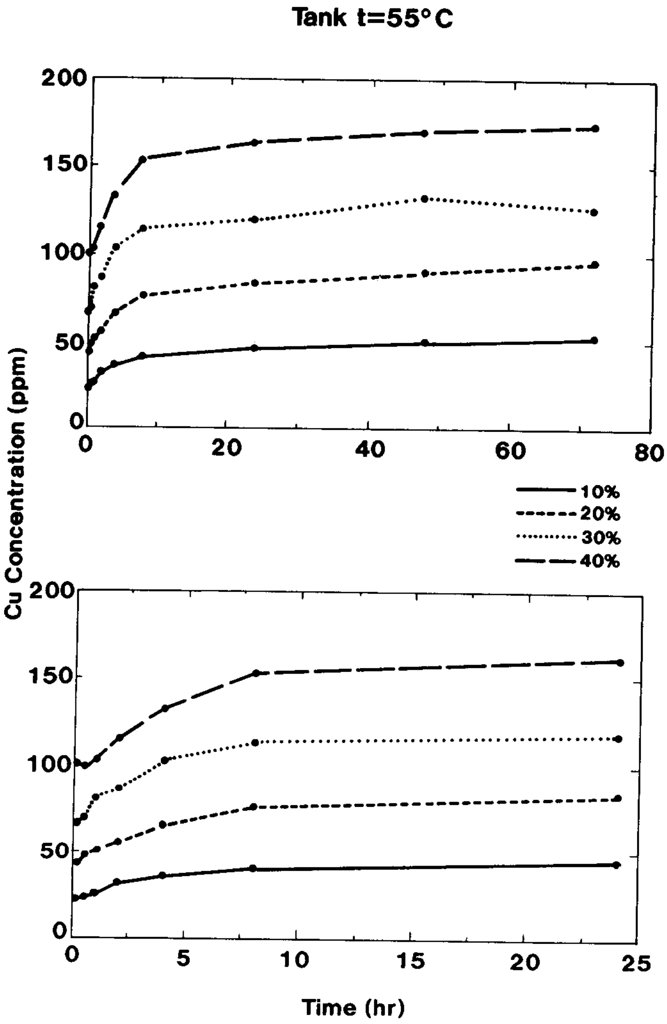

Figure 6. Concentration of Copper in the Liquid Phase after the Biotreatment of the Sludge Solid Phase. Agitated Tank Bioreactor at 55°C.

and high sludge loadings. Under experimental conditions used, the biotreatment brings the concentration of the metals to below the total threshold limitations. Therefore, a single 25 h cycle may be sufficient and can be incorporated in the process design. Further, concentrations of metals appearing in the liquid phases (although dependent on the initial concentration in the solid) are well below the toxicity levels to the microorganisms themselves allowing recycling, to remain a viable option.

Mass Balance

In order to have a "quality control" handle for the system, a mass balance calculation has been carried out. In these calculations, the mass balance represented the total concentration of the metal in the solid and aqueous phases at the beginning of biotreatment and 72 hours later. Typical results are shown for zinc and copper, in Table 3 for fluidized bed, and in Table 4 for agitated tank experiments. For all practical purposes, the net loss (-) and/or gain (+) is within the experimental error of analytical techniques used.

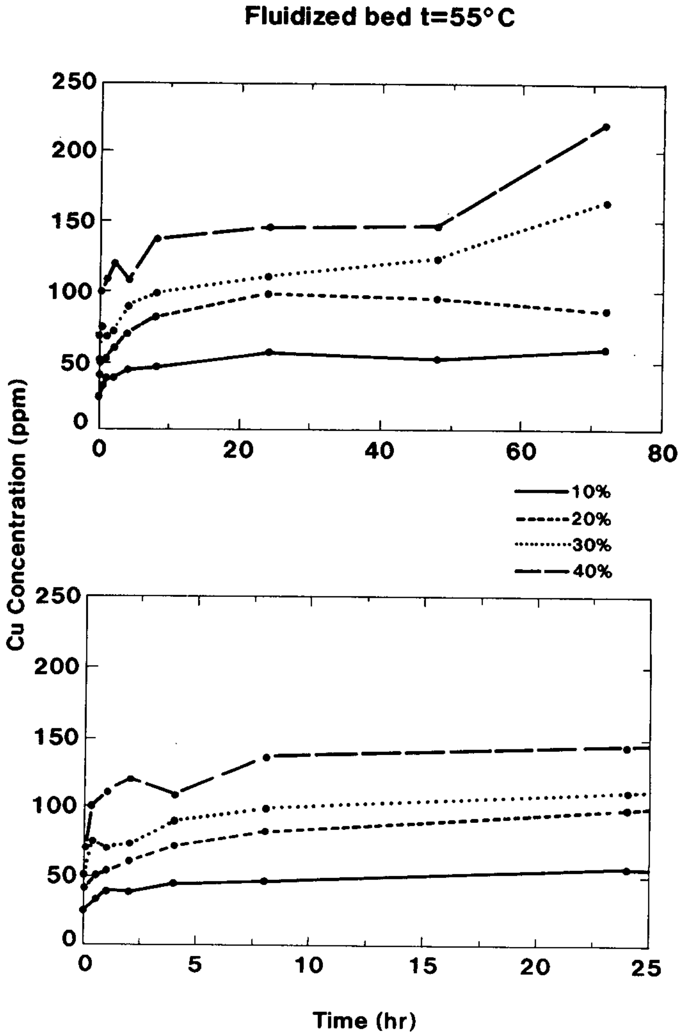

Figure 7. Concentration of Copper in the Liquid Phase After the Biotreatment of the Sludge Solid Phase. Fluidized Bed Bioreactor at 55°C.

Table 3. Fludized Bed Bioreactor

Mass balance for zinc and copper including a net gain/loss in grams per seventy-two hour cycle at 40% loading.

Expt. No.		Zn	Cu
1	5 min.	1.2470	0.4658
	72 h	1.19350	0.4150
	±	0.0535 (-)	0.0508 (-)
2	5 min.	1.5380	0.6533
	72 h	1.3842	0.5220
	±	0.1538 (-)	0.1313 (-)
3	5 min.	1.4070	0.5315
	72 h	1.4278	0.4812
	±	0.0208 (+)	0.0503 (-)

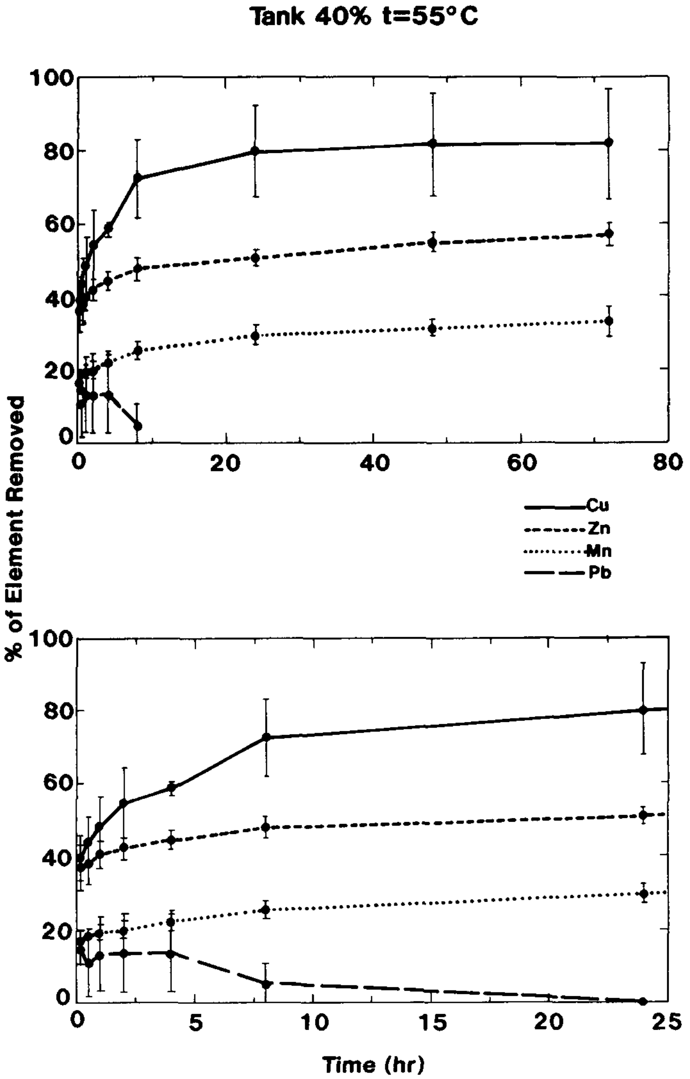

Figure 8. Removal of Copper, Zinc, Manganese, and Lead in an Agitated Tank Bioreactor at 55°C and 40% Sludge Loading.

Metal Recovery

In the development of new biotechnology for the removal of toxic metals from geothermal sludges, an aqueous effluent containing toxic metals is being generated. At the present time the toxic metal content under field conditions does not cause any problems, because at this time the effluent can be reinjected. Because there are no reinjection facilities at BNL (and possibility of future regulations), the aqueous phase has to be disposed of by conventional means, i.e., discharged into the sewer system. For this purpose, however, the concentration of toxic metals is too high. Therefore, although programmatically not called for, this program has to develop an effluent detoxification process in order to handle the waste generated during the ongoing R&D effort. To accomplish this, several chemical and biochemical methods have been tried. Efficiency of co-precipitation for several metals by chemical means is shown in

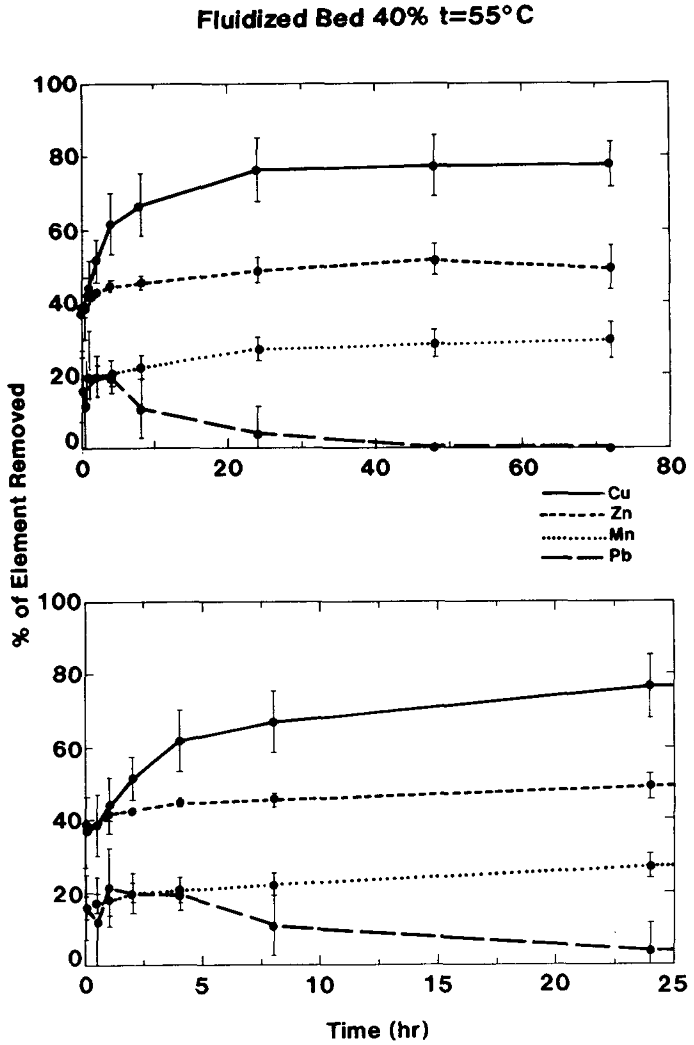

Figure 9. Removal of Copper, Zinc, Manganese, and Lead in a Fluidized Bed Bioreactor at 55°C and 40% Sludge Loading.

Table 4. Agitated and Tank Bioreactor

Mass balance for zinc and copper including a net gain/loss in grams per seventy-two hour cycle at 40% loading.

Expt. No.		Zn	Cu
1	5 min.	1.7280	0.5488
	72 h	1.4909	0.46248
	±	0.2371 (-)	0.1243 (-)
2	5 min.	1.9590	0.7208
	72 h	1.523	0.5522
	±	0.436 (-)	0.1683 (-)
3	5 min.	1.6590	0.5338
	72 h	1.4180	0.4777
	±	0.2410 (-)	0.0561 (-)

Table 5. In this table, percent removed means the total amount of metal precipitated from the aqueous phase produced after the biotreatment of geothermal residual brine sludge. For the metals tested the efficiency is remarkably high. This technology is being explored further. It is also worthwhile to note that recovery of metals, including the recovery of valuable ones such as chromium may, under some circumstances, be an attractive option. A combined sludge detoxification-metal recovery process will offset the overall costs, since detoxified sludge may be used for landfill and other purposes, while metal concentrates would yield marketable metals.

CONCLUSIONS

In the development of biotechnology for detoxification of geothermal residual sludge the influence of process variables on the cost and plant design is of paramount importance. For example, the choice of bioreactor may well be influenced by the cost of air supply to the reaction mixture. To further the development of the emerging biotechnology, construction materials for holding tanks and reaction vessels will have to be also considered. This need arises from the fact that high efficiencies of detoxification are achieved at temperatures above 50°C and pH of 1 to 2. Quality control, such as that of mixed cultures, pH, air supply, etc., at strategic points in the overall plant design will lead to considerable streamlining and lowering of the costs associated with the design and operation of biochemical process under consideration.

Table 5. Removal of Metal from the Aqueous Phase

	Treatment		
	Scrap iron	Aluminum foil	Lime
Metal: Pb % removed	83	88	94
Metal: Mn % removed	7.5	0.7	99
Metal: Cr % removed	94	95	96
Metal: Cu % removed	97	97	99
Metal: Zn % removed	4	10	99

ACKNOWLEDGMENTS

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OVERVIEW OF THE HEAT CYCLE RESEARCH PROJECT

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ABSTRACT

The Heat Cycle Research project is developing the technology base that will permit a much greater utilization of the moderate-temperature, liquid-dominated geothermal resources, particularly for the generation of electrical power. The emphasis in the project has been the improvement of the performance of binary power cycles. The investigations have been examining concepts projected to improve the brine utilization by 20% relative to a "Heber-type" binary plant; these investigations are nearing completion. Preparations are currently underway in the project to conduct field investigations of the condensation behavior of supersaturated turbine expansions. These investigations will evaluate whether the projected additional 8% to 10% improvement in brine utilization can be realized by allowing these expansions. Analytical studies of an "ideal" cycle's performance have shown that the concepts under project investigation, are approaching the practical limits of performance (these limits are imposed by rotating equipment efficiencies and heat exchanger approach temperatures). Future program efforts will focus on the problems associated with heat rejection and on the transfer of the technology being developed to industry. Geothermal resources are typically found in the semi-arid regions of the western United States. In some instances, the lack of an adequate make-up water supply for a conventional "wet" cooling system presents a barrier to the development of the resource or results in the utilization of a less efficient power cycle. The project will examine schemes for rejecting heat which provide a performance similar to the "wet" systems with decreased make-up water requirements, or would allow a lower quality water to be used. Innovative schemes will also be examined for areas where the lack of make-up water prohibits the use "wet" systems. Future project efforts will attempt to intensify the assimilation of the technology base being developed into industry to assist in the removal of barriers or constraints to the development of a resource.

BACKGROUND

The objective of the Heat Cycle Research Project is to develop, or promote the development of, technology which will result in a more effective utilization of moderate temperature geothermal resources. The emphasis of the program to date has been directed towards the binary cycle technology which more effectively utilizes the energy contained in the liquid-dominated, moderate-temperature hydrothermal resources. The project is also defining the technology need to utilize resources having technical or institutional barriers to development.

During the scoping and analytical studies in the initial phases of the program, several concepts were identified which showed significant potential for performance improvements. These concepts were, and continue to be, the subject of field investigations conducted by the project with a small binary plant. These field investigations, which were initiated over 10 years ago at the Raft River site in southern Idaho, have been carried out at geothermal facilities in the Imperial Valley of southern California since the mid-1980's. The small plant used for these investigations, referred to as the Heat Cycle Research Facility (HCRF), is shown schematically in Figure 1. The plant contains most, if not all, of the components found in a typical binary power plant. The components are designed to allow the specific concepts/components under consideration, to be investigated. The design of the facility allow for components to be readily changed; its size allows these changes to be made at reasonable costs, while maintaining component configurations similar those that would be found in a commercial facility.

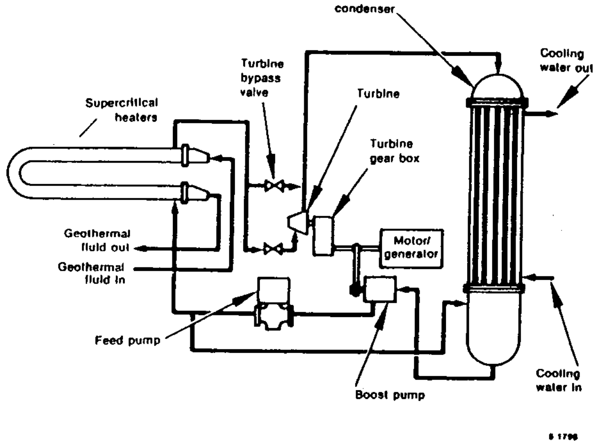

Figure 1. Schematic of the Heat Cycle Research Facility

As indicated, analytical studies[1-4] conducted projected significant performance gains could be achieved relative to a reference plant. For these studies, the conditions for the Heber binary plant were selected as the reference plant; it was felt this plant represented the "state-of-the-technology" at that time (this assumption appears to continue to be valid). Relative to the Heber-type plant, the studies indicated that performance improvements of 20% to 30% (in terms of the net power produced per unit brine flow rate, or brine effectiveness) were possible. Utilization of supercritical cycles with optimized selection of a working fluid mixture and turbine inlet conditions provided the significant portion (20% of the total 30%) of the performance improvement. The improvements result from taking advantage of the non-isothermal phase changes that occur when mixtures are used (this characteristic reduces the irreversibilities during the heat transfer processes). In order to take advantage of this working fluid characteristic, the heat exchangers must be designed for, and operate with, countercurrent flow paths and integral phase changes. By vaporizing the mixture at supercritical pressures, it was felt the concerns relative to being able to achieve "integral" boiling would be alleviated; the HCRF heaters were designed accordingly. The HCRF condenser was design for in-tube condensing and a vertical tube orientation, a design felt to provide the best opportunity to achieve the countercurrent "integral" condensation necessary to achieve the performance gains. (The model of the Heber-type plant used for these studies did not achieve the countercurrent flow paths or integral phase changes in the condenser.)

It was projected that the remaining performance improvement (approximately 10%) could be achieved by allowing supersaturated turbine expansions with the advanced cycle.[5] In this type of expansion, the vapor enters and leaves the turbine at conditions outside of the two-phase region. However, during the expansion process in the turbine, the fluid, if at equilibrium, would be two phase. Studies suggested that condensate droplets would not form, or if they did form would remain small (too small to damage the turbine internals or adversely effect performance). This is the current area of project activities.

Geothermal resources are primarily located in the semi-arid western states where the availability of a cooling water make-up source, in sufficient quantity and quality, can pose a barrier to development. In the original analytical studies[1-5], the non-isothermal condensation of the working fluid mixtures suggested that this characteristic might allow some alternative means of heat rejection to be utilized which could reduce the consumptive use of cooling water (and make-up requirements). The non-isothermal condensing could allow a portion of the heat rejected, to be transferred in a sensible heat exchange process (as opposed to a latent heat exchange process) without significant performance penalties. In the future, the project will investigate this area in more detail, and attempt to define alternative schemes for heat rejection which do not have the same degree of consumptive use of cooling water.

RESULTS TO DATE

The supercritical cycle investigations at the Heat Cycle Research Facility are nearing completion. The analysis of the data collected at the facility indicate that the currently available "state-of-the-technology" design methods and working fluid property codes do an acceptable job of predicting the actual performance of the supercritical preheater and vaporizer heat exchangers.[6,7] Countercurrent flow paths are achieved in the preheater and vaporizer, and the supercritical vaporization of the working fluid mixtures was successful in alleviating concerns relative to achieving "integral" boiling. A typical example of the ability of the heat exchanger codes to predict the preheater and vaporizer performance in shown in Figure 2. In this figure, the solid circles represent the observed temperatures and the solid lines the computer predicted performance. The heat exchanger codes were typically conservative in predicting the required heat exchanger area, that is, the predicted area was generally about 20% greater than the actual area.

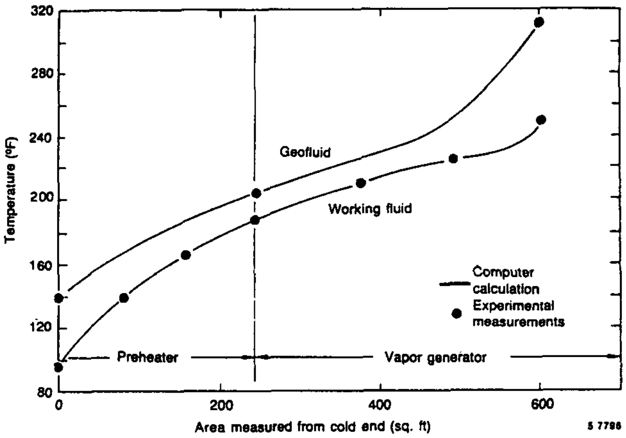

Figure 2. Heater Temperature Profile, 90% propane, 10% isopentane working fluid

The evaluation of the condenser data at the vertical orientation indicated the available design methods and property codes were adequate to predict the performance of the condenser. Figure 3 shows the ratio of calculated to observed overall heat transfer coefficients as a function of both working fluid composition and the amount of desuperheating accomplished. A ratio of greater than one implies the code would under predict the required area; less than one implies the code would over predict the required area. As shown in Figure 3, the calculated heat transfer coefficient was generally less than that

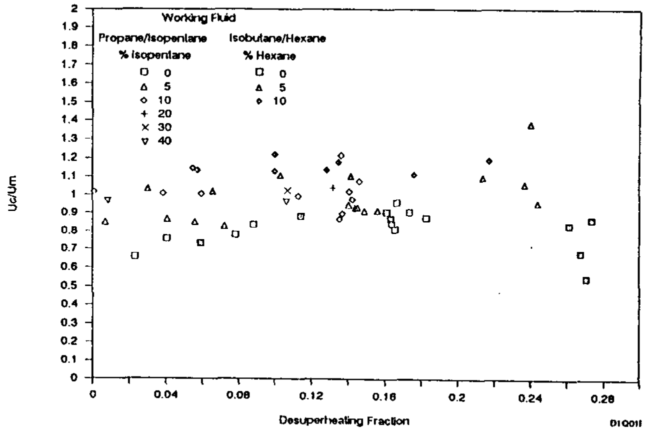

Figure 3. Calculated to Observed Condenser Performance (overall heat transfer coefficient) for Vertical Orientation

observed, which would result in a slightly conservative condenser design. Counter-current flow paths were achieved during the vertical condenser testing, and no deviation was observed from the assumption of "integral" condensation during operation with mixtures.

For commercial applications, a vertical condenser orientation would be less desirable than an orientation closer to the horizontal. When the HCRF condenser was oriented more closely to the horizontal, deficiencies were noted in the ability of the existing design methods to adequately predict the observed performance. Figure 4 presents the data from the near-horizontal testing in a manner similar to those shown in Figure 3. At this condenser orientation, the predicted heat transfer coefficients were higher than those observed, and there appears to be a trend with the amount of desuperheating accomplished. This data indicates that the codes would under-predict the size of a condenser. The trend with desuperheating suggests that the portion of the code which deals with condensing is incorrectly modeling this phenomena at the non-vertical orientation (as the ratio of the desuperheating increases, there is better agreement between the predicted and observed heat transfer coefficients). Countercurrent flow paths and integral condensation were still noted at the non-vertical orientations, indicating that these two assumptions, which are critical to achieving the performance gains, were valid. The project is continuing to gather data under different operating parameters at the non-vertical condenser positions; this data is utilized to evaluate different methods of modeling the condenser with the existing "state-of-the-technology" design methods.

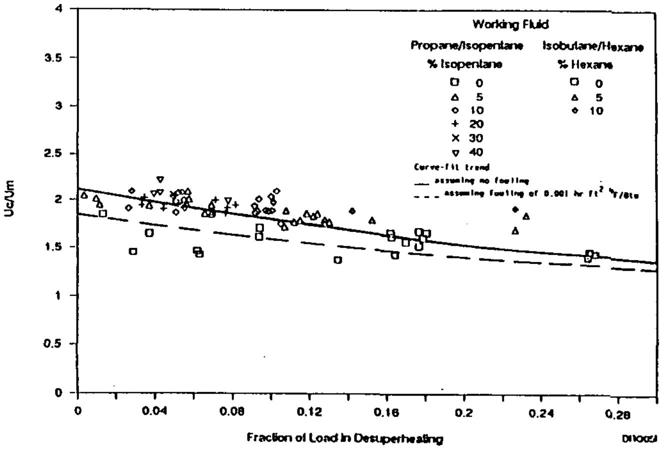

Figure 4. Calculated to Observed Condenser Performance (overall heat transfer coefficient) for Near-Horizontal Orientation

Although the project has identified some areas where the present technology base is inadequate for the design of component, the investigations to date have confirmed the validity of the assumptions necessary to achieve the projected 20% performance gain. The property codes used to project the performance gains possible with the working fluid mixtures, are adequate for predicting the fluid properties and component/-cycle performance. Vaporization at supercritical pressures provides the "integral" phase change required to achieve the projected gains. Countercurrent flow paths were achieved in each of the heat exchangers, and "integral" condensation was noted with the in-tube condensing design, regardless of the condenser orientation. As the project continues to gather and interpret data from the non-vertical condenser operation, the technology base will be expanded to allow for the design of the components to achieve these gains. It is anticipated that this effort will be completed in 1992.

In an effort to assess further improvements in cycle performance, a study^{8} was made which evaluated how closely the cycles under investigation approached the performance of a cycle utilizing an idealized working fluid. The performance of this idealized cycle was based on operation with the constraints imposed by the practical performance limits of the cycle components (approach temperatures in heat exchangers and rotating equipment efficiencies). A second law analysis was made of the idealized cycle where the availability was reduced by the irreversibilities introduced by the practical constraints imposed. This defined a maximum practical performance which is shown in Figure 5 as the second law efficiency. This study indicated that the supercritical cycle being investigated by the project was approaching the practical performance limits (see Figure 5). While small gains in performance over the supercritical cycle are possible, significant improvements can not be achieved unless one revises the operating constraints for the equipment, i.e., allow smaller temperature differences in heat exchangers, or improve the efficiency of rotating equipment (turbine).

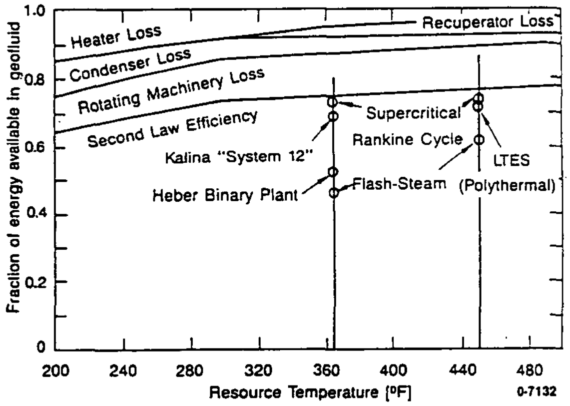

Figure 5. Advanced System Performance Relative to Practical Limits

SUPERSATURATED EXPANSIONS

The project interest in supersaturated turbine expansions developed during the analytical studies of binary cycles which utilize a working fluid, such as isobutane, which becomes drier (more superheated) on expansion^{5}. These working fluids have a considerable amount of superheat when they exhaust from the turbine. This superheat adds to the amount of heat rejected in the condenser (resulting in larger heat exchangers), as well as increasing the irreversibility in the condensing process (decreasing cycle efficiency). In binary cycles where these working fluid are vaporized at subcritical pressures (boiling cycles), it is necessary to completely boil the working fluid to assure liquid does not enter the turbine. These cycles, therefore, inherently have significant amounts of superheat in the turbine exhaust. During the analytical studies of the supercritical cycles, it was noted that the working fluid vapor could expanded isentropically from a supercritical pressure, passing through the two phase region, and exit as a slightly superheated vapor. This "supersaturated" expansion (point 3' to point 5) is shown schematically in Figure 6, along with a "dry" expansion (point 3 to point 4). Because the vaporization is done at supercritical pressures, there is not the concern relative to liquid entrainment in the vapor entering the turbine that one would have with a boiling cycle. This supersaturated expansion process was evaluated, and it was concluded that condensation droplets would not form (for the expansions of interest) as the working fluid was expanded through the two phase region. If drops did form they would remain small, or possibly evaporate, thus one would not expect turbine damage to occur. If it is possible to operate a cycle at these conditions, an additional 8% to 10% improvement in performance was projected.

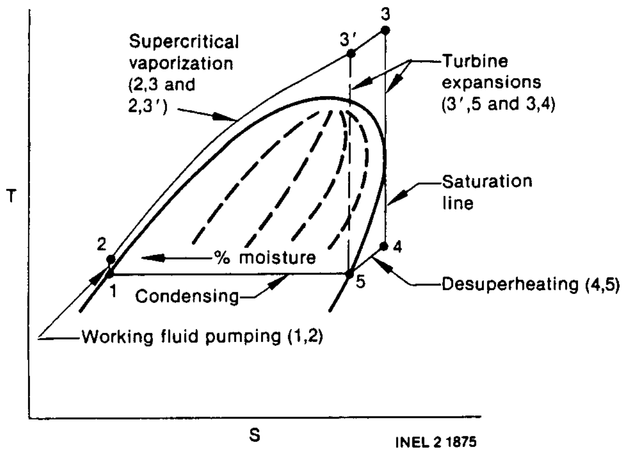

Figure 6. Binary Cycles Showing Two Types of Turbine Expansions

Based on these studies, an investigative program is in underway to study these types of expansions. The initial focus of this effort will be to investigate the condensation behavior of these expansions. These investigations will be carried out at the HCRF utilizing a laser detection system and a two-dimensional expansion nozzle which simulates the turbine expansions of interest. This laser detection system (developed for the project by North Carolina A&T) will detect the scattering of a laser beam passed axially through the nozzle, by any condensation droplet present. In the laboratory it was possible to detect particles as small as 10 angstroms with this detection system (as a point of comparison, a single isobutane molecule has a size a little over 5 angstroms). The expansion nozzle has a glass window with photomultiplier tubes, which detect the light scattering, located along the length of the nozzle. The nozzle will be utilized in a loop by-passing the turbine at the HCRF. Nozzle inlet working fluid conditions will be varied to simulate the range of expansions of interest, ranging from completely "dry" expansions, to those where one would expect condensate to form. By identifying those turbine inlet conditions which promote condensation during expansion, it will be possible to determine how far into the two phase region these supersaturated expansions can proceed without formation of droplets large enough to damage the turbine internals.

In conjunction with the testing of the nozzle, a reaction turbine will be installed at the HCRF. After utilizing the nozzle and laser detection system to "map" the turbine inlet conditions which result in condensate formation, this turbine will be used to investigate the impact of the supersaturated expansions on turbine performance. One manufacturer indicates that a reaction turbine can be operated "wet" without damage and have high efficiencies. Both of these topics will be elements of investigations at the HCRF with this turbine. The impact of the supersaturated expansions on the turbine efficiency will be examined, along with the impact, if any, of mixtures on performance. Prior to concluding these investigations, it is anticipated that the turbine will be operated with supersaturated expansions for an extended period. This test will specifically address whether there is any adverse affect with time on performance, or the turbine internals with these types of expansions.

ADVANCED HEAT REJECTION

Geothermal resources in the United States are predominately found in the western states in locations where the lack of an adequate source of make-up water for heat rejection may be a barrier to the development and utilization of a resource. If binary cycle technology is utilized, this lack of make-up water may force the use of a "dry" heat rejection system, as opposed to the preferred conventional "wet" cooling system. In a "dry" heat rejection system, the heat is transferred to air in a sensible heat exchange process. In a "wet" heat rejection system, the heat is transferred primarily in a latent heat exchange process where a portion of the circulating cooling water is evaporated in the cooling tower, or on the tubes of an evaporative condenser. The "wet" systems are preferred because the "dry" systems produce higher condensing temperatures (on an annual basis) resulting in lower turbine power outputs. However because water is evaporated in the "wet" system during the heat rejection process, there is a consumptive use of the cooling water, thus the requirement for make-up water.

If make-up water is not available, a power plant developer's options are limited. These options may include flashing a portion of the brine and utilize the steam condensate for make-up, utilizing a "dry" heat rejection system, or utilizing a flash-steam power plant. In a flash-steam cycle, the steam condensate provides an inherent source of make-up water to the heat rejection system. Although there is little, if any, need for make-up water to a flash-steam plant, the use of the condensate as make-up represents a non-renewable or consumptive use of the geothermal resource; less fluid is being returned (by injection) to the reservoir, and the salinity of the fluid returned is increased as a result of the flashing process. Although the authors are not aware of a serious degradation of a resource where a flash-steam plant is currently being utilized, it is not improbable that with time, the resource may degrade in a manner similar to that experienced at the Geysers.

In instances where make-up water is available, but the quantities are limited, the developer has additional options. Simply increasing the efficiency of the power cycle will reduce the cooling water make-up requirements. An earlier study[10] in the program indicated 20% to 30% reductions in make-up water requirements (relative to the Heber-type binary plant) were possible by utilizing the supercritical cycle concepts currently under investigation. These reductions are achieved because of the 20% to 30% improvement in performance. This technology represents a viable option for developments where the availability of make-up water is marginal or slightly submarginal. In instances where the make-up water reductions achieved by improving cycle efficiencies are not adequate, combination wet and dry heat rejection systems may be feasible.

The Heat Cycle Research project has initiated the scoping studies to identify potential schemes for rejecting heat when the consumptive use of water in heat rejection (for binary cycles) is not possible. The initial study will examine the impact of utilizing the "dry" heat rejections systems with the supercritical cycles currently under investigation. For these studies, a flash-steam power cycle will be utilized as the reference for performance. Over the next two to three years, this project effort will be expanded to consider other innovative schemes for addressing the consumptive use of water in conventional "wet" heat rejection systems. The intent of these investigations will be to define methods of reducing or eliminating the make-up water requirement with the minimal impact on the cycle performance. Although the focus of the investigations is anticipated to be on binary cycles, flash-steam systems and possibly existing facilities, will also be considered if a need for investigation in these areas is identified.

SUMMARY

The following summarize the present status of the Heat Cycle Research project:

- The investigations to date have shown that the proposed concepts that substantially increase the performance of binary cycles are thermodynamically possible. The assumptions required for the projected performance gains, have been validated with field investigations.
- The field investigations have revealed deficiencies in the available design technology which continue to be addressed. The continuing effort on the development of the technology base will address the design of a condenser for non-vertical (user-preferred) orientations. With the completion of this work, it is anticipated that the technology will be available to realize the projected 20% performance gains.
- The verification of assumptions made relative to the 8% to 10% performance improvements possible with supersaturated turbine expansions is in progress. These field investigations will determine whether the conditions promoting condensate formation are in present in the expansions of interest, and whether these expansions adversely affect the performance of the turbine.
- There is a practical limit to the performance of the binary power cycles, imposed by operating constraints of the cycle components. The performances of the supercritical cycles being studied in the project are approaching this practical limit, as are the performance of other advanced binary power cycles.
- Significant reductions in make-up water requirements can be achieved with binary cycles, by increasing the performance of the cycles. Those cycles currently under investigations could have make-up water requirements 20% to 30% lower than the referenced binary facility.

The future project efforts will focus on the issue of improving heat rejection systems, particularly with regard to their consumptive use of water. Innovative schemes with the potential to reduce cooling water make-up or allow lower quality cooling waters to be used, will be examined and investigated.

As the development of the technology base to utilize the supercritical cycles under investigation nears completion, increased emphasis will be placed on industry's assimilation of this technology. This effort to transfer this technology to industrial users will be the major project emphasis prior to the anticipated project termination in the mid-1990's. The definition as to how this transfer will occur is a planned project activity for the next two years.

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Models of Geothermal Brine Chemistry for Optimizing Resource Performance

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ABSTRACT

The DOE brine modeling program is providing a computer model for predicting the chemical behavior of geothermal fluids during production, energy extraction and reinjection. Chemical processes, such as scale formation in wells and plant equipment have been shown to cause expensive downtime for equipment and well cleanup. The model we are developing can be used to predict the severity of these problems as a function of operating conditions and reservoir properties. It can also be used to cost effectively examine methods of abatement as well as in exploration and resource assessment. We are continuing to generalize and improve the accuracy of the model. However, a version which treats many important problems is presently available to geothermal operators and engineers. A Macintosh version has been developed and is being tested.

The present model can predict the solubility of various scale forming minerals (e.g., carbonates and amorphous silica) under formation and operating conditions in a temperature range from 0°-250°C and as a function of CO_2 pressure. This model has been successfully tested against laboratory and field measurements. The results agree well with data. Scale predictions are consistent with operating experience. Progress has also been made to model the H_2S-H_2O system over a range of pressures. Because of data limitations, this model cannot be extended beyond 100°C.

Recent work has focused on modeling the behavior of mixtures in the $H_2O-CH_4-CO_2$ system. Gas phases in this system are often present in geothermal reservoirs, and gas partial pressures or fugacities of the components can control the precipitation of scales (e.g. CO_2 in the carbonate system). Multiple phase behavior in this system is important to the analysis of fluid inclusions, which provide sensitive probes of the thermal history of geothermal formations and other reservoir properties.

In order to model this ternary system, an equation of state (EOS) has been developed which can describe the pressure, volume, and temperature properties of the pure end members within experimental accuracy for a range of pressure from 0-8000 bar and a range of temperature from 0°-1000°C. This EOS is unique in its ability to describe both gas phase and liquid phase properties with accuracy. At high temperatures and low pressures we have shown that mixing is very nearly ideal. However, at the lower temperatures at which multiple phases may be present nonideal behavior becomes very important. In order to model these mixtures a mixing rule has been developed based on the end member EOS. Unfortunately, there are very little PVT data in the appropriate region for evaluating model parameters. Therefore, we used two phase equilibrium data. With these data we have developed a highly accurate thermodynamic model. This model is unique in its ability to pass continuously from the single phase region to the two phase region. This modeling capability is essential for analyzing phase equilibria in fluid inclusions. The model is complete from a parameterization point of view, but additional work must still be done to incorporate it into our general equilibrium codes.

INTRODUCTION

Chemical problems can have a significant impact on the efficient operation of a geothermal resource. Problems can range from the rather common occurrence of mineral scale in well bores and operating equipment to the destruction of plant equipment and heat exchangers due to contact with corrosive brines. There are also chemical problems which must be considered in the assessment and projection of geothermal resource performance. It is imperative that development and operational problems be forecast before large sums are invested. Furthermore, it is desirable to be able to evaluate the origin, energy density, and extent of the resource in order to assess the behavior of the reservoir during operation. To evaluate and solve the chemical problems associated with the exploitation of geothermal energy resources requires a good understanding of the chemistry of the geothermal fluids and gases and their interaction with formation minerals. In order to facilitate such chemical analysis the DOE has provided funds for the development of a computer model of geothermal brine chemistry. This model will be highly correlated with laboratory and field data. It will serve the geothermal community by providing a rapid, accurate and cost effective way to analyze chemical problems.

Table 1. CAPABILITIES OF PRESENT MODELS

- Predicts solubility of $CaCO_3$ (calcite) scale for the temperature range of 0 to 250 °C in NaCl solutions.
- Predicts solubility of CO_2 in NaCl brines for T=0 to 250 °C.
- Predicts solubility of amorphous silica in seawater brines for T=0 to 250 °C.
- Predicts solubility of methane in seawater brines for T= 0 to 250 ° and P = 0 to 1600 bar.
- Calculates dissolution-solution characteristics of rock-water systems containing Na, K, Ca, Cl and SO_4 from 0 to 250°C.
- Predicts solubility of hydrogen sulfide in H_2S-HS^- $-H_2O-NaCl$ system (preliminary).
- Predicts partial fugacity in mixed system $CO_2-H_2O-CH_4$.
- Predicts gas-liquid equilibrium and PVT properties in the CH_4 $-CO_2-H_2O$ system from 0 to 1000 °C and 0 to 3500 bar.

A computer program is currently available which can be used to analyze many of the chemical problems encountered in geothermal operations. A summary of its capabilities is given in Table 1. The model is based on recently developed phenomenological descriptions of the thermodynamics of condensed and gaseous phases. Extensive efforts have been made to insure that the predictions of the model agree with laboratory data. The model has been used to predict the behavior of oil and geothermal wells with remarkable success. Recently the documentation for the model has been improved. There is now a document facilitating the use of the model, including sample input files and a series of tutorial problems designed to introduce the potential user to its capabilities. A version for the Macintosh computer has been developed and is ready for testing.

The model has application to many industries other than geothermal. Problems in the oil industry are similar in many ways to those encountered in geothermal energy production. Therefore the model or other implementations of the parameterization that we have developed are used in this industry. The nuclear waste industry has incorporated our model as their standard for the treatment of concentrated brines. Mineral industry researchers also need an efficient way to analyze their production processes. The model has recently been tested for use in the potash mining industry. These investigators have found that the DOE model is the only available code that predicts mineral solubilities within experimental accuracy. Model technology transfer is also now taking place for coal desulfurization processes.

A MODEL OF THE CH_4–CO_2–H_2O SYSTEM

Recently, a great deal of our effort has focused on the last entry of Table 1. Improved models of gas phase thermodynamics are necessary to predict the solubility of gases in geothermal fluids. These gases can control the solubility of important scaling minerals, such as in the CO_2 partial pressure control of the solubility of calcite. Dissolved gasses may also be one of the sources of energy in produced fluid, as is the case for the gulf coast geopressured systems. For these systems gas phase models are necessary to predict the solubility of energy rich gases, such as CH_4, in the production phase (see below).

An application of models which can treat both liquid and gas phases has recently become very important. Fluid inclusion studies are providing new highly informative data for the interpretation of the thermal history and origin of geothermal reservoirs. These studies rely on the microscopic observation of small fluid-filled cavities in the formation rocks. The fluid in these cavities presumably represents the brine from which the minerals were formed. Interpretations of the origin, thermal history, *etc.* of the resource may therefore be derived from their analysis. Unfortunately, these inclusions are so small that it is not possible to extract the fluids and directly measure their compositions. However, it is possible to measure phase equilibria in the trapped fluids by observation of the inclusion under the microscope during heating and cooling cycles. If there is sufficient information relating the observed transition temperatures to fluid compositions, the concentrations of the fluid in the inclusion can be inferred. Such studies can be greatly facilitated by the model we have developed because it can predict gas-liquid phase transition temperatures and pressures as a function of composition with near experimental accuracy.

Our model is based on the mixing of the highly accurate equations of state (EOS) of the pure endmembers, CH_4, CO_2 and H_2O, that we reported at the DOE Geothermal Program Review VIII. We first develop equations accurately predicting the PVT (pressure, volume and temperature) properties of the endmembers. These equations, which are the same form for each endmember, are the basis for the mixture EOS. The mixed EOS is formed by finding a smooth interpolation of the parameters in the EOS of one of the endmembers to the like parameters in the EOS of the other endmembers as a function of composition. The interpolation equations (one for each binary) have parameters which are evaluated from data in the mixed systems.

The EOS we have developed is discussed in detail in a publication in preparation. It has the form:

$$Z = \frac{PV}{RT} = \frac{P_r V_r}{T_r} = 1 + \frac{A_1}{V_r} + \frac{A_2}{V_r^2} + \frac{A_3}{V_r^4} + \frac{A_4}{V_r^5} +$$

$$\frac{\alpha}{T_r^3 V_r^2}(\beta + \frac{\gamma}{V_r^{2)}} \exp(-\frac{\gamma}{V_r^2} \quad , \tag{1}$$

where

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

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

$$V_r = \frac{P_c V}{RT_c} \tag{4}$$

and

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

In this equation P and T are taken to be the independent variables and V is the dependent variable. P_c and T_c are the critical temperatures and pressures for the endmembers. All the other symbols represent parameters to be evaluated from experimental data. Given P and T, V_r is calculated by solving the nonlinear equations. Eq's. (1)-(5) can predict the PVT properties of the endmember systems with near experimental accuracy in both the liquid and gaseous phases of the system.

The mixing equations giving the parameters for this equation as a function of composition in the ternary are given by the expressions:

$$T_{pc} = \sum_i^n x_i T_{ci} - \sum_i^n \sum_{j \neq i}^n k_{ij}^T (\sum_i^n x_i T_{ci}/T) x_i x_j \sqrt{T_{ci} T_{cj}}, \tag{6a}$$

$$P_{pc} = \sum_i^n x_i P_{ci} - \sum_i^n \sum_{j \neq i}^n k_{ij}^P (\sum_i^n x_i T_{ci}/T) x_i x_j \sqrt{P_{ci} P_{cj}}, \tag{6b}$$

$$V_r^M = \frac{P_{pc} V}{RT_{pc}}, \tag{6c}$$

$$a_{ij}^M = \sum_{k=1}^n x_i a_{ijk} \quad , \tag{6d}$$

where n is the number of species in the system of interest. k_{ij}^T and k_{ij}^P are functions of temperature and pressure and have the following form:

$$k_{ij} = b_1 + b_2 T + b_3 T^2 + b_4/T + b_5 P + b_6 TP + b_7 P \ln T$$

$$+ b_8 P^2 + b_9 T/P + + b_{10} T \ln P + b_{11} T^2 \ln P \quad . \tag{7}$$

All the parameters in these expressions have been evaluated from experimental data and will be reported in detail in a future publication. In order to accurately describe phase coexistence it was necessary to include gas liquid coexistence measurements in the data set. The resulting EOS is unique in its ability to describe both the available PVT data and two phase equilibria for very large ranges of pressure and temperature. In the following sections we describe some of the applications of the model.

SOLUBILITY OF CH_4 IN NACL SOLUTIONS

The first application we discuss is the calculation of the solubility of CH_4 in brines of high ionic strength. This is a straight forward application of the CH_4 endmember EOS. The solubility is determined by the usual chemical potential balance equation:

$$\mu^{l}_{CH_4}=\mu^{v}_{CH_4} \quad , \qquad (8)$$

where $\mu^{l}_{CH_4}$ is the chemical potential of CH_4 in the liquid phase and $\mu^{v}_{CH_4}$ is the chemical potential in the vapor. The gas phase chemical potential can be calculated from the EOS. In order to proceed it is necessary to provide a model for μ_{CH_4} in the liquid phase. The model we have used is based on the methods we have developed for other aqueous solution species (Moller 1989). The liquid phase chemical potential is a function of the composition of the brine and the temperature and pressure. Examples of model predictions of solubilities vs. pressure for various brines are compared with experimental data in Fig's. (1) and (2). Agreement with the data is excellent.

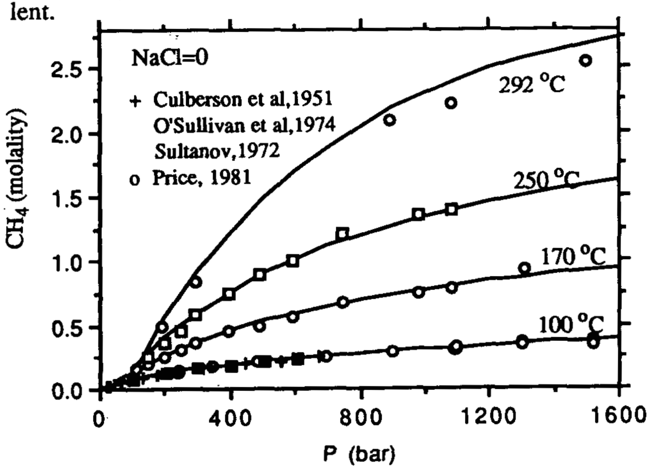

Fig.1 Model prediction of methane solubility in water

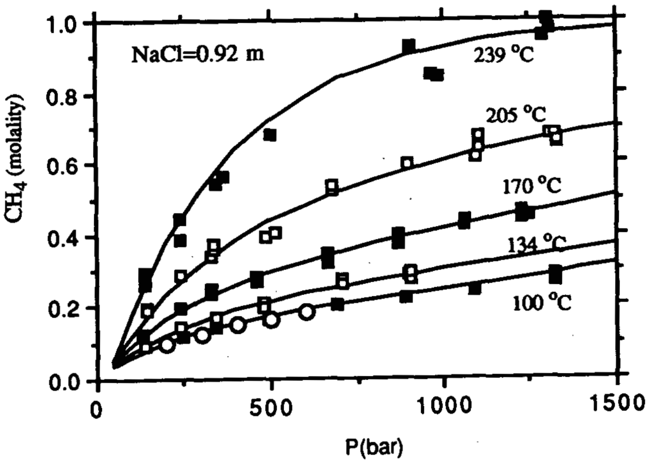

Fig. 2 Model prediction of methane solubility in NaCl Solutions. Data of Blount et al (1979) and O'Sullivan et al (1970).

Table 2. Solubility of CH_4 in Salton Sea Geothermal Brine

Comparison of the model prediction with measurements

T(°C)	P(bar)	ln(f/m)	
		model prediction	measurements(Cramer)
60.2	11.4	7.931	7.908
88.1	11.6	8.001	7.929
121.7	13.2	7.8521	7.860
166.8	34.1	7.643	7.829

The model may be used to predict solubilities in brines of arbitrary composition. An example of the prediction of methane solubility in Salton Sea brines is given together with experimental data in Table 2. The composition of the brine is given in Table 3. We note that the results agree with experimental data within a few percent. Note that there are no adjustable parameters in these calculations. These results will be presented in more detail in a future publication (Duan, Moller and Weare, submitted for publication, Geochim. Cosmochim. Acta).

Table 3. Composition (in molality) of Seawater and Salton Sea Geothermal Brine

Constituents	Seawater (Holland)	SSGB (Cramer)
Na+	0.4850	2.4414
K+	0.0106	0.44716
Li+	0.0026	0.032
Cs+	<0.0001	0.0002
Rb+	0.0014	0.0009
Ca++	0.0106	0.7610
Sr++	0.0001	0.0053
Fe++	<0.0001	0.0378
Mg++	0.0551	0.0004
Mn++	<0.0001	0.0265
Cl-	0.5651	4.64397
SO4--	0.0292	0.0010
HCO3-	0.0018	0.
CO3--	0.0005	0.

SOLUBILITY OF CH_4-CO_2 MIXTURES IN WATER

In most problems encountered in energy production the gas phase is a mixture of at least two species, CH_4 and CO_2. At higher temperatures H_2O vapor may play a significant role. As we have mentioned, we have developed a model of the complete ternary system, CH_4 - CO_2 - H_2O. This model has the unique capability of describing both single phase PVT behavior and multiple phase equilibria. It, therefore, can be used to predict the solubility of CH_4 and CO_2 in the aqueous phase when the temperature of the mixture is below the critical temperature and the pressure is high enough to cause condensation.

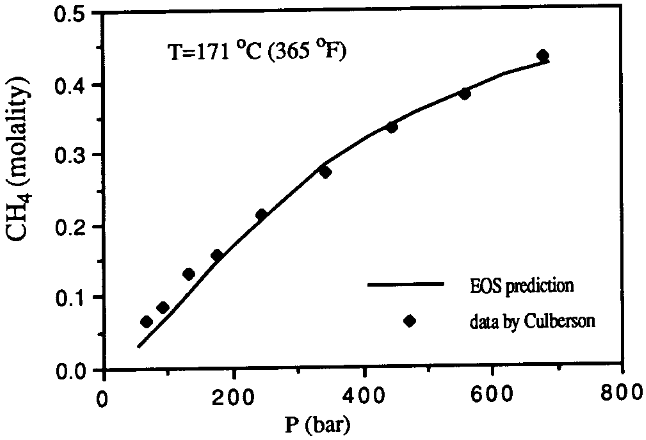

Fig. 3 EOS prediction of CH_4 solubility in water

The solubility for the binaries, CH_4–H_2O and CO_2–H_2O, were part of the solvus data used to define the parameters in the mixing equation for temperatures below the critical point of water. The agreement between the model predictions and the data for these systems is given in Fig's. (3) and (4). The agreement for binary compositions is excellent. The interpolation into the center of the ternary is speculative, since there are very little data in this composition range and none were used in the developing the model. However, it is probable that the primary interactions in the mixture are binary and well described by our mixing model. An example of the prediction of solubilities in the ternary is given in Fig. (5). The model predicts that for temperatures and pressures typical of geopressured systems the composition of the gas phase has an appreciable effect on the solubility of gases. This effect is in addition to the decrease in partial pressure (P_T times mole fraction) just due to the percent removal of one of the species in the gas phase (straight line Fig.(5)). It is important to note when estimating the energy content of geopressured fluids that the presence of CO_2 in the gas phase greatly reduces the concentration of methane dissolved in the brine.

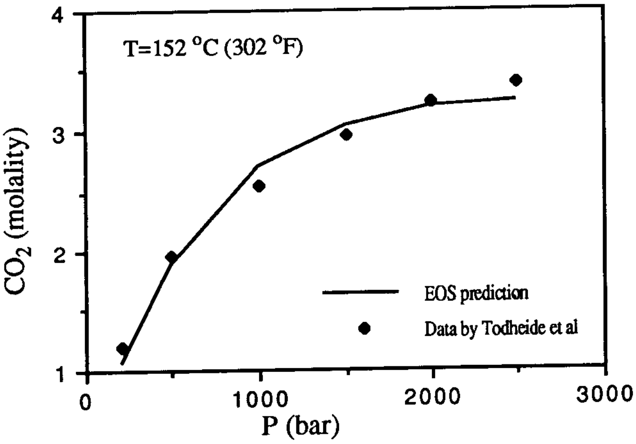

Fig. 4 EOS prediction of CO_2 solubility in water

Unfortunately, there are very little data to confirm these predictions. Sometime ago, under DOE funding, Price *et al.* (1981) carried out a series of measurements of the solubility of methane- carbon dioxide mixtures in NaCl brines. Our predictions at this point can only be made for pure water systems. However, the major effect of NaCl in the brine (as in Price's experiments) is to uniformly decrease methane solubility for all compositions. Scaling Price's solubility measurements allows us to plot his data in Fig. (5). The results are in remarkably good agreement with our model predictions.

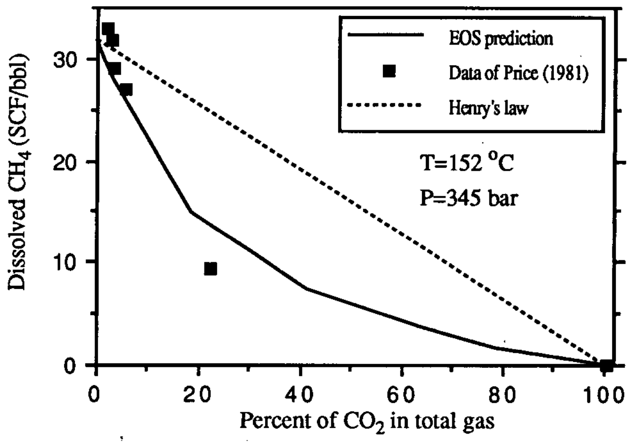

Fig. 5 The CH_4 solubility in water as a function of gas composition

APPLICATION TO FLUID INCLUSIONS

As we mentioned, one of the primary reasons for selecting the EOS given by Eq.(1) is its ability to describe the thermodynamics of both the liquid and the gas phase. In the fluid inclusion application this is an essential feature. Consider the measurements of Ramboz (1985) of the compositions of inclusions in granitic rocks. Taking a sample with composition $X_{H_2O} = 67.7\%$ and $X_{CO_2} = 31.1\%$, he reports a homogenization temperature of 320°C. Using the model we can predict a molar volume of 80.4 cm^3/mole and a trapping pressure of 340 bar. From other evidence Ramboz believes that the minerals were formed at a somewhat higher temperature of 550°C. Using the model we can predict a trapping pressure of 750 bars for this molar volume and higher temperature for the formation process. This example illustrates the kind of information that can be obtained from fluid inclusion studies.

IMPROVEMENTS IN THE SCALING MODEL

In the previous meeting we reported that our model of the solubility of the important scaling mineral, calcite, gave unexpectedly high predictions in some Gulf Coast brines. We noted that this was because of the unusually high concentration of calcium in these brines and that the model was not well determined in such composition regions. Calcium parameters of the prior model were established primarily from measurements either in pure systems or from measurements in NaCl brines. We have discussed in other places (Moller 1988, Weare 1987) the problems that may be created with such a parameterization. During this period we reinvestigated the data situation. Some Russian measurements of solubility in $CaCl_2$ brines at 150°C and 225 °C (Mallinin 1963) were found. This data set is not complete but with other data from the DOE measurement program, we have enough information

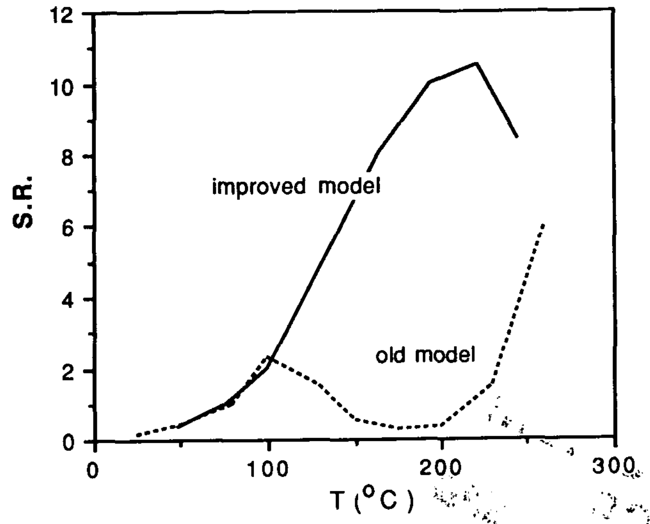

Fig. 6 Calcite saturation ratio as a function of temperature in Wills Hulin Well No.1.

to define the model in the high calcium region. The solubility predictions (Fig. (6)) of the improved model are more consistent with the retrograde behavior of calcite noted in other composition regions.

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LOW TEMPERATURE UTILIZATION AND ASSESSMENT

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

PROGRESS IN LOW TEMPERATURE UTILIZATION AND ASSESSMENT

Ken Taylor
U.S. Department of Energy - Idaho Operations Office

Low temperature (less than 250 degrees Fahrenheit) geothermal resources occur with a large frequency in the United States. The Geothermal Program has tasks taking place to better define the location of low temperature resources and determine efficient uses for them. Presently, a new activity to combine these efforts is getting underway. These projects were all discussed during this session.

Howard Ross, University of Utah Research Institute, presented many of the accomplishments that resulted in the State Team Program. This program is intended to better define geothermal resources in various western states. A number of grants awarded by the Department of Energy to various states and universities have projects in the final stages of completion.

Paul Lienau, Oregon Institute of Technology (OIT), discussed the work taking place at OIT's GeoHeat Center. This work is centered around developing and assisting in efficient uses of low temperature geothermal resources. The GeoHeat Center provides assistance to direct use developers at no cost. They also perform various R&D including work on Heat Pumps.

Finally, P. Michael Wright, University of Utah Research Institute, discussed the future low temperature activities. These activities will be performed by the University of Utah Research Institute, Oregon Institute of Technology, and the Idaho Water Resources Institute. The information developed in the State Team Program will be consolidated, and utilization schemes will be developed to include the further development of Geothermal Heat Pumps. Installation of Heat Pumps allow utilities to reduce demand and ultimately avoid building new power plants.

A large number of accomplishments from these tasks have resulted in very successful direct use projects. With continued success, it appears that many more low temperature geothermal resources will be developed.

DOE/GD STATE COOPERATIVE PROGRAM, 1988-91: RESULTS

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ABSTRACT

The Department of Energy/Geothermal Division issued a Program Research and Development Announcement (PRDA) for State Geothermal Research and Development in April 1987. Twelve grants were awarded for cost-shared state-oriented research and development on geothermal energy topics not currently being addressed by private industry, but which had the potential for results applicable by industry in the development of geothermal resources. Eight grants have been completed and three others are nearing completion. Several outstanding results have been achieved by the state research teams, including such varied topics as the genesis of Great Basin geothermal fluids; a detailed characterization of a hidden Basin-and-Range resource and recognition of its binary power potential; the discovery of a geothermal system with binary power production potential in the southern Rio Grande rift; and substantial progress on the chemical treatment of high silica geothermal brines. The results summarized here indicate the program was highly productive.

INTRODUCTION

The State Cooperative Reservoir Analysis Program (SCP) was established by DOE in 1977, as the State Coupled Program to assess low-and moderate-temperature geothermal resources in the U. S. The early efforts of the SCP were national in scope. Geoscientific investigations were made in all states, with the more intensive activity focusing on states with either known geothermal resources or a large user potential. These studies provided extensive input to the USGS assessment of low-temperature geothermal resources (Reed, 1982), and demonstrated that most moderate-and high-temperature geothermal resources are found in the western portion of the country. These and subsequent studies have led to the publication and distribution of a series of state geothermal resource maps. More recent work has expanded upon earlier resource assessment activities and included detailed reservoir analysis and generic studies.

Research activities within the SCP are carried out by a state agency or group given the responsibility for geothermal resource evaluation within that particular state. Past participants have included state geologic surveys, water resource departments, and university geoscience departments within the western United States. SCP programs are managed by the Geothermal Division and are implemented by the Idaho Operations Office. UURI provides technical and administrative support to DOE/HQ and DOE/ID, and technical geoscience support to various state teams.

Congressional Funding

The U. S. Congress provided funding for Fiscal Year 1987 in the amount of $2,000,000 to continue an effort in hydrothermal industrialization. These monies would include funding to assist those states with significant hydrothermal resources to continue programs relating to resource assessment, development or technical assistance and related activities. Funding of the state teams was implemented through a Program Research and Development Announcement (PRDA) issued by the DOE Idaho Operations Office.

FY87 STATE GEOTHERMAL R&D PRDA

A PRDA for State Geothermal Research and Development was issued by the Department of Energy Idaho Operations Office on April 1, 1987. The PRDA called for proposals from state agencies which desired to cost-share on state-oriented research and development on those aspects of geothermal energy that were not being studied by private industry, but which had the potential for results that will be applicable by industry in the development of geothermal resources. The solicitation noted that approximately $1,200,000 was available for this program of cost-shared research, and that the maximum DOE cost-share would not exceed $200,000. Awards would be made to a state agency or state-designated agency, and that agency must cost-share a minimum of 10 percent of the gross amount proposed. The PRDA sought geographic and resource diversity for research in resource assessment, resource development, and technical assistance and related activities on hydrothermal systems. The closing date for proposals was June 19, 1987.

Proposal Response and Awards

DOE received 23 proposals from 21 organizations. It was possible to fund 11 Grants and one Cooperative Agreement (Idaho-Dept. of Water Rights) at amounts varying from $45,511 to $194,814, for a program total of $1,317,051. The original project periods varied in duration from 12 to 24 months. One additional grant was cost shared with industry which supported deep scientific drilling in the Oregon Cascades as a joint DOE-state-industry project. Because this project is not reported elsewhere, and has similarities with the State Cooperative Program research, it will be discussed with the SCP grants.

RESEARCH SUMMARY

Table 1 lists the project participants, Principal Investigators, abbreviated research titles, and research categories for the grants. Several Principal Investigators left the program and were replaced by other scientists who concluded the studies. Those leaving the program include: Dr. Donald Turner (U AK-GI), Ms. Leah Street (ID-DWR) and Dr. Larry Icerman (NMRDI). The replacement PI's are also listed in Table 1. The studies encompass a broad range of activities, including regional resource assessment, detailed reservoir evaluations, case studies, and generic activities. Figure 1 indicates participating state teams, and the locations of detailed and regional studies in map form.

All research was conducted on a part-time basis over a period of time, since all Principal Investigators had teaching, regulatory or other project assignments concurrent with their

Table 1 State Cooperative Research Program, 1988 - 1991

State Team	Principal Investigator (s)	Reserach Topic	Research Period Initial (mo)	Research Period Final (mo)
Univ. Alaska Geophysical Inst.	Donald Turner* Christopher Nye	Geothermal Resource Assessment in the Aleutian Islands and Alaska Peninsula	18	31
Alaska-DGGS	Roman Motyka	Geothermal Resource Assessment in the Aleutian Islands and Alaska Peninsula	24	38
Hawaii-DBEDT U. Hawaii	Donald Thomas	Silica Control and Recovery in Geothermal Fluids	24	36
Idaho-DWR	Leah Street* Paul Castelin	Geothermal Resource Analyses in Idaho	24	31
U. Nevada-DES	Tom Flynn	Geothermal Fluid Genesis in the Great Basin	12	26
U. Nevada-DRI	Elizabeth Jacobson	Evaluation and simulation of Moana Geothermal System	22	34
New Mexico-NMRDI - STDI	Larry Icerman* James Witcher Rudi Schoenmackers	Time-Integrated Radon Soil-Gas Surveys in the Southern Rio Grande Rift	18	27
U. North Dakota	William Gosnold	Stratabound Geothermal Resources in North Dakota and South Dakota	24	36
Oregon-DOGAMI	George Priest	Investigation of the Thermal Regime of the High Cascades, Oregon	40	40
Utah-UGMS	Robert Blackett	Geothermal Resource Assessment of Newcastle Utah	14	22
Washington-DNR	Michael Korosec	Definition and Delineation of the Southern Washington Cascade Range Heat Flow Anomly	12	21
Washington-WSEO	Gordon Bloomquist	Modify, Field Test and Verify the GEODIM Computer Program	18	36
U. Wyoming-DGG	Henry Heasler	Improved Computational Schemes for the Calculation of Subsurface Termperatures	12	33

• *Former Principal Investigator; left organization and did not complete the study.*

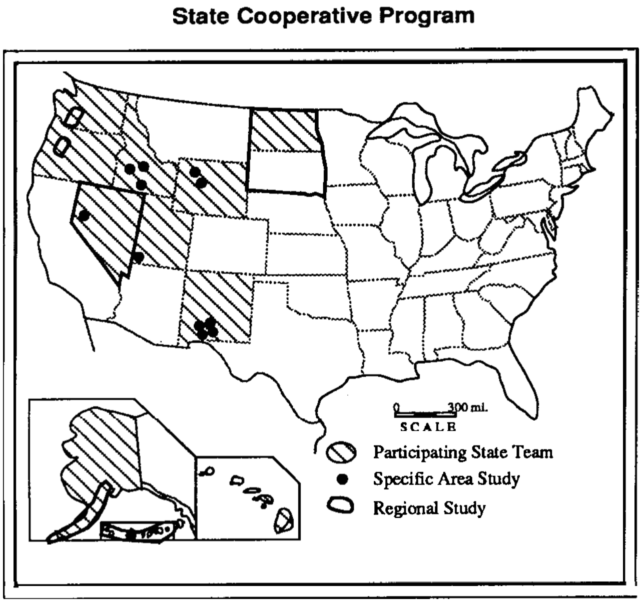

Figure 1. State Cooperative Program: Participants and study areas.

geothermal research. These and other factors led to a variety of conflicts and project delays, and the projects and reporting invariably required more time than even conservative initial estimates. Each project required one or more no cost time extensions (NCTE). The project time schedules are indicated in Table 1.

Initial cost shares ranged from as low as 10 percent to as high as 44 percent. In some grants the DOE funded only direct project costs such as drilling or analytical work, and all salary costs were borne by the state team. With such substantial grant extensions it is clear that all state team cost shares were actually much higher. The research activities reported here represent more than a $2,500,000 research effort.

RESEARCH RESULTS

Many of the SCP research projects are worthy of presentation as a single paper in these Proceedings. The objective of this paper is to present an overview of the program and program results so the industry may be aware of the results completed. A brief summary of each research effort and principal results follows.

State Team Projects

The University of Alaska, Geophysical Institute (U AK-GI), has completed a geological and geochemical study of the Geyser Bight geothermal resource, Umnak Island, under the direction of Principal Investigators Drs. Donald Turner and Christopher Nye. This study was completed in cooperation with the Alaska Division of Geological and Geophysical Surveys. Geyser Bight is located on a remote, uninhabited Aleutian Island, and is the hottest and most extensive area of thermal springs in Alaska. A previously unreported fumarole field, 4 km south of Geyser Bight valley, was discovered during the course of this study, and has been mapped and described in great detail. A zoned plutonic rock unit, dated at 9.5 Ma, is the probable reservoir rock, and volcanic rocks range in age from 75,000 to 534,000 years. Heat for the geothermal system is derived from the Mt. Rechesnoi volcanic system. The upper reservoir system is believed to contain about 5.4 x 10^{18} J of thermal energy, sufficient to produce up to 132 MW of electrical power for 30 years. The deeper reservoir may contain up to 7.3 x 10^{18} J of thermal energy, sufficient to provide 225 MW for 30 years (Nye et al, 1990).

The State of Alaska, Division of Geological and Geophysical Surveys (AK-DGGS), completed a fluid chemistry study of the Geyser Bight resource in conjunction with the U AK-GI geological study. Dr. Roman Motyka found that thermal spring water chemistry indicates spring waters are derived from two intermediate-level hydrothermal reservoirs with minimum temperatures of 165° and 200° C, and a probable deeper reservoir with a minimum temperature of 265° C. The thermal spring waters have low- to moderate- concentrations of Cl (650 ppm) and total dissolved solids (1760 ppm), but are rich in B (60 ppm) and As (6 ppm) compared to most other geothermal systems in Alaska. The $^3He/^4He$ ratio of 7.4 found in gases emanating from the thermal springs provides evidence for a magmatic influence on the hydrothermal system (Nye et al., 1990). In a second task, AK-DGGS is preparing a 1:1,000,000 scale technical geothermal energy resource map for the Aleutian Island-Alaska Peninsula region, and a compilation and evaluation of all available geochemical data on geothermal fluids for this region.

The State of Hawaii, Department of Business, Economic Development, & Tourism (HI-DBEDT) provides the state cost-share for a study by Dr. Donald Thomas, **University of Hawaii (U HI)** to study methods of controlling silica deposition from geothermal fluids of high-temperature, high-silica geothermal systems and to characterize the fluid chemistry. Dr. Thomas reports that mixing of 60% condensate and 40% brine, and treatment with weak acids, shows great promise in retarding silica precipitation. The high surface area of precipitated silica may have commercial value. The grant has been extended to allow additional time for acquiring geothermal fluids and for characterizing the precipitated silica. Retardation of silica precipitation during production and injection has major economic and environmental benefits for geothermal producers.

The State of Idaho, Department of Water Resources (ID-DWR) has completed a three-task study initiated by Leah Street. A geochemical study of the Big Wood River geothermal systems indicates the resources are dilute Na-HCO_3-SiO_2 type waters. Geothermometry indicates reservoir temperatures below 100° C except for Magic Hot Springs (108° C). A comparison of anion to cation ratios and the trace element concentrations of thermal springs to the rocks and minerals indicate a chemical affinity to the Cretaceous and Tertiary intrusions, and not the Paleozoic sedimentary rocks. These intrusions are thought to be the source of the high fluoride and arsenic concentrations found in the thermal waters (Street, 1990).

A second study completed by Paul Castelin (new Principal Investigator) and Steven Baker extends the hydrologic and geologic analyses of the Banbury-Twin Falls reservoirs and presents a simplified, unifying conceptual model of the Twin Falls County geothermal systems (Figure 2). Although significant declines have been observed in the potentiometric surface in areas where development of the thermal resource is most concentrated, it appears that current withdrawals from the system do not exceed the amount of recharge entering it (Castelin and Baker, 1990). Continued monitoring and management of the resource will nonetheless be required.

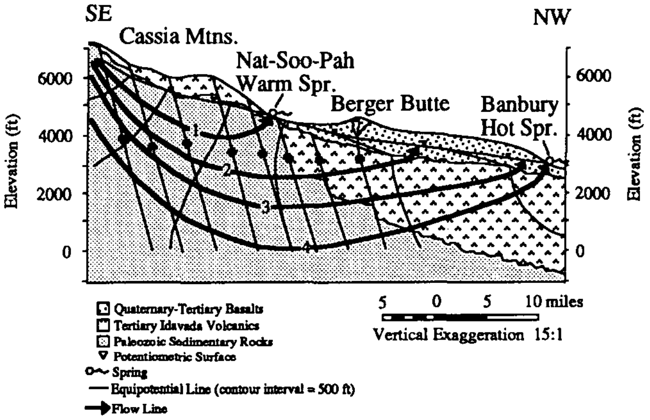

Figure 2. Conceptual hydrogeologic profile of Twin Falls County geothermal systems (after Baker and Castelin, 1990).

In a third ID-DWR study, **The Berkeley Group, Inc. (BGI)** was awarded a subcontract to complete a detailed review of all existing data on the Boise geothermal aquifer. BGI used the most reliable data to constrain a numerical model simulation of present and future reservoir behavior under various development scenarios. BGI concluded that well interference occurs between major production wells and affects water levels along the fault zone in general. Increased production since 1983 has resulted in water level declines along the Boise Front Geothermal Aquifer, and this decline should establish a new equilibrium level below current production depths for some historic wells now producing from the fault zone (BGI, 1990).

The Division of Earth Sciences, University of Nevada-Las Vegas (NV-DES) has completed an integrated study of the genesis of geothermal fluids of the Great Basin. Tom Flynn, Principal Investigator, and Paul Buchanan employed fluid chemistry, stable light isotopes, radioactive isotopes, and paleoclimatology data bases to develop a new conceptual model of geothermal recharge which applies to many Basin and Range geothermal resources (Figure 3). They conclude that geothermal fluids currently being produced are of Pleistocene origin. Rising Pleistocene lake levels such as in Lake Lahontan, Lake Bonneville, and Lake Russell contributed isotopically distinct waters to the groundwater system via porous alluvial fans which mixed with range runoff and migrated downward through the basin and range fault zones beneath the alluvial fans. In eastern Nevada where the Pleistocene lakes were not as large, widespread, or deep, the bulk of the recharge was supplied by runoff from the adjacent mountains directly to the fault conduits. The thermal characteristics of the systems are a complex function of depth of penetration of principal fault zones and proximity of recent volcanic activity (Flynn and Buchanan, 1990).

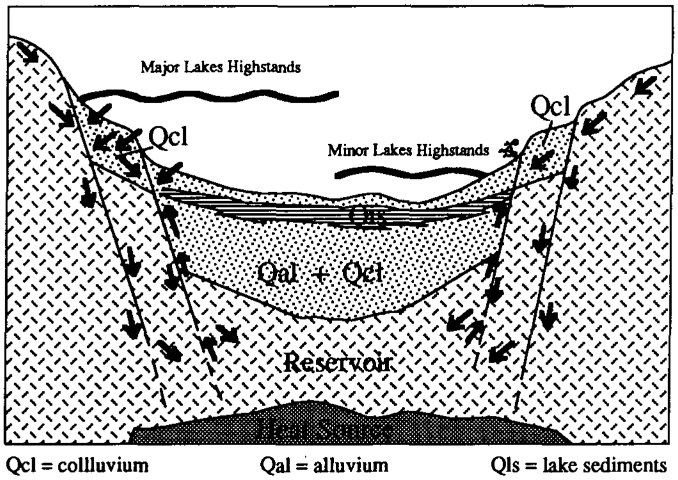

Figure 3. New conceptual model of recharge for Great Basin geothermal systems (after Flynn and Buchanan, 1990).

The Desert Research Institute, University of Nevada System (NV-DRI) completed a 13 month hydrologic monitoring program and geologic study of the Moana geothermal system. The Moana system has undergone rapid, uncoordinated development, and substantial water level drawdowns have been observed in the central production area. An attempt to produce a definitive numerical model for the Moana reservoir to assist developers and regulators proved unsuccessful due to the complexity of the system and the lack of reservoir test data. Accurate temperature data was available for only a few of the 26 monitor wells, due to the well construction, hardware, and well thermal loads. A technique was developed in the course of this study which uses temporal changes in chemical data at geothermal wells to indicate temperature changes at those locations. The extensive data base developed during this study indicates specific data needed to achieve the initial goal of a definitive numerical model of the system, and provides a reference base for future investigations (Jacobson and Johnston, 1991).

The New Mexico Research and Development Institute (NMRDI) provided the state cost-share for technical studies conducted by **Southwest Technology Development Institute (STDI)** at New Mexico State University with Jim Witcher and Rudi Schoenmackers as the

Principal Investigators. STDI has completed an evaluation of the time-integrated radon soil-gas survey method as an exploration technique for geothermal resources in the southern Rio Grande Rift. A method was developed which determines field measurement deviation from an ideal model based upon pure diffusion to enhance the value of survey results. The effects of deep-seated radon sources and advective transport are better resolved and evaluated with this method. An initial calibration survey was conducted around Tortugas Mountain on the Las Cruces East Mesa geothermal field, and subsequent surveys were conducted in a true exploration mode near Radium Springs and Rincon.

The larger positive radon residuals discovered by this study occur over or immediately adjacent to upflow zones and/or areas associated with very high temperature gradients. Temperature gradient holes were drilled as the NMERDI cost-share to test the radon anomalies and provided the following results. A shallow and probable intermediate-temperature (90°-150° C) geothermal system, the first in the southern Rio Grande Rift, has been discovered in the Rincon study area. Two areas north of Radium Springs, with positive radon anomalies and high temperature gradients (>300° C/km) were delineated which are associated with significant shallow geothermal resources with near-term development potential. Hydrothermal alteration in a borehole at Rincon may indicate potential for undiscovered, Neogene epithermal disseminated-silver deposits in the Rio Grande rift (Witcher and Schoenmackers, 1990).

The University of North Dakota (U ND) has cooperated with the Geological Surveys of North and South Dakota in a comprehensive geothermal resource assessment of these states directed by Dr. Wil Gosnold. Eight heat flow holes have been drilled and logged in the South Dakota heat flow anomaly, and two more test hydrologic anomalies in North Dakota. Several other holes of opportunity provide new heat flow data. A new quantitative estimate of the total accessible geothermal resource base considers all potential geothermal aquifers, as many as 12 regional aquifers in the Williston Basin, and results in a new resource estimate. The identified, accessible, geothermal resource base in these northern Great Plains states is about 36 exajoules (36 x 10^{18}J) essentially double those of earlier studies. Temperature-depth data are presented for most major communities in the resource areas of these two states. A companion study by Dr. Min Chu examines aquifer production rates, temperatures, and water quality to evaluate the more promising aquifers in the Williston Basin and identifies the Inyan Kara Formation as the preferred geothermal aquifer (Gosnold et al, 1991).

The State of Oregon-Department of Geology and Mineral Industries (DOGAMI) with Dr. George Priest as Principal Investigator, has drilled a deep scientific and heat flow hole at Santiam Pass on the crest of the Oregon Cascades. Oxbow Geothermal contributed $100,000 to the drilling of this hole. The completed depth of Santiam Pass 77-24 was 3046 feet (928 m). A preliminary, non-equilibrated bottom hole temperature is 24° C, with increasing temperature gradients of about 60° C/km from 700-900 m and 120° C/km from 905-920 meters. It appears that the hole is sited in a hydrologic downflow zone that was penetrated near the base of the hole. Preliminary K-Ar dates indicate that the age of rocks at total depth is 1.81+/-0.05 m.y., and that the section above 500 meters is younger than 1 m.y. Scientific study of this site will continue until October 1992.

The Utah Geological and Mineral Survey (UGMS) has completed a multidisciplinary study of the Newcastle geothermal resource which currently provides space heating for greenhouses, a church, and several residences. Robert Blackett, Principal Investigator, integrated studies by the USGS, UGMS, the University of Utah Department of Geology and Geophysics, and UURI in this study. Geological, geophysical, and geochemical studies have characterized this hidden resource in detail, and have determined a reservoir temperature in excess of 130° C, with an anomalous heat loss of 12.4 MW. The probable upflow zone for thermal fluids is well defined by heat flow, self-potential, and electrical resistivity data, and corresponds to the buried intersections of northwest-trending faults with the Antelope Range fault. This study has called attention to the binary power potential of the Newcastle system, and has suggested new approaches for the discovery of other hidden Basin and Range geothermal systems.

The State of Washington, Department of Natural Resources (WDNR) drilled eight 152 m temperature gradient holes to better define the Southern Washington Cascade Range heat flow anomaly. Two holes did not penetrate the effects of cold surface waters, but four holes had temperature gradients of 50° to 58° C/km (Barnett and Korosec, 1989). In a related study Michael Korosec, Principal Investigator, integrated K-Ar age dates, geochemistry and volcanic stratigraphy of the Indian Haven Quaternary volcanic field to evaluate volcanic production rates. The Indian Haven volcanic field is shown to be younger than previously believed, with all of the known flows exposed at the surface erupting over the past 730,000 years. The average production rate appears to have remained relatively constant over that interval, at a rate not too different than the more silic stratavolcanoes (Korosec, 1989).

The State of Washington, Energy Office (WSEO) is completing a modification of the computer program (GEODIM) which optimize the design of wells, pipes, pumps, and heat transfer systems. This work, under the direction of Dr. Gordon Bloomquist, is being completed at the University of Lund (Sweeden) where GEODIM was initially developed. The program will be verified and field tested on selected U.S. operating district heating systems. A users manual will be written, printed, and distributed by WSEO.

The University of Wyoming (U WY), Department of Geology and Geophysics has completed an improved three-dimensional modeling scheme for solving the combined heat conduction and forced convection equations for determining subsurface temperatures. The resulting computer programs will operate on IBM compatible PCs and will be available from U WY. A numerical model has been developed for the Cody hydrothermal system.

SUMMARY AND CRITIQUE

The State Cooperative Program has addressed a broad range of research topics and geographic areas. Most projects must be judged as successful studies, although some results have only a long term potential for utilization (i.e. Alaska resource studies). Monitoring studies of the Moana, Boise, and Banbury-Twin Falls geothermal reservoirs provide valuable data about district heating systems already stressed by uncoordinated development. Work by the Utah and Nevada teams may lead directly to small, binary power plant development in the near term. The silica treatment studies completed by the Hawaiian team address DOE environmental and power production goals.

The 1987 PRDA for State Cooperative Geothermal Research has been a major success. Detailed results of these studies have been presented in ten papers at several different technical conferences in 1989 and 1990, and are available as more than 12 technical papers and reports, with additional presentations and publications yet to come. The quality of the research has been excellent and the results directly address DOE goals of increased geothermal energy utilization, reduced dependence on imported petroleum, and the development of environmentally acceptable power alternatives. The DOE funds made available to the state teams have helped develop and maintain geothermal expertise within several states, and to expand upon the national database at a minimal cost, at a time when the geothermal industry itself was facing difficult economic conditions.

The substantial results and cost-effectiveness of this program are gratifying. Without new funding, this program will be terminated with the completion of the present grants.

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DIRECT USE INDUSTRY ASSISTANCE

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Abstract

Progress in technology transfer and R&D of geothermal direct uses in three areas, by the Geo-Heat Center, are reviewed in this paper. First, technical assistance was provided to 81 projects covering the entire development process from resource information to troubleshooting problems after a project has been completed. Second, applied research was conducted on: the performance of materials and equipment used in 13 geothermal district heating systems; wellbore/aquifer interaction and worldwide utilization of downhole heat exchangers; development of information on transmission and distribution piping and analysis of uninsulated piping for geothermal district heating systems; and development of a U.S. direct-use site data base. Third, an overview is presented on a technology transfer program which included: publishing a Guidebook, topical papers and quarterly Bulletin; advising and referrals on projects; presentations and tours; geothermal library; and reporting of activities to the Geothermal Progress Monitor. Finally, based on growth trends in the geothermal direct use industry, a research plan is described on collocation of hydrothermal resources and geothermal heat pump analysis and use.

INTRODUCTION

In recent years, developers have made appreciable strides in exploiting low-temperature resources; however, the enormous potential of these resources is greatly under utilized. Geothermal energy is the nations's third largest energy reserve, and low-temperature resources are widely distributed throughout the United States. It is essentially non-polluting and offers one alternative to the environmental problems associated with the burning of fossil fuels. To obtain increased utilization of the large direct-heat resource base, the Geo-Heat Center provided the direct-use industry with: 1) engineering, technical and development assistance, 2) research to aid in resource and technical development problems, and 3) information and educational materials to stimulate development. The program provided strong support to state energy offices, potential and existing users, the consulting engineering community, and the public.

TECHNICAL ASSISTANCE

The engineering and technical assistance program concept is to provide potential geothermal developers with: 1) information and data about specific geothermal resources, 2) preliminary engineering design, cost estimating, and economic analysis on direct use projects, 3) review of a consultant's design, 4) assistance on specific portions of a project; i.e. well pumps, heat exchangers, terminal equipment, etc., and 5) troubleshooting of problems after the project has been completed.

During a period of 33 months, technical assistance was provided to 81 projects. In general, 8 hours per project guidelines were adhered to although several program users requested additional time which was allocated through a justification process with DOE - Idaho. Typical users of the program were businesses (46%), public institutions (21%), municipal governments (21%), and individuals (12%). Figure 1 illustrates the number of projects receiving technical assistance according to the type of application. Review of consultants designs and/or discussions with consultants during the design phase accounted for an increasing number of requests - 25% during the 33 month period.

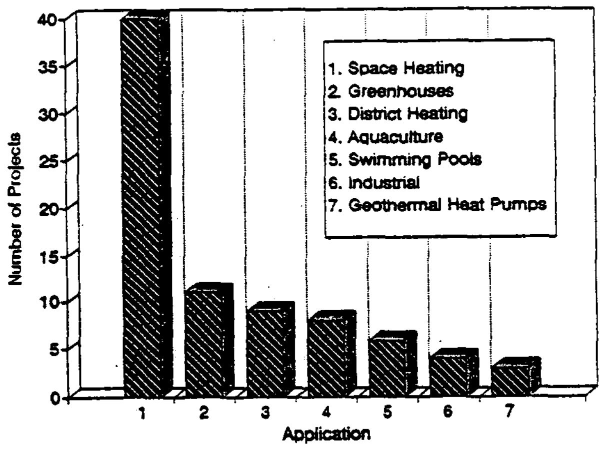

Figure 1. Projects receiving technical assistance according to application.

RESEARCH AND DEVELOPMENT ACTIVITIES

Direct use research and development was applied in four areas to provide the industry with reduced costs of developing, designing and operating low-temperature geothermal projects.

A Materials and Equipment Review of Selected U.S. Geothermal District Heating Systems (Rafferty, 1989).

The objective was to investigate the performance of materials and equipment in 13 geothermal district heating systems. Specific areas of investigation included equipment type and materials of construction for: production facilities, central plants, distribution, customer connections, metering, and disposal. Most of the systems included in this review have logged a minimum of 5 years operating experience. As such, they have encountered many of the problems likely to occur as a result of fluid chemistry and initial design. These systems are located generally in the western U.S. and particularly concentrated in the states of Nevada, California, Idaho and Oregon.

The systems reviewed in the course of this work have all experienced materials and/or equipment problems to some degree. For the most part, however, these difficulties have been overcome and the systems serve as a reliable energy source for their customers. The experience gained from the combined 182 years of operation of these systems allows one to describe conceptually, the ideal geothermal district heating system from a materials and equipment perspective. In summary, this system would consist of:

- Production well pumps of the enclosed lineshaft, oil lubricated design with bowl assemblies containing enameled cast iron impellers with keyed shaft connections, leaded red brass bearings and stainless steel shafts.
- Production pumps equipped with a variable-speed drive (preferably a multi-speed motor or variable frequency drive) feeding directly into the main production line (no wellhead storage tank).
- Open-type distribution system with asbestos cement piping (or some similar substitute).
- Butterfly valves (EPDM/316 SS trim).
- Automatic temperature activated valves for crossovers if used.
- Customer branch lines of a non-metallic material.
- Volume metering for billing purposes.
- Surface disposal if regulatory authorities permit.

Downhole Heat Exchanger Wellbore/Aquifer Interaction Research (Culver, 1990).

The objective was to perform experiments that would provide insight into wellbore/aquifer interaction and thereby provide more information on which to base downhole heat exchanger (DHE) design.

The use of DHEs for residential and small commercial space and water heating, and other applications has several desirable features. Systems are nearly or completely passive--little or no water or steam is produced from the well reducing or eliminating disposal problems, or the need for injection wells. Initial costs of pumps and installation are eliminated or reduced along with maintenance and pumping power. Residential and small commercial systems can operate with no outside energy consumption at all--a decided advantage where electricity is costly or not available.

Computer flow modeling studies used an established groundwater flow package to which a random walk dye dispersion routine was added. Because the package was designed to simulate flow in a uniform porous media, it was not well suited to modeling the "dual-permeability" of the Klamath Falls reservoir. Assumptions made in the model and unknown reservoir parameters limited the results of this work to helping with design of the dye tests. Estimation of the required dye injection quantity was based on the computer model and several tracer dye transport equations.

The results of the first dye test showed that a nearby pumped city district heating well has considerable influence on the underground flow. A rapid breakthrough of dye occurred in this test indicating that there is a good hydraulic connection between the two wells. The dye concentration was, however, quite low, considering the breakthrough time, indicating that mixing volumes are high. Large flow rate variations occurred in the city heating system pumped wells during the remainder of the test period and this interfered considerably with subsequent tests. Better results may be obtained if testing is carried out in winter since natural flow in the reservoir is higher, due to draw off in downstream wells, and the pumped wells operate in a more stable condition.

The downhole heat exchanger supplied 500 kW of steady heat load during a twelve-day test. More heat was obtained during the first hour of the test, as heat stored in the wellbore was extracted. Temperatures in the well declined quickly during this period, but leveled off to steady values for the remainder of the test. At the completion of the test, the well quickly regained the temperature it had before testing began.

Currently, not including heat pumps, DHEs supply about 40 MWt worldwide. This is not the installed capacity. In Klamath Falls, which has about 16 MWt being utilized, one well usually supplies one house; but, most could easily supply two and many three or four homes. In Reno, wells are probably utilized to near their capacity. The situation in other parts of the world is currently unknown. DHEs are utilized in five countries. The largest output from a single well with a DHE is 6 MWt in Turkey.

In 1990, the estimated United States total geothermal heat pump capacity was 1,470 MWt for space heating. It was estimated that 30% of these used vertical earth-coupled DHEs for a capacity of 445 MWt.

Worldwide, it would seem, there are many potential uses for DHEs--particularly in developing countries. There is a considerable number of developing countries with shallow low-to-moderate temperature resources that could be used for direct heat applications. In developing countries, electricity may not be readily available or costly, and pumping equipment difficult to obtain and maintain. Since some DHE applications require neither electricity nor sophisticated pumps, they seem to be a method for utilization of those resources.

Piping Materials for Geothermal District Heating System (Rafferty, 1989).

The objective was to provide information to the district heating industry regarding transmission and distribution piping on: relative costs, purchase considerations, existing material performance, and new products.

Transmission and distribution piping can constitute a significant cost component in a geothermal system. For district heating systems, the cost associated with the distribution network is frequently 40 - 60% of the overall capital cost of the project. For this reason, it is important to select the least cost material which is suitable for the application. Historically, most piping (approximately 55%) in these systems was of asbestos cement construction. This material was very successful in terms of installed cost and chemical compatibility with the fluids. Unfortunately, concern regarding the health related aspects of asbestos cement products has rendered this product unusable from a practical standpoint.

As a result, it is important to identify cost effective alternative piping materials for future project construction. There is a definite shift away from asbestos cement to fiberglass and ductile iron materials on the basis of economics and ease of installation compared to previously used asbestos cement.

High capital costs are one reason development has lagged in the area of district heating. The use of uninsulated piping for a portion of the distribution offers the prospect of reducing the piping material costs by more than 50%.

Although the uninsulated piping would have much higher heat loss than insulated lines, this could be compensated for by increasing system flow rates. The additional pumping costs to maintain these rates would be offset by reduced system capital costs. Preliminary analysis indicates that it would be most beneficial to use uninsulated lines in sizes above about 6" in certain applications.

Figure 2 illustrates the relationship of heat loss and temperature loss. The figure is based upon 6" pre-insulated (1.8" insulation, PVC jacket, FRP carrier pipe) and a 6" uninsulated pipe buried 4 feet below the ground and operating at 170°F inlet temperature. Temperature loss per 1,000 feet is plotted against flow rate. As discussed above, the graph indicates a substantial increase in temperature loss at low flow rates.

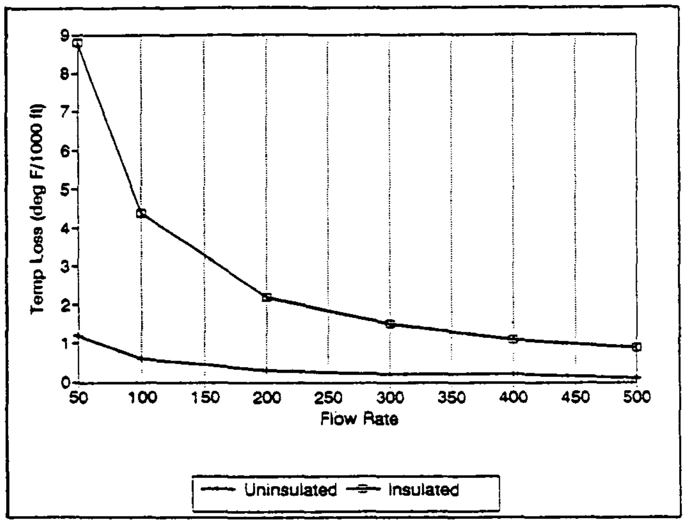

Figure 2. Buried pipeline temperature loss versus flow rate.

Systems designed for an existing group of buildings or those which serve process loads are more likely candidates for the use of uninsulated piping.

Development of a U.S. Direct-Heat Utilization Data Base (Lienau, 1988).

The objective of this study was to characterize how and where geothermal energy is used, the extent of that use, the economics and growth trends.

The use of low-temperature (40 to 300°F) geothermal resources for direct-heat applications has increased significantly since the late 1970s. The oil price increases of the 1970s revived interest in the use of geothermal resources as alternative energy source. Beginning in 1978, DOE initiated numerous programs that also caused significant growth in the industry. The use of geothermal heat pumps contributed to the growth, starting in 1980.

This study identified 452 sites, which included approximately 130,000 individual installations, using geothermal energy for geothermal heat pumps, space and district heating, greenhouses, aquaculture, industrial processes, and enhanced oil recovery. The results are presented in Table 1, which was updated in 1990.

Table 1. Summary of U.S. Geothermal Direct-Heat Projects, 1990

Application	No. of Sites	Thermal Capacity (x 10^6 Btu/hr)	Annual Energy (x 10^9 Btu/yr)
Geothermal Heat Pumps[a]	147	5,010	5,666
Space and District Heating[b]	126	560	1,476
Greenhouses	36	183	464
Aquaculture	20	224	1,180
Resorts/Pools	114	234	1,452
Industrial Processes	12	100	403
Enhanced Oil Recovery[c]	4	1,164	8,156
	452	7,475	18,797

a. Includes residential and commercial geothermal heat pumps totalling over 110,000 units.
b. Includes two systems reported under construction: Mammoth (118 x 10^9 Btu/yr) and Bridgeport (14 x 10^9 Btu/yr).
c. Enhanced oil recovery located in four states (Reed, 1983).

The potential is large for the growth of the direct heat industry in the United States. Based on historical data, presented in this paper, projected growth of each direct heat technology was constructed for a base case ("business as usual") and a high case. The high case assumes extensive resource evaluation takes place, federal incentives are instituted and economic conditions change due to conventional fuel prices increases. The cumulative growth of six direct heat technologies, excluding enhanced oil recovery, are illustrated on Figure 3.

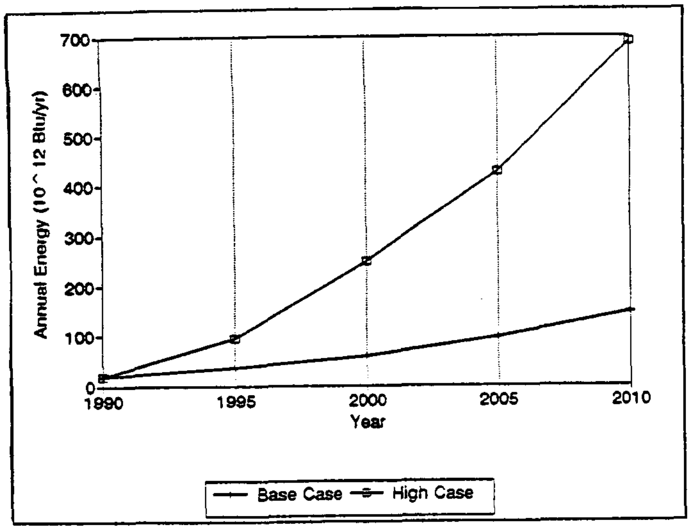

Figure 3. Projected growth rate of the direct use industry (excluding enhanced oil recovery).

Geothermal space and district heating systems, other than geothermal heat pumps, need to be collocated with resources of greater than 50°C, which occur primarily in 15 western states. It is estimated that the space and district heating potential load is greater than 50 trillion Btu per year corresponding to a thermal capacity of 7,850 MWt. These cities are within 5 miles of a resource with a temperature greater than 50°C; however, large population centers could be located within a 25 mile economic transmission distance. There are hundreds of collocated low-temperature resources for which exploration and development strategies need to be applied.

At the present time, earth-coupled and groundwater heat pump systems are being installed in great numbers. Groundwater aquifers in the range of 5° to 30°C are being used in these systems in just about every state in the nation (mainly in the midwest and east). Geothermal heat pumps utilize groundwater in wells or by direct earth coupling with vertical or horizontal heat exchangers.

It is estimated that almost 60,000 groundwater systems and over 50,000 closed-loop, earth-coupled systems (2/3 of these are vertical installations and 1/3 horizontal) are being used. The estimated capacity of the heat pumps installed is 1,470 MWt and the annual energy use is estimated to be 5.7 X 10^{12} Btu/yr.

Geothermal heat pumps providing space heating and cooling will have the largest growth in the direct use industry, because the technology has applications nationwide and they reduce energy consumption by 30% when compared to air-source heat pumps. It is estimated that by the year 2010 vertical closed-loop units will have captured 15% of the air-source heat pump market--presently estimated at 800,000 units installed per year. This amounts to a 24-fold increase or 17.2% growth per year over 20 years for the high case. The base case amounts to approximately a 4-fold increase or 7.5% per year over 20 years. Also, the large increase in geothermal heat pump use is due in large part to incentives from electric utility companies. These incentives benefit both the user by reducing installation and heating costs, and the utility because of the load leveling effects of groundwater heat pumps.

For example, Ontario Hydro will pay $2,000 Canadian to customers who now heat with electric resistance if they will install a geothermal heat pump. They estimate that they can save 5 kW per installation (for a cost of $400 per installed kW) and avoid the construction of 2,250 MW of capacity if they can get their 450,000 candidate customers to convert. New capacity would cost between $2,000 and $2,500 per installed kW, so the geothermal heat pump program is highly cost effective.

TECHNOLOGY TRANSFER

The technology transfer program was designed to provide the general public, potential users, consulting engineers, local, state and federal agencies information on geothermal resources and their uses, including geothermal heat pumps. This information was distributed to educate the public on the nature and distribution of geothermal energy, its beneficial uses, and the potential cost savings of geothermal heat pump installation. Technical information on project designs, technology advances, new products and materials selection were provided to potential users and designers of geothermal systems. The Geo-Heat Center acted as a clearinghouse of general and technical information on geothermal energy. This effort also acts as a catalyst for initiating direct heat projects and increased public awareness of geothermal energy.

The effort included: 1) publishing the Geothermal Direct Use Engineering and Design Guidebook, 2) publication of a quarterly Bulletin, 3) writing topical papers (29), 4) answering questions, advising, providing referrals and meeting with groups on direct use technology (1,371), 5) presentations at technical meetings (39) and tours of Klamath Falls geothermal facilities (33), 6) maintenance of a geothermal library, and 7) reporting of project progress and development in the USDOE Geothermal Progress Monitor. A total 1,371 inquiries were logged during a 33 month period. The categories of the *inquiries, are shown on Figure 4 which also indicates areas of* most interest.

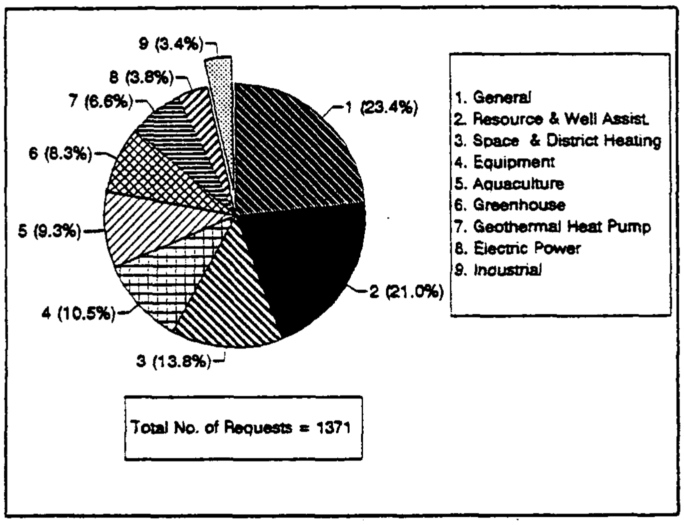

Figure 4. Profile of requests for assistance and information.

CONCLUSIONS

Although, the above program assisted many individuals and organizations in implementing direct-heat projects and increased awareness of the tremendous potential low-temperature geothermal energy offers, there is a continuing need to stimulate the conversion to, and utilization of these resources throughout the United States.

In the coming years, to provide technological support for development of low-temperature reservoirs and user assistance, the following are recommended:

- Evaluation and confirmation of low-temperature reservoirs near hundreds of population centers that have potential for district heating and other direct utilization.

- Develop improved testing techniques of production potential and injection strategies for low-temperature reservoirs.

- Geothermal heat pump analysis and use that includes: user feedback, resource data, R & D opportunities, and integrated resource planning.

- Technology assistance for direct use that includes: project technical and development assistance, research and development activities which will reduce the cost of developing, designing and operating low-temperature geothermal projects.

- Outreach and public education to inform and educate the public on the nature and distribution of geothermal energy, its beneficial uses, and the potential cost savings of geothermal heat pump installations.

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GEOTHERMAL LOW-TEMPERATURE RESERVOIR ASSESSMENT PROGRAM

A NEW DOE GEOTHERMAL INITIATIVE

by

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ABSTRACT

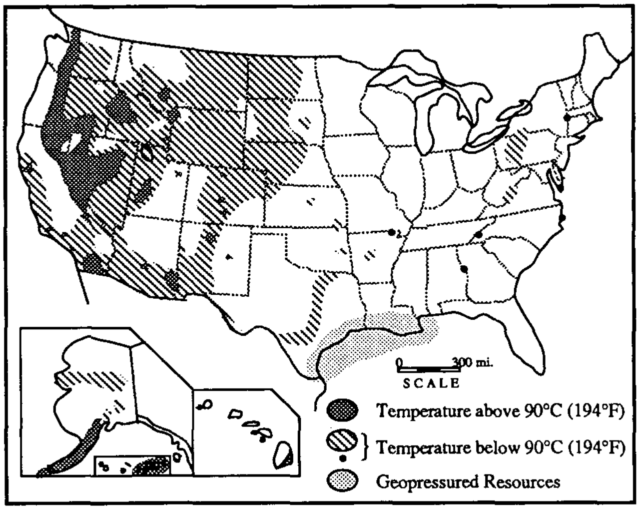
In Fiscal Year 1991, Congress appropriated money for the Department of Energy to begin a new program in the evaluation and use of low- and moderate-temperature geothermal resources. The objective of this program is to promote accelerated development of these resources to offset fossil-fuel use and help improve the environment. The program will consist of several components, including: (1) compilation of all available information on resource location and characteristics, with emphasis on resources located within 5 miles of population centers; (2) development and testing of techniques to discover and evaluate low- and moderate-temperature geothermal resources; (3) technical assistance to potential developers of low- and moderate-temperature geothermal resources; and, (4) evaluation of the use of geothermal heat pumps in domestic and commercial applications. Program participants will include the Geo-Heat Center at the Oregon Institute of Technology, the University of Utah Research Institute, the Idaho Water Resources Research Institute and agencies of state governments in most of the Western states.

INTRODUCTION

Man has made use of direct heat from geothermal resources for thousands of years. Many tribal villages and early communities were built around surface thermal features. A number of cities and villages in the United States now include" Hot Springs" as part of the community name. The United States is the eighth largest user of direct heat, behind (in order) Japan, China, Iceland, Hungary, the USSR, Italy and New Zealand (Freeston, 1990).

Geothermal Resource Base

Low- to moderate-temperature geothermal resources are widely distributed throughout the western United States (Reed, 1983) in contrast to the distribution of the highest grade geothermal resources, as summarized by Muffler (1978). The distribution of these resources is shown in a general manner in Figure 1. While numerous resources may occur in the areas indicated, individual reservoir areas may be as small as one square kilometer or less. In the northern Great Plains, stratabound resources in major aquifers with fluid temperatures exceeding 50°C may extend in a continuous manner for thousands of square kilometers (Gosnold, 1987; 1990). While high-temperature resources are relatively rare, the number of low- and moderate-temperature resources increases exponentially as the reservoir temperature decreases, as shown in Figure 2, and the resources become much more widely distributed.



Figures 1. Generalized distribution of geothermal resources in the United States.

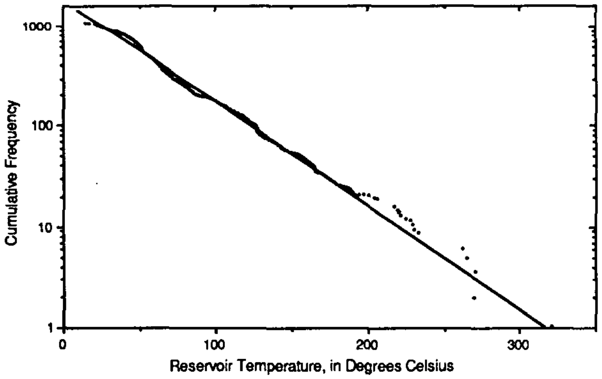


Figure 2. Cumulative frequency versus reservoir temperature for 1,346 hydrothermal convection systems in the United States, including 1,125 low-temperature geothermal systems and 220 intermediate- and high-temperature systems (from Reed, 1983).

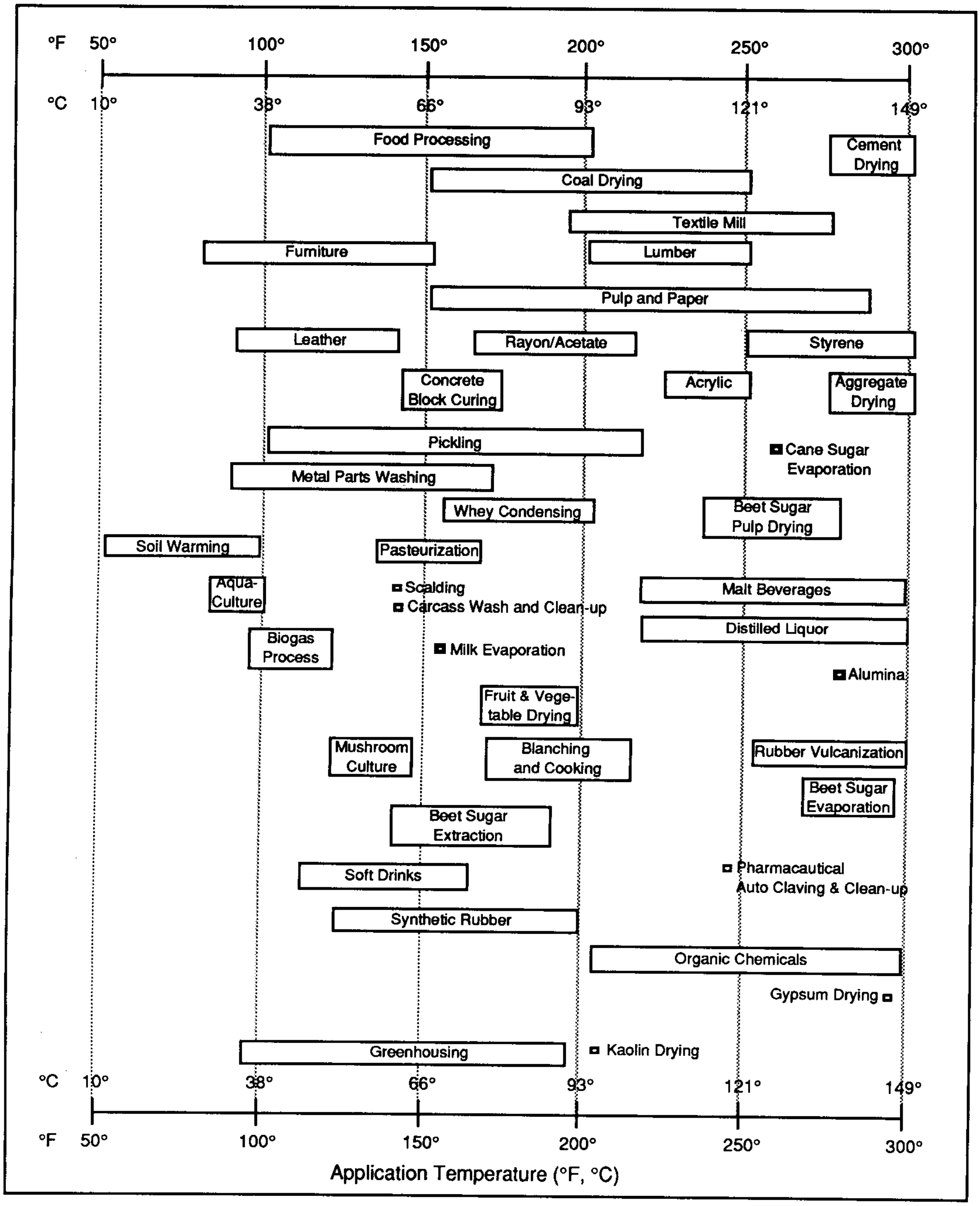


Figure 3. Temperature ranges for some industrial processes and agricultural applications.

Much of the recent interest in developing direct-heat resources may be attributed to a Department of Energy initiative, the State Coupled Program, which began in 1977. As a result of this program, geothermal resource maps were compiled and distributed for 18 western states. The maps, typically printed at a scale of 1:500,000, identify wells and springs with anomalous temperatures, and were released from 1980 to 1983. These maps, and the data and reports upon which they were based, have been extremely useful to the more aggressive developers, and form an important starting point for the proposed study.

The Oregon Institute of Technology authorized a study of the collocation of geothermal resources and communities for eight western states (Eliot Allen & Associates, 1980). The criteria used in this study included incorporated cities located within five miles of a thermal well or spring having a temperature of 50°F or greater. This inventory identified a total of 1,277 hydrothermal sites within five miles of 373 cities, having a combined population of 6,720,347 persons, in the eight states. The total heat load for all cities, exclusive of industrial loads, was estimated at 133 E12 Btu/yr.

While the 1980 Allen study was quite instructive and arrived at impressive population and heat-load estimates, it was limited in scope to only eight states, and did not account for low-temperature uses for agriculture, greenhousing, or aquaculture. Also, it predated the publication of results from the DOE State Coupled Program. Clearly, the Allen study is outdated.

We believe a complete inventory of collocated resources and population centers will indicate a potential heat load for the western states (exclusive of industrial loads) more than 10 times the Allen estimates. It is apparent that geothermal energy could make a much more substantial contribution to our energy picture, but the private sector needs the necessary information and stimulation.

Potential Uses

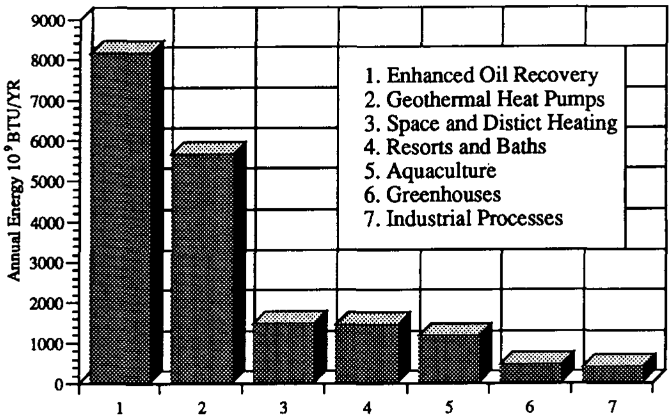
Enormous potential exists in the United States for geothermal heat pumps (GHPs) and direct-heat projects to make a significant contribution to our national energy needs by offsetting electricity and replacing conventional fuels. Greater geothermal use would reduce emissions of greenhouse and acid-rain gases that adversely impact our environment by displacing use of fossil fuels.

Geothermal heat-pump potential exists in all states. GHPs use either closed-loop ground heat exchangers or wells, and are 30 percent more efficient than air-source units. In fact, no system for heating and cooling of homes or buildings is more efficient than the geothermal heat pump. An estimated 110,000 units currently installed in the U.S. produces 5.67 trillion Btu per year or 1,470 MWt, and 15,000 to 25,000 new units are being installed annually. If technical and economic advances were instituted, it is believed that installations of GHPs could increase to between 200,000 to 400,000 annually. This would amount to an increase of 12 trillion Btu per year, which would total approximately 1.0 Quad by the year 2010.

Geothermal space- and district-heating systems, other than geothermal heat pumps, generally need to be collocated with resources of greater than 50°C, which occur primarily in 15 western states. It is estimated that the space- and district- heating potential load is 54.2 trillion Btu per year, corresponding to a thermal capacity of 7,850 MWt, in cities that are within 5 miles of a resource having a temperature greater than 50°C. Five miles is estimated to be an economical transmission distance, although greater transmission distances may be feasible for some resources.

Other direct-heat applications include enhanced oil recovery, industrial process heat, greenhouse heating, aquaculture and swimming pool heating. Figure 3 shows temperature ranges for selected applications.

The total installed capacity of direct-use projects in the United States is about 2,100 MWt, with an annual energy use of 18.8 trillion Btu/yr, equivalent to the combustion of roughly 5 million barrels of oil per year. Approximately 43% of this use is for enhanced oil recovery, while geothermal heat pumps account for about 30%. The relative energy that geothermal resources contribute to the seven major direct applications is shown in Figure 4.



Figures 4. Direct-heat geothermal use in the United States, 1991.

OBJECTIVE OF PROGRAM

The objective of the Geothermal Low-Temperature Reservoir Assessment program is to achieve greater utilization of the nation's widely distributed low- and moderate-temperature geothermal energy and earth-heat resources. By achieving this objective, we will: (1) increase energy security by helping to develop an important domestic energy resource; (2) reduce the trade deficit by displacing need for importing so much oil; and, (3) contribute to environmental preservation by displacing the use of fossil fuels, which emit greenhouse and acid-rain gases and create damaging ground-level ozone.

PLANNED PROGRAM

The program will be a cooperative effort among a number of academic and state institutions working with potential direct-heat developers. The three principal institutions will be the Geo-Heat Center at the Oregon Institute of Technology, the Idaho Water Resources Research Institute at the University of Idaho and the Earth Science Laboratory of the University of Utah Research Institute. Resource teams from selected states in the West will also participate. In addition, participation of eastern institutions knowledgeable in geothermal heat pumps is planned. The tasks for this project are discussed below.

Task 1. Compilation of Data on Hydrothermal Resources.

We will make a compilation of data on geothermal resources in the western U.S. with emphasis on those occurrences that have temperatures of 50°C or more and are within 5 miles of population centers. The compilation will also include resources that have somewhat higher temperatures or high flow rates or are favorably located with respect to a potential user.

Simultaneously, we will collect and interpret demographic and other data to evaluate potential heat loads, fossil-fuel displacement, utility electrical-demand reduction and load-leveling opportunities, and environmental benefits for potential geothermal direct-heat and heat-pump applications.

These two data sets, resource and demographic, will be jointly interpreted with the main objective of making a prioritized list of resources which have highest potential for economic development with significant benefit.

At the same time, we will undertake R&D on better methods for locating low- and moderate-temperature geothermal resources and on siting successful test and production wells. Part of this work will encompass development of better well-testing methods and better hydrologic models of these hydrothermal resources. These tasks are expected to pay off in further discoveries of resources and in better methods to evaluate reservoir production and ultimate-development capacity at an earlier stage in the development cycle than is possible now.

Task 2. Geothermal Heat Pump Analysis and Use.

We will collect and interpret information on the performance of home and industrial installations of GHPs. This will yield information on: (1) the most effective and successful marketing and incentive programs to expand GHP markets; (2) the potential total national energy savings contribution from GHPs; (3) the benefit to utilities from reduced peak demand and higher annual load factors; and, (4) suitability of GHPs for northern climates. We will also document energy-use patterns before and after installation of GHPs in typical residential and commercial situations, and determine energy savings and life-cycle costs. We will produce an analysis of costs and compare them with those of competitive space-conditioning and water-heating systems.

We will also gather and compile information helpful in making successful GHP installations. This information will include shallow ground-water temperature, soil and geologic conditions, and drilling conditions and costs on a local level.

In the course of the above work, we will identify weaknesses in the technology and data base, with the objective of describing needed R&D that would accelerate GHP use.

Task 3. Outreach and Public Education.

All project personnel will work cooperatively and closely with state and local agencies, energy offices and other public entities. This network will bring information on geothermal resources and their uses to the public and to potential geothermal developers. We will also work closely with the Geothermal Resources Council, the National Geothermal Association, the Geothermal Education Office and other entities in the geothermal community. We will develop brochures on direct-heat geothermal energy, GHPs and geothermal energy in general. We will also produce an informative video for general national distribution on geothermal energy and its advantages.

FUTURE PLANS

We envision the present program to be the first part of an ongoing effort that will take possibly 5 years to complete. Funding was provided for only the first two years, however, and additional funding will be required if the entire effort is to be successfully undertaken.

Further information on this program can be obtained by contacting any of the authors, or by contacting Mr. Marshall Reed or Mr. Lew Pratsch, U.S. Department of Energy, 1000 Independence Ave. SW, Washington, DC 20585.

ACKNOWLEDGEMENT AND DISCLAIMER

This work was supported by the U.S. Department of Energy under Contract No. xx. Such support does not constitute an endorsement by the Department of Energy of the views expressed herein.

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HYDROTHERMAL HARD ROCK PENETRATION TECHNOLOGY

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

SUMMARY - HARD ROCK PENETRATION

George P. Tennyson, Jr., Session Chairman
U. S. Department of Energy, Albuquerque Operations Office

The most fundamental feature of geothermal technology is its reliance on penetration to the resource -- that is, drilling. It follows immediately that the utilization and maintenance of the borehole for extracting energy and data are the first and continuing concerns of the geothermal industry whether the purpose be research or commercial energy production. There is, then, probably no subject more applicable to the geothermal partnership we speak of today: that of industry, utilities and the Government. And there is probably no other area where advances in the state-of-the-art can be more directly and more profitably applied to the challenge of the decade of the '90's.

The several subjects in this session reflected the program underway at Sandia National Laboratories (SNL). Specifically, the program as a whole was discussed, including: lost circulation control, rock penetration mechanics, instrumentation, and industry/DOE cost-shared projects of the Geothermal Drilling Organization.

As David Glowka (et al) stated at the review, "The most costly problem routinely encountered in geothermal drilling is lost circulation. This occurs when the drilling fluid 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 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." Since lost circulation costs represent an average of 10% of the total well costs in mature geothermal areas, the early detection and amelioration of lost circulation in the drilling process represents an area wherein there is a large potential for reducing drilling costs and thereby making geothermal energy more competitive in the utility market.

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 four projects (out of eleven) in the Lost Circulation Technology Development Program at SNL which made significant progress in the last year were described.

A prototype Velocity-Level Meter has been designed, built and tested. This device is aimed at providing an accurate, economical, and simple means for measuring the rate of drilling fluid flow in the partially filled, inclined mud return line that runs from the top of the well bore to the mud pit. There is currently no commercial device with these characteristics that can be used for lost circulation detection in geothermal wells. In addition, a Wellbore Hydraulics Flow Facility was also designed and constructed to evaluate both inflow and outflow meters for lost circulation detection and quantification. The initial results with the V-L meter (and, indeed, the flow facility) have been most encouraging, and it appears that with a reasonable amount of development of the parameterization and the instrument, as well as ruggedization of the instrument for field use, that a very valuable tool will be available.

A drillable straddle packer is under development which provides for delivery through the drill string of cement at the site where lost circulation occurs. The detachable cement delivery unit is designed of plastic so that after the cement is placed in the selected interval, the drill string can be withdrawn while the cement hardens. The drill string is then reintroduced with a drill bit attached, and drilling can be restarted, going right through the plastic device. Two variants of the configuration have been fabricated and will be evaluated.

Involved in the evaluation will be the full-scale packer test facility that has been constructed at Sandia.

Additionally, a Porous Packer is also under development. This device could be either wireline- or drillstring emplaced. Basically, this device is a porous bag containing components of a fast-setting liquid. When this assembly is in place, the setting fluid is activated and forces the bag against the wellbore, temporarily retarding or stopping the fluids from other formation levels from entering the loss zone and washing away or altering the chemistry of the setting fluid. The Porous Packer assembly is then detached and after the setting fluid is sufficiently cured, drilling can resume. The development of the device is at the stage where materials of various porosities are being tested for the bag.

A conceptual design study of alternative packer emplacement methods is also underway. This type device is based on an inversion technique invented by Science and Engineering Associates (SEA) who are conducting the design study. The technique might be likened to rolling a sock on and off of one's foot, except inside out. That is, the borehole is congruent to one's foot and the sock is laid along the inside of the borehole. Two concepts have been selected for advanced conceptual design, and the candidate fabrics will be tested for the "sock".

The utilization of advanced instrumentation systems to obtain better data from the borehole is necessary to the overall progress of the technology. Utilizing a borehole to look deep into the surrounding structures is the equivalent of adding the sense of sight to the vital process of feeling the texture and temperature of the borehole by means of instrumentation and analysis of drilling mud and the cores.

Borehole radar for geothermal applications has received substantial attention over the years. The objective, of course, is to locate fluid filled fractures in a geothermal reservoir.

Electromagnetic techniques have seemed promising because of the expected significant conductivity contrast between the fluid filled fracture and the surrounding rock. High frequencies have also been preferred because of the narrow spatial extent of some fractures and the consequent need for good range resolution. Many of the systems which have been evaluated have been pulsed radar utilizing high frequencies.

However, this combination has several severe, if not crippling, shortcomings. Pulsed radar requires a wide bandwidth antenna, which is difficult to package within the space available. Such antennas also require compromises in coupling efficiency and directionality. Also, the high frequencies lead to high attenuation in the geothermal medium.

The work described at PR IX emphasized continuous wave (CW) systems of lower frequency which uses a directional, steerable beam antenna. It appears that this system could lead to a less costly radar system than current instruments and a simpler data interpretation technique.

This system, as conceived would use separate antennas for transmitting and receiving. Initial evaluation of this system shows that such a unit could meet the size requirements for borehole applications and can be steered adequately to allow the volume of earth within several meters of a borehole to be investigated. This would be accomplished while alleviating many of the most significant problems of existing units.

Technology for acoustic telemetry of data through drill pipe had been developed in previous years and described in previous reviews. However, until such technology is transferred to the commercial sector, our work is only partially complete. Transfer of this technology is now complete and commercial feasibility is being evaluated.

The geothermal community pioneered the Geothermal Drilling Organization a few years ago and thereby founded a new way of industry and the Government working together. That pioneering work formed a strong background for the Technology Transfer activities that have become so important to the partnerships that are being emphasized in this review. That is a justifiable source of pride for the agency, the technology and the industry. Once again, we have been able to show the way, beyond the bounds even of our technical field.

There were several significant accomplishments this year in Geothermal Drilling Organization projects. The high temperature borehole televiewer has now been transferred to Unocal Geothermal for commercial operation. They have been able to demonstrate operations beyond the design temperature limit of 275 degrees Celsius on several different occasions.

The life of stripper rubbers for rotating heads used on geothermal wells has long been a problem. Work with A-Z/Grant International has resulted in a new design configuration that shows promise of increasing lifetime by a factor of at least two. Further, the new design is now available in both oil and gas markets as well as that for geothermal.

Finally, then, the more detailed presentations prepared for this review indeed have shown that we are making advances in the state-of-the-art which will be directly and profitably applied to the challenges the nation will meet in the decade of the 90's.

OVERVIEW - HARD ROCK PENETRATION

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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. To more rapidly recognize lost circulation problems during drilling, a new flow instrument that measures drilling mud outflow rates was designed, built and tested. Also progress has been made in a number of areas to develop downhole hardware for more effective control of cementing operations in lost circulation zones.

Transfer of technology developed for acoustic telemetry of data through drill pipe has been completed and commercial feasibility is being evaluated. The borehole directional radar project has been redirected and will be described in an accompanying paper.

Several significant accomplishments were achieved this year in projects of the Geothermal Drilling Organization. The high-temperature borehole televiewer was transferred to Unocal Geothermal for commercial operation. Operation in excess of the design temperature limit of 275 °C has been demonstrated on several occasions. Work with A-Z/Grant International on improved stripper rubbers for rotating heads used on geothermal wells has resulted in a new design configuration that promises to extend lifetime by at least a factor of two. The new design is now available in both oil and gas as well as geothermal markets. Extended testing under design conditions of elevated temperature and pressure remains to be completed.

PROGRAM SUMMARY

The Hard Rock Penetration project is composed of four tasks: lost circulation control, instrumentation, rock penetration mechanics, and the Geothermal Drilling Organization. Lost Circulation will be described by Dave Glowka.

Instrumentation development is ongoing for borehole radar and downhole memory tools. The radar work is presented in a following paper by Marion Scott. Downhole memory tools are being developed for operation in geothermal wells where temperatures exceed 300 °C and high temperature wireline cables break down. We currently have one slim (2-inch diameter) temperature tool and one larger (3.5-inch diameter) temperature/pressure tool. Both tools have successfully operated in high-temperature geothermal wells for several hours during a run. These tools are designed for operation up to 400 °C and will be tested in a well near this design limit during April of this year. The current temperature/pressure tools have limited memory capacity and this restricts use of this concept to simple measurements. We are also designing a downhole microprocessor/memory module for more complex, data intensive, measurements. This past year, we completed a breadboard design based on the TI TMS 320C30 processor with 32 megabytes memory.

In Rock Penetration Mechanics, we are evaluating advanced drilling systems, updating our overall systems analysis of geothermal drilling, and evaluating practices and costs associated with installing the heat exchangers for geothermal heat pumps. The advanced drilling is considering the advantages of slim hole coring for geothermal exploration. The major advantage is lower drilling cost (often by a factor of 2). The primary issue to be addressed initially, is reservoir evaluation in a slim hole. If the reservoir properties can be adequately determined, then their are a number of technical challenges to optimize the core drilling. Normal mining coring operations need to be extended to higher temperatures and deeper depths. Drilling fluids, downhole tools, bits, cementing and instrumentation are all affected.

Our new drilling systems study will update our last evaluation published in 1979. The current study will develop the framework for evaluation of the impact of new tools and procedures on the cost of drilling geothermal wells. This is being done by extending existing cost models, developing new common trouble models, and using the previously developed IMGEO cost of power model. This study also includes a survey of the geothermal drilling industry to determine the most important problems encountered today and to determine interest in future joint projects. Preliminary results indicate four major areas of concern and support for future work: (1) lost circulation and cementing, (2) high temperature tools and instrumentation, (3) improved directional drilling, and (4) exploration/resource definition.

Market penetration of geothermal heat pumps is currently limited by the high installation costs of the heat exchanger. Drilling equipment and installation procedures will be evaluated to determine if cost reduction is possible. Similar technology is currently being developed in a joint project with Charles Machine Works for application to shallow drilling at hazardous waste sites.

Two GDO projects are active. The high temperature borehole televiewer is being transferred to Unocal. Unocal will provide technical direction and interpretation and will contract field logging operations and maintenance. Several field tests were completed this winter leading to a decision to modify the lower rotating section for rugged field handling. A-Z Grant has completed a new rotary head seal design that is entering their product line. Much longer lifetimes are expected.

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PROGRESS IN THE LOST CIRCULATION TECHNOLOGY DEVELOPMENT PROGRAM

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ABSTRACT

Lost circulation is the loss of drilling fluid from the wellbore to fractures or pores in the rock formation. In geothermal drilling, lost circulation is often a serious problem that contributes greatly to the cost of the average geothermal well. The Lost Circulation Technology Development Program is sponsored at Sandia National Laboratories by the U. S. Department of Energy. The goal of the program is to reduce lost circulation costs by 30-50% through the development of mitigation and characterization technology. This paper describes the technical progress made in this program during the period April, 1990 - March, 1991.

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 wellbore, 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 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 often 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 cement 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 formations. 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%. 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. 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. This compares with a cost of 4-15 cents/kWh in 1986.

LOST CIRCULATION PROJECTS

There are currently 11 projects in the Lost Circulation Technology Development 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. These projects are described in Glowka (1990). Significant progress was made in Projects 2, 6, 7, 8, and 10 during the reporting period (April, 1990 - March, 1991). This progress is described in the following sections.

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

Major-Fracture Fluid Loss Control:
3. Development of Cementitious Mud Formulations
4. Development of Cementitious Mud Flow Models
5. Downhole Injector Development
6. Porous Packer Development
7. Drillable Straddle Packer Development
8. Packer Emplacement Feasibility Study

Loss Zone Characterization:
9. Wellbore Hydraulics Model Development
10. Development of Wellbore Hydraulics Data Acquisition System
11. Borehole Televiewer Fracture Characterization Study

V-L METER DEVELOPMENT

As part of Project 10 (Development of Wellbore Hydraulics Data Acquisition System), a meter for measuring the outflow rate from a well was designed and tested. This meter, called the V-L (Velocity-Level) Meter, is intended to provide an accurate, reliable, economical, and simple means for measuring the rate of drilling fluid flow in the partially filled, inclined mud return line that runs from the top of the wellbore to the mud pit. There is currently no commercial device with these characteristics that can be used for lost circulation detection in geothermal wells.

A simplified schematic of the V-L meter is shown in Figure 1. The transducer consists of a rolling float that measures both the fluid velocity and level in the return line. Detailed design and fabrication of a prototype of the meter were completed during the reporting period. A photo of the assembled prototype is shown in Figure 2. The meter uses a pendulum potentiometer to measure the wheel moment-arm angle and thus the fluid level. A magnetic switch is used to measure the wheel rotary speed and thus the fluid velocity. The box in which the meter is housed is mounted directly on top of the mud return line. Transparent panels were provided on the prototype box to aid in evaluation of the meter operation.

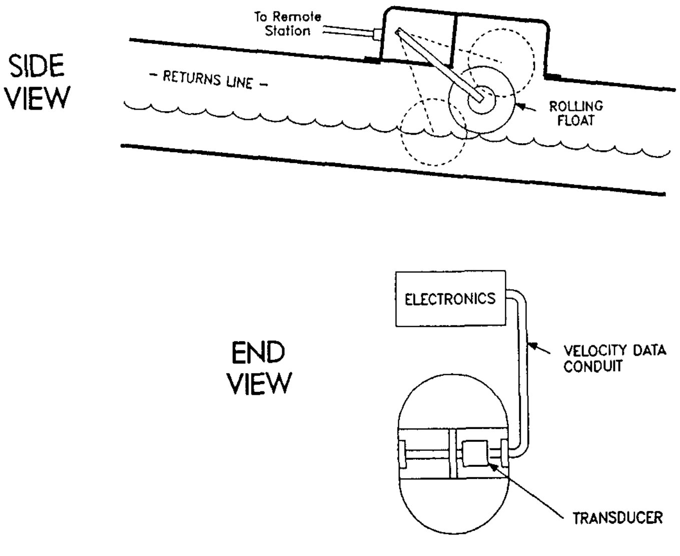


Fig. 1 - Schematic of Velocity-Level (V-L) Meter concept.

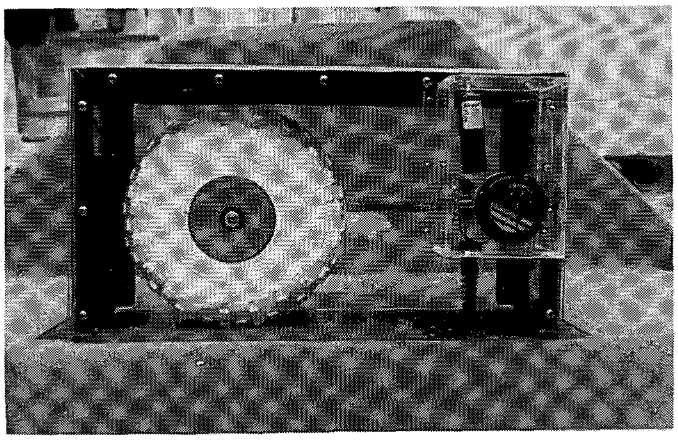


Fig. 2 - Assembled prototype V-L Meter.

A Wellbore Hydraulics Flow Facility was also designed and constructed during this reporting period. This facility is used to evaluate both inflow and outflow meters for lost circulation detection and quantification. A photo of the facility is shown in Figure 3. During operation, water or drilling mud is pumped from the mud tank (shown on the left) by a 1000-gpm centrifugal pump (shown on the right). The fluid flows up a vertical section of pipe and through a commercial magnetic flow meter, which provides an accurate measurement of flow rate in the filled pipe. The fluid then flows into the top of the simulated wellbore (upper right), which provides annular flow similar to that in an actual wellbore. The fluid exits the simulated wellbore and flows through the transparent return line back to the mud tank. The transparent return line allows visual evaluation of the flow meter operation and direct measurement of the fluid level. The prototype V-L Meter is shown mounted to the top of the return line.

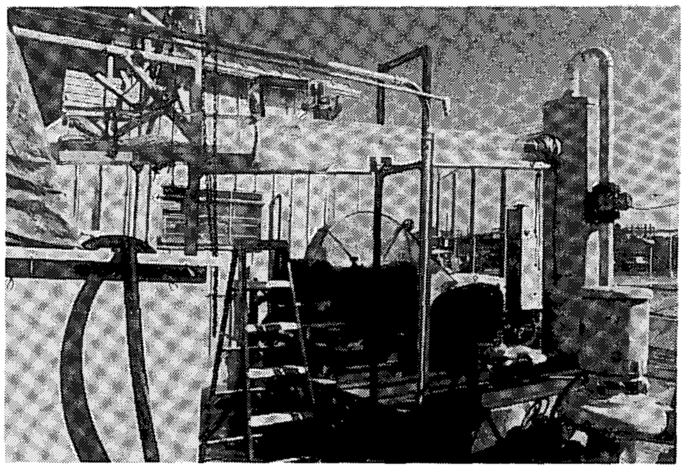


Fig. 3 - Wellbore Hydraulics Flow Facility

Prior to testing the V-L Meter, analytical modeling was performed to determine the theoretical fluid velocity and level in the mud return line. The model is based on an energy balance of the flow in a circular open channel. Typical results from the model are shown in Figure 4 for a cross-section 3 ft downstream of the return line entrance. Shown here is the theoretical fluid level plotted as a function of fluid flow rate and return line angle (with respect to horizontal). Also shown are experimental results obtained by direct measurement of the fluid level in the transparent flow line. The agreement between theoretical and experimental results indicates that the relatively simple analytical model is successful in accurately predicting the unperturbed fluid level in the inclined flow line.

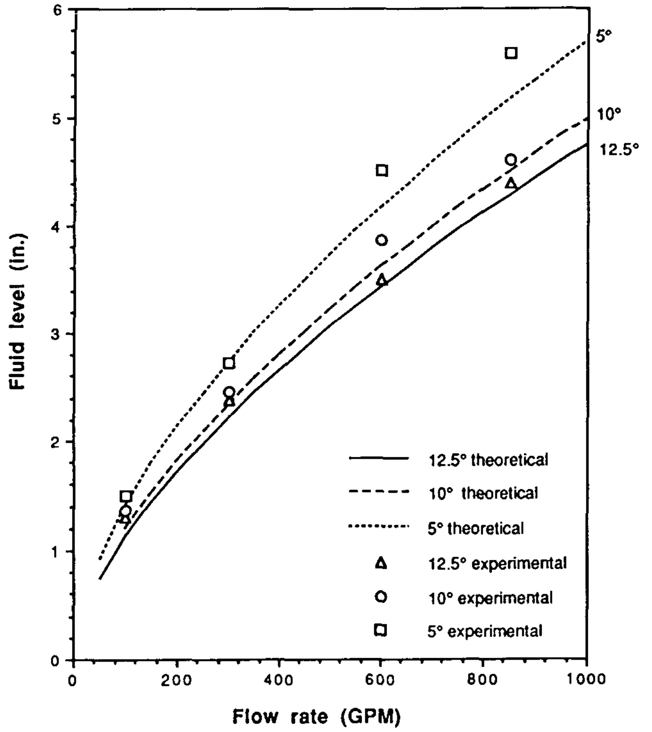


Fig. 4 - Theoretical and experimental return line fluid level for various return line slopes.

The prototype V-L Meter was tested with water during this reporting period. Typical results are shown in Figures 5 and 6. Shown here are the measured fluid velocity and level as a function of flow rate. Two conclusions can be drawn from these results. First, the measured fluid level is a monotonic function of the flow rate, while the measured fluid velocity reaches a peak and then experiences a negative slope. This implies that a correlation between the measured fluid level and the flow rate can be easily developed, but a reliable correlation between the measured fluid velocity and the flow rate would be more difficult to implement in the field. Secondly, the measured fluid level displays significant repeatability with the flow rate. This implies that a correlation developed in the field between the flow rate and the measured fluid level should be a reliable indication of the outflow rate from the wellbore under varying flow rate conditions.

Various design parameters of the V-L Meter were also evaluated. Typical results are presented in Figure 7, which shows the effects of the excess wheel weight after being partially balanced by a counterweight. These results indicate that the results are relatively insensitive to the excess wheel weight; thus the correlation developed between fluid level and flow rate should not be greatly affected by drilling mud accumulation on the wheel during operation.

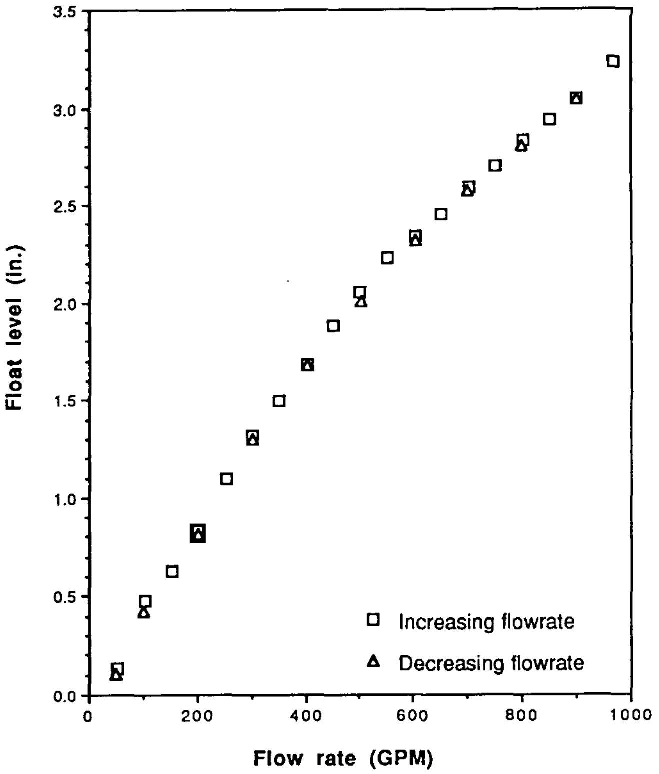


Fig. 5 - Measured fluid level with the V-L Meter as a function of flow rate.

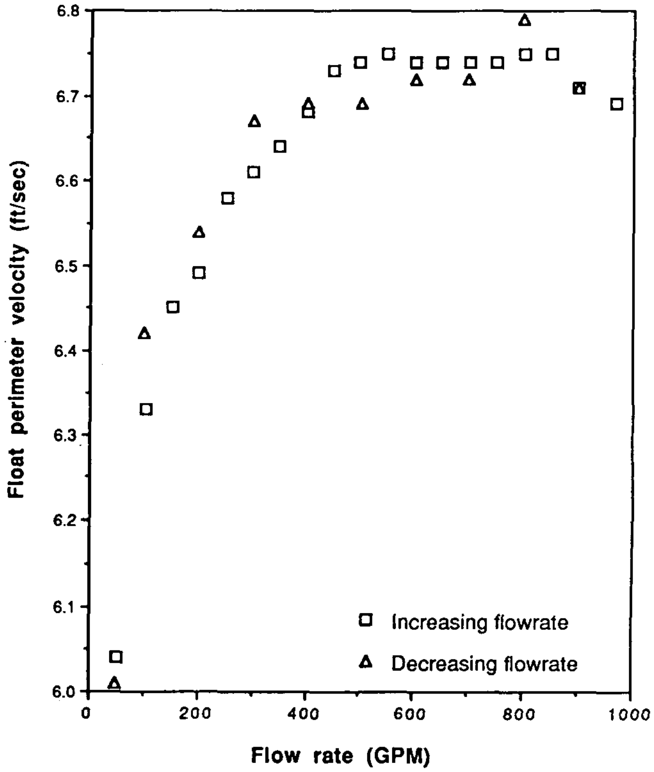


Fig. 6 - Measured fluid velocity with the V-L Meter as a function of flow rate.

Other design parameters investigated include: the wheel shape, diameter, and width; the wheel moment-arm length; and the dashpot setting (used to dampen the wheel movement). Optimal settings for these parameters were determined.

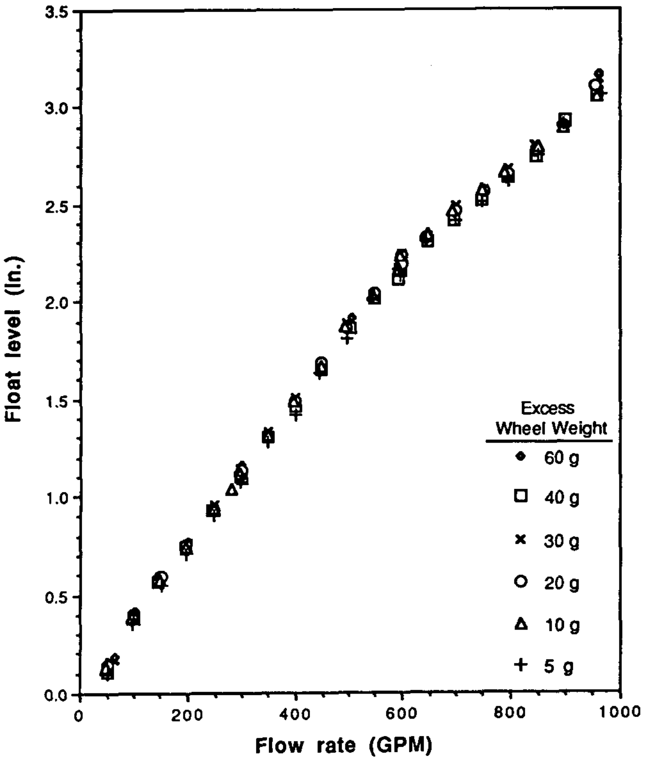


Fig. 7 - Effect of excess wheel weight (weight-counterbalance) on measured fluid level.

Near-term future work on the V-L Meter includes: an investigation of the effects of mud viscosity, density, and solids content; an investigation of the behavior of the wheel perimeter velocity; and development of a data acquisition and display processor that can be used in the field. Ruggedization of the V-L Meter design will also be completed before field trials begin in the Summer of 1991.

DRILLABLE STRADDLE PACKER DEVELOPMENT

The Drillable Straddle Packer under development (Project 7) is a packer assembly for directing the flow of cement into a selected loss-zone interval, as shown in Figure 8. It is intended to prevent channeling of the cement through the mud to the bottom of the wellbore, which is a common problem during lost circulation cementing operations, particularly in large-diameter wellbores. During operation of the Drillable Straddle Packer, cement flows down the drillstring, through the upper packer element, out the exit ports, and into the wellbore and loss zone. The differential pressure that develops across the exit ports causes both the upper and lower packer elements to inflate. This is the primary difference between this packer concept and current commercial packers, which use downhole valving to inflate the packer elements and thus are relatively expensive and cumbersome to use for lost circulation control. The goal of the Drillable Straddle Packer development project is to develop a packer assembly that can be constructed for $500 or less.

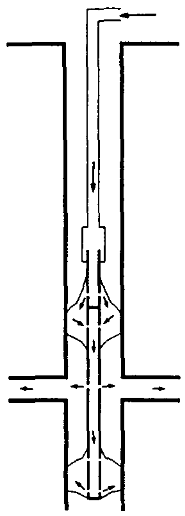


Fig. 8 - Drillable Straddle Packer concept.

The Drillable Straddle Packer is designed to remain downhole after the cementing operation through the activation of a releasable coupling between the packer assembly and the drillstring. Upon completion of the cement pumping operation, a brass ball is dropped down the drill pipe, where it activates the release mechanism to free the packer from the drillstring. The drillstring is then withdrawn from the hole, a drill bit is coupled to the drill pipe, and the packer assembly is drilled through after the cement has set.

Progress made in this project area during the reporting period includes detailed design and fabrication of a prototype drillstring coupler and design and construction of a Packer Test Facility. A photo of the drillstring coupler is presented in Figure 9. The coupler, shown mounted to a stand, would be attached to the bottom of the open drill pipe. Below the coupler is the packer pintle, constructed of CPVC plastic, which would constitute the upper end of the packer assembly. When the brass ball reaches the coupler, it impinges on and seals against a sliding piston. The resulting increase in drill pipe pressure causes the piston to move, which breaks several shear pins and causes the grappling hooks inside the coupler to release the pintle. Two different designs of this coupler have been fabricated and will be evaluated in the near future.

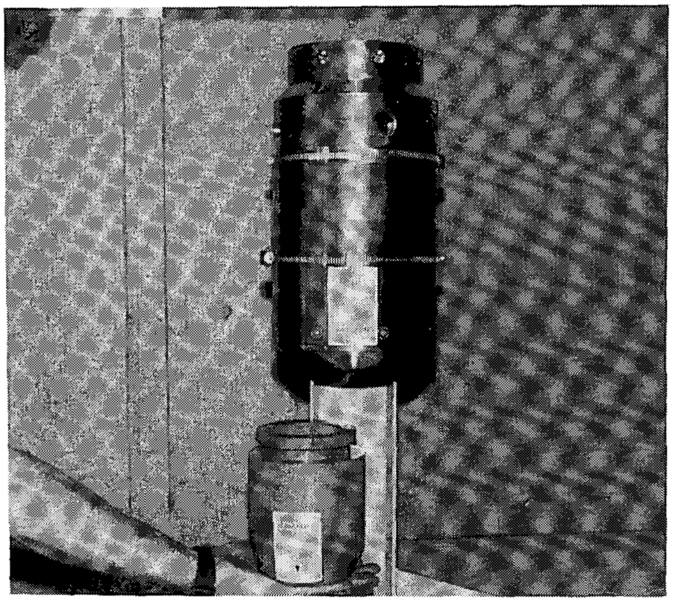


Fig. 9 - Prototype drillstring coupler for the Drillable Straddle Packer.

The Packer Test Facility is shown in Figure 10. This facility is designed to allow evaluation of full-scale packer assemblies. A schematic of the facility is shown in Figure 11. During operation, a packer assembly is placed inside the 16-inch-diameter (14-ft-high) casing, which simulates a wellbore. Drilling mud or water is pumped through the packer, thereby inflating the packer assemblies. The fluid then flows through the packer exit ports and out a port in the side of the casing that simulates a loss zone. Side inlets at the top and bottom of the casing simulate production zones, and fluid is pumped into these inlets with a centrifugal pump to simulate wellbore production. As the packer assemblies inflate, pressure builds behind the packer assemblies. This pressure buildup and the measured flow rates at various points throughout the facility provide a measure of the sealing effectiveness of the packer assemblies against the wellbore wall. Roughness elements attached to the inside surface of the casing provide a simulation of a rough wellbore wall. This test facility will also be used to test the drillstring coupler at the top of the packer assembly. Testing of a prototype Drillable Straddle Packer is planned in the near future.

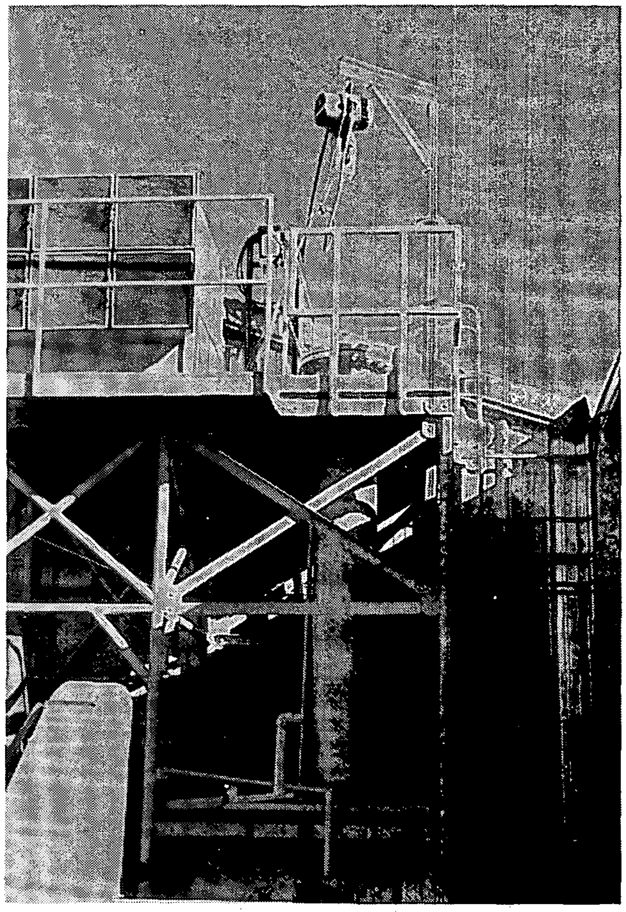


Fig. 10 - Packer Test Facility for testing full-scale packer assemblies.

POROUS PACKER DEVELOPMENT

The Porous Packer under development (Project 6) is a single-element packer assembly that employs a permeable fabric. The concept is shown in Figure 12. The packer is deployed either as a wireline-emplaced or drillstring-emplaced assembly. During operation, a fast-setting fluid such as polyurethane foam or other polymer is pumped into the packer element. As the packer becomes pressurized and expands, the setting fluid leaks through the fabric at a rate controlled by the fabric permeability, fluid viscosity, and downhole pressure. Expansion of the packer against the wellbore wall temporarily prevents or retards the flow of wellbore fluids produced at other formation intervals from entering the loss zone and washing away or altering the chemistry of the setting fluid. Leakage of the setting fluid through the fabric allows the fluid to enter the loss zone and bond with the wellbore and fracture walls. Upon completion of the pumping operation, the packer assembly is uncoupled from the service module (if wireline-deployed) or drillstring (if drillstring-deployed). The packer assembly is then drilled through upon the resumption of drilling.

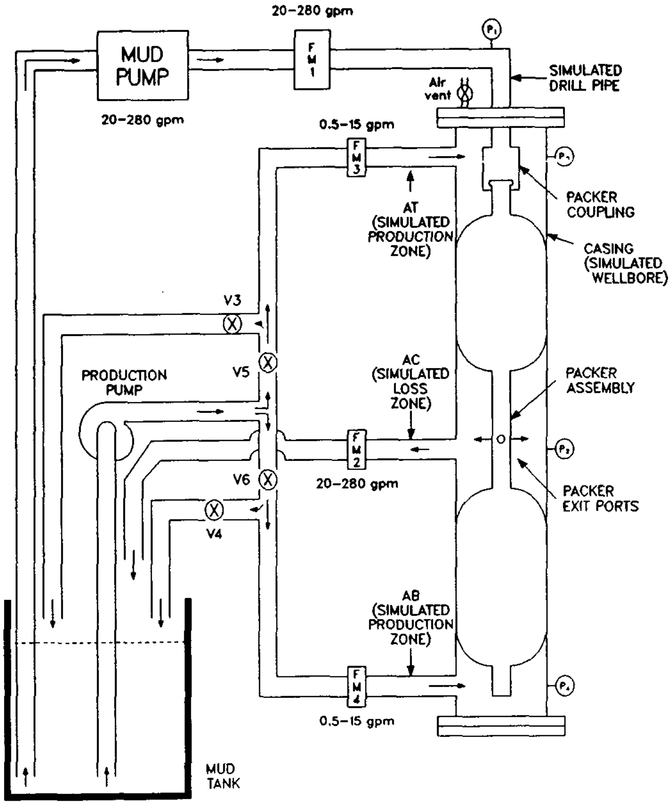


Fig. 11 - Schematic of Packer Test Facility.

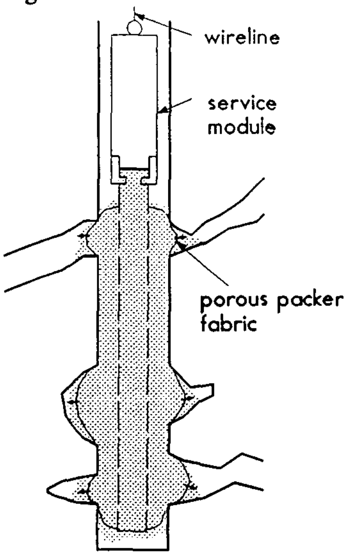


Fig. 12 - Porous Packer concept.

The feasibility of the Porous Packer in large part depends on the feasibility of employing a permeable fabric in the manner required. Consequently, the Packer Fabric Test Facility shown diagrammatically in Figure 13 was designed and constructed. This facility allows a 1-inch-diameter fabric sample to be tested for permeability by extruding a viscous fluid through the sample. Corn syrup is being used as the test fluid because its viscosity can be varied over several orders of magnitude by changing its temperature. During a test, the flow rate of the corn syrup, its temperature, and the pressure drop across the fabric are recorded. This data allows the permeability and strength of various types of fabric to measured and the viscosity requirements of the setting fluid to be determined.

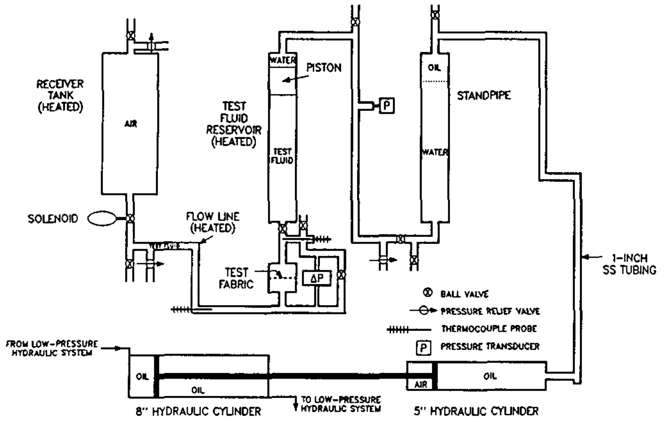


Fig. 13 - Schematic of Packer Fabric Test Facility.

During the reporting period, testing procedures for the facility were developed, the data acquisition and control software were written, and testing was initiated. The fabric samples shown in Figure 14 are currently being tested because of their strength and high-temperature capabilities. These fabrics are various grades of woven fiberglass, some of which are coated with Teflon to control permeability. Testing of these fabrics is expected to be completed in the near future.

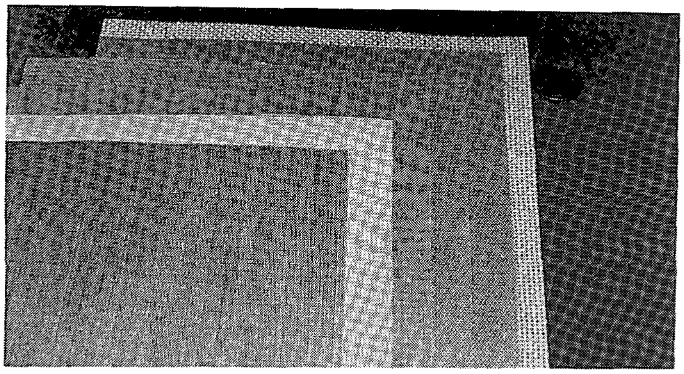
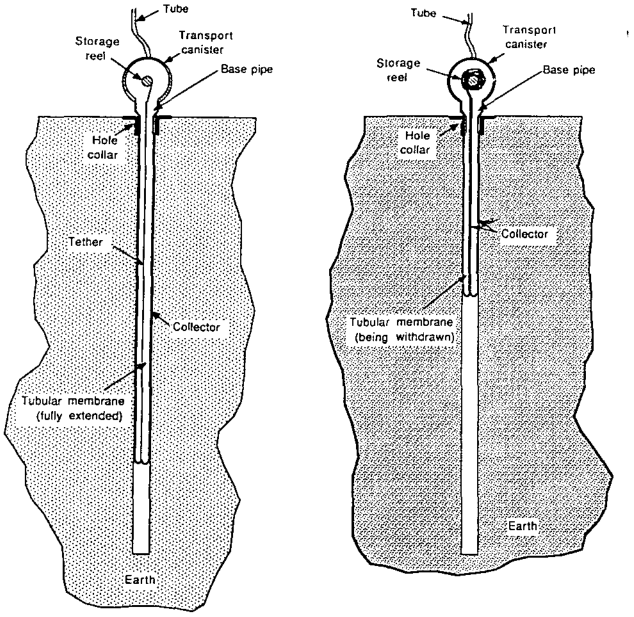


Fig. 14 - Woven fiberglass fabrics under evaluation for the Porous Packer.

PACKER EMPLACEMENT FEASIBILITY STUDY

A conceptual design study of alternative packer emplacement methods (Project 8) was initiated during the reporting period. This study was contracted to Science and Engineering Associates (SEA), Inc., of Santa Fe, NM. SEA has a patent pending on an inversion technique for emplacing membranes downhole for fluid sampling in monitoring boreholes drilled around hazardous waste sites. The concept, shown schematically in Figure 15, employs a thin-fabric membrane that is inverted by internal pressure and forced against the borehole wall. The similarity of the membrane to a packer assembly suggests that this inversion technique might be used to emplace downhole packer assemblies, such as the Porous Packer.



DEPLOYMENT RETRIEVAL

Fig. 15 - SEA-MIST (Membrane Instrumentation and Sampling Technique) concept for pore-fluid sampling.

The contract with SEA provides for development of conceptual, advanced conceptual, and detailed designs of at least one system for emplacing a packer downhole at a depth of 4,000 ft. If the contract is successful in identifying a feasible design, prototype fabrication and testing of such a system may be conducted in later phases of the project.

During the reporting period, conceptual designs for a number of different systems were developed. From these, Sandia selected two systems for advanced conceptual design. When these designs are completed in the near future, a single system will be selected for detailed design. Fabrics selected for the system will be tested in Sandia's Packer Fabric Test Facility.

TECHNOLOGY TRANSFER

The design of laboratory equipment developed under Project 2 (High-Temperature LCM Development) was transferred to two corporations in the oil drilling industry during the reporting period. The detailed design and operating procedures for the Modified API Bridging Materials Tester were sent to these organizations, which had requested the information in order to duplicate our test capabilities for evaluating their LCMs for oil and gas drilling applications. The API Tester is a bench-scale device for pressuring LCM-laden drilling mud against a machined-steel slot and measuring the slot-plugging capability of the LCM. Experimental data obtained by one of the organizations using the tester was found to compare favorably with predictions of the analytical bridging models previously developed at Sandia (Loeppke *et al.*, 1990).

At the request of one of the industry organizations, we also used our Particle Material Properties Tester (PMPT) to measure the mechanical properties of ground walnut shell particles after soaking in water and mineral oil. Such particles are of interest as a second component of a combination LCM that the industry organization is developing. By soaking the particles in water and in mineral oil, the effects of water- and oil-based mud on the compressive strength and elasticity of the particles were determined. It was found that mineral oil does not significantly affect the mechanical properties of walnut shells at room temperature but that water tends to make the shells slightly more elastic. An elevated temperature of 200°F does not significantly affect the water-soaked shells, but it does increase the elasticity of the oil-soaked shells.

SUMMARY

As described above, several lost circulation projects have significantly advanced during the period April, 1990-March, 1991. The primary accomplishments for the year are: design, fabrication, and initial testing of the V-L Meter; and the development of three laboratory test facilities that will allow us to fully evaluate our lost circulation hardware before it is taken to the field. In addition, work on several other projects is underway but has not progressed significantly enough to merit reporting at this time.

The V-L Meter and Drillable Straddle Packer should be ready for field testing this year. Other technologies, such as the Porous Packer and cementitious mud formulations, will require significantly more development and laboratory testing before they will be ready for field trials.

As discussed in Glowka (1990), the technologies being developed under the various projects are estimated to reduce lost circulation costs by an average of 27-48%. These estimates are based on detailed cost and time estimates for using the various technologies in lieu of the standard cement treatment currently in common use in geothermal drilling.

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ACKNOWLEDGEMENT

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BOREHOLE RADAR FOR GEOTHERMAL APPLICATIONS

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INTRODUCTION

Locating fluid-filled fractures in a geothermal reservoir has been the objective of several instrumentation development programs. Electromagnetic techniques have seemed particularly promising because of the expected significant conductivity contrast between the fluid-filled fracture and the surrounding rock. High frequencies have also been preferred because of the narrow spatial extent of some fractures and the consequent need for good range resolution. This type of target may not be apparent to a seismic sensing technique. These considerations have led to the investigation of borehole radar for geothermal applications.

The type of borehole radar system which has been most extensively evaluated is pulsed radar. Measurement of distance with a pulsed radar requires the generation of a fast rise time pulse to be transmitted to the target and back to the receiver. The receiver must accurately measure the time of arrival of the leading edge of this return pulse. Although this technique is capable of giving good range resolution, a thorough evaluation reveals several limitations.

One limitation of the pulsed radar is its requirement for a wide bandwidth antenna. The wide bandwidth is required to preserve the pulse rise time and provide good range resolution. But wideband antennas are difficult to package in the small size needed for the borehole environment. Achieving the required bandwidth also forces trade-offs of other desired antenna properties, such as good coupling efficiency and directionality.

Another disadvantage of a pulsed borehole radar is a result of the nature of the geothermal medium. A typical geothermal reservoir has a high water content, leading to high attenuation of electromagnetic signals with frequencies above a few megahertz. This high attenuation could be avoided using a low operating frequency, but the low frequency will result in poor range resolution since the sharp rise time pulse required for good range resolution will necessarily have a high frequency content. The geothermal medium is also characterized by severe dispersion in the material's properties (i.e., the material properties vary with frequency, and the significant conductivity leads to a frequency dependent wave velocity). Because a pulse is composed of a broad frequency spectrum, the pulse will be highly distorted in propagating through the medium. The pulse will not retain its sharp rise time, and therefore range resolution will be lost.

The effects of dispersion are illustrated in Figure 1 for a square wave input pulse with a center frequency of 50MHz as shown in this figure. For the simulation, the earth is assumed to be a 0.6 percent porosity granite with 0.75 ohm-m pore water, which is representative of some geothermal reservoirs. Shown in the figure are the resultant wave forms after the square wave input pulse has propagated 5m (solid line) and 10m (dashed line) through the earth. The decrease in magnitude of the pulse between the 5m and 10m results is due to wave attenuation. The fast rise time of the input pulse, which contains significant frequency content, is lost due to dispersion (i.e., due to the frequency dependence of the phase velocity). The range resolution of the pulsed system in the dispersive medium will be very poor.

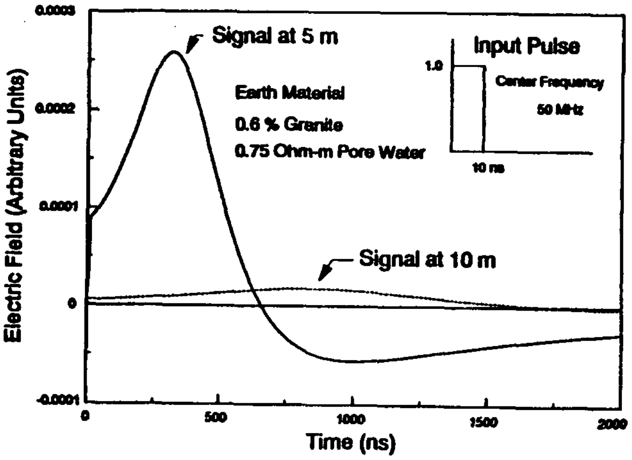

Figure 1

Simulated Response of Geothermal Medium to Pulse Input Showing the Effect of Dispersion

The effects of dispersion can be minimized or even eliminated by using a CW system. For a continuous wave (CW) radar system, the transmitting antenna transmits a single, continuous sinusoidal wave at a single frequency. Since the wave contains only a single frequency, the wave travels at a single velocity and dispersion does not exist. The CW wave is still attenuated in the same way as the pulse.

A CW radar has other advantages when the instrument must be packaged for the borehole application. The antenna for the CW system will be a narrowband antenna, which is more suited to a small volume package. For comparable range resolution between the CW and pulsed systems, the CW system can operate with a frequency about equal to the fundamental frequency of the pulsed system. The high frequency content of the pulse is not required for the CW system. This avoids the problem with high attenuation of these frequencies. It also alleviates the need for high frequency electronics which complicated the design of the pulsed system.

These considerations have led us to begin the evaluation of a CW borehole radar system. In particular, we are considering a CW system which uses directional, steerable antennas to provide another measure of distance to the target, in addition to the time-of-flight measurement. This system could lead to a less costly radar than existing instruments and a simpler data interpretation technique.

THE CW RADAR WITH BEAM STEERING

Whether considering pulsed or CW systems, the classical radar approach to distance measurement is based on measuring the time delay for the propagation of the electromagnetic energy to the target and back. Distance is computed from time-of-flight by dividing by the propagation velocity in the intervening medium. Unfortunately, the propagation velocity depends on the dielectric constant, which is not always a known parameter of the earth. To alleviate this concern with the time-of-flight systems, we conceived the concept of a narrow-band, CW radar, using simple antenna elements, which would augment the distance measurement by the use of geometry. Figure 2 shows the concept: Two antennas are separated by a vertical distance "S" within a borehole, and their antenna patterns make angles θ_1 and θ_2 with the vertical. The target is illuminated by the upper antenna, the source, and its reflection is detected by the lower antenna as a receiver. The horizontal range to the target, "D", is given by:

$$D = \frac{S}{\text{Cotangent } \theta_1 + \text{Cotangent } \theta_2} \quad \bullet$$

If either θ_1 or θ_2, or both, can be varied electrically, the reflecting feature can be examined in more detail.

While this measurement is conceptually simple, there are complications associated with its practical implementation. For example, the beam widths of even the most directional borehole antennas will still be wide, and their region of overlap will typically be larger than the desired range resolution. This difficulty can be mitigated by the CW system, which allows coherent detection and accurate phase measurement of the return. Since different ray paths within the total beam width will have different propagation distances, and hence, different phases at the receiver, they can still be discriminated at the receiver by "locking" the receiver to a particular phase angle. Scanning the antennas to produce a maximum return amplitude will then enable the triangulation formula given above to be applied with the angles θ_1 and θ_2 set equal to the angles corresponding to the maxima of the antenna patterns. The phase of the return still provides time-of-flight information, so two distance estimates are obtained with this system. Comparison of several measurements of this type could also provide an estimate of the dielectric constant of the media.

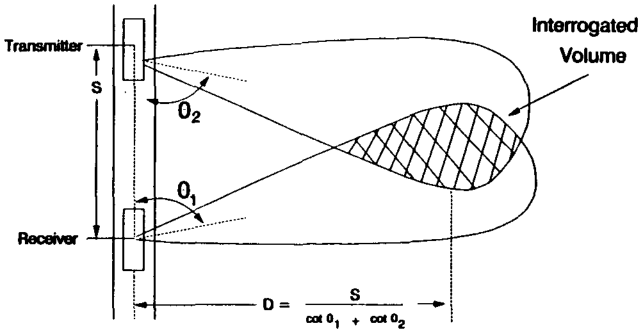

Figure 2
Measuring Distance by Triangulation Instead of Time-of-Flight

ANTENNA DESIGN

Feasibility of the steerable borehole radar concept is dependent on the availability of a suitable antenna. The direction and width of the beam pattern should be independent of the media properties. That this is difficult to achieve in a conducting media has been recognized for many years. This is because, in the words of R. K. Moore [1], "there is attenuation of the contribution of one end of the antenna relative to that from another end of the antenna closer to the point of observation". Since the ranges from the antenna that the fields can be expected to propagate in the geothermal media are only on the order of tens of meters, the beam pattern of antenna whose length is a very few meters or more would be strongly dependent on media properties.

We have modelled the vertical electric dipole antenna in a conducting media, following the work of Moore and others [1-7]. We have found that an array of short dipoles can produce a beam pattern which is independent of media properties provided it obeys a "size rule". This size rule requires that the maximum array dimension not exceed one-tenth of a wavelength in order for the pattern to be independent of media properties at distances greater than one wavelength from the antenna.

Polar patterns from a two element dipole array are shown in Figure 3. The overall length of the array is 0.1λ. The direction and width of the major lobe of the pattern changes very little from one to four wavelengths away from the antenna. This illustrates that the short dipole array can provide a stable, well-formed pattern in a conducting media.

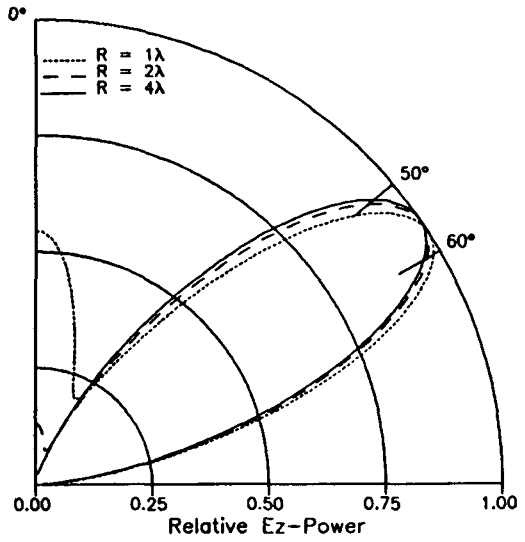

Figure 3

E_z-Power Patterns For 2 Colinear Dipoles

The beam direction is varied by controlling the phase with which the dipole outputs are combined. Figure 4 shows this behavior for an array of 2 dipoles operated in-contact with a wet geothermal media. The combined angle can be varied about 34° with this arrangement.

If electric dipoles are used for both source and receiving antennas, there will be substantial direct coupling between them. However, if a small horizontal loop is used as source, its electric field cannot be detected by an array of vertical electric dipoles centered beneath it. Moreover, if two horizontal magnetic dipoles, at right angles to each other, are used as a source, and the phase of their currents adjusted, the source beam can be used to perform an azimuth-scan.

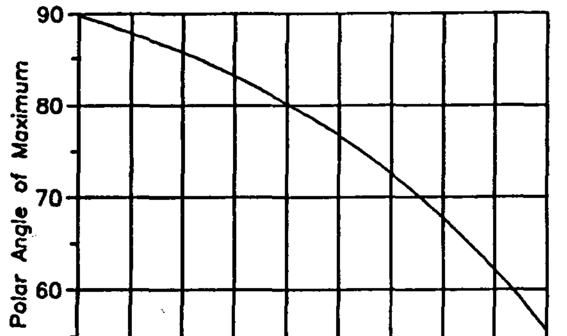

Figure 4

Polar Angle of Maximum Field vs Phase Angle Two-Antenna Array

The patterns of a two-magnetic dipole array for various values of phase difference between the dipoles are shown in Figure 5. The figure illustrates that ten degrees of scan angle (which may be all that is required for many applications) can be obtained by varying the phase difference between the dipoles by only ten degrees.

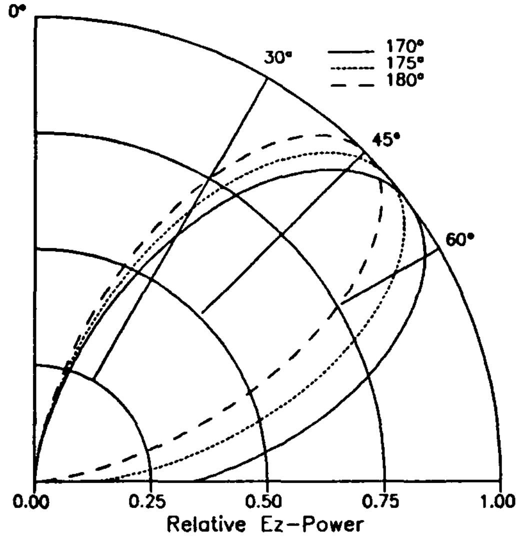

Figure 5

E_z-Power Patterns From an HMD 2-Array With Phase-Shift Angle as a Parameter

CONCLUSION

An initial evaluation of a CW borehole radar system with steerable antennas has been completed. Candidate antennas have been identified which meet the size requirements for borehole applications. The patterns of these antennas are not dependent on the properties of the surrounding media when the antenna dimensions are less than one-tenth wavelength. The beam patterns can be steered adequately to allow the volume of earth within several meters of a borehole to be investigated.

ACKNOWLEDGEMENT

The authors would like to acknowledge L. C. Bartel for providing Figure 1.

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HOT DRY ROCK TECHNOLOGY

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

SUMMARY - HOT DRY ROCK

George P. Tennyson, Jr., Session Chairman
U. S. Department of Energy, Albuquerque Operations Office

The utilization of geothermal energy sources has, up till now, been limited almost entirely to locations which combine a source of suitable heat and a source of water beneath the surface of the Earth. That is, we mined steam. However, there are much larger resources available which have the heat (the energy resource) without the water to transport that heat to the surface for use. Further, as the water supplies are used up in the hydrothermal fields currently being utilized, there is a strong motive in the existing capital investment to revitalize those fields. That is, we must begin to mine heat as well as steam. Generally this is accomplished by introducing water to the hot dry region and then recovering the heat energy as steam.

The techniques for introducing, recovering and utilizing the water necessary to recover the heat from below the surface of the earth is the subject of Hot Dry Rock (HDR) Heat Mining Geothermal Energy Development Program. The added element of supplying the water introduces costs which must be recovered and still leave us with energy which is cost competitive. It has long since been demonstrated that Hot Dry Rock technology can supply energy. The basic barrier to its utilization as a source of energy is the long term cost of that energy. The stated Level I objective of the HDR Program is to develop the technology of HDR heat mining sufficiently by 1997, to demonstrate that electric power can be generated from the heat of the earth at costs in the range of 5-8 cents per kilowatt-hour. This is a problem worthy of the industry/utility/Government partnership that is the central theme of this review.

About two decades of work have been done to prove the feasibility of the HDR concept and to provide a test case. However, before investment in the first commercial system can be justified to investors, there must be sufficient data on which to base reservoir lifetime computations and a reasonably accurate knowledge of the associated energy extraction rates, water requirements, and system costs.

The purpose of the first paper was to outline a path toward the commercialization of HDR heat mining technology, discuss the problems associated with that path, propose solutions to those problems and then to show what a commercial facility might look like which would be completed about the year 2000.

The economics of hot dry rock are the most sensitive to the cost of drilling down to the hot rock, and therefore to the local rate of temperature increase with depth or, more directly, to the depth required to obtain the desired temperature. Several economic studies have shown that where there is a high thermal gradient, electrical energy can be produced from HDR at costs competitive with fossil plants and which meet the program objectives. But despite the economic promise of HDR, no operating HDR electrical generation facility exists at present. Thus, the assumptions on which these studies are based remain to be directly supported. At present they are based on broad geothermal industry data, information from other related industries, and extrapolations of the meager data from HDR experiments conducted to date. Long term testing at the HDR reservoir at Fenton Hill, New Mexico, is expected to provide the next substantial step in support of these favorable cost forecasts.

From an environmental standpoint, when combined with environmentally sensitive plant engineering including closed loop operation, HDR systems can have environmental impacts in a class with the best of the alternative energy sources. There would be no releases to the atmosphere except waste heat. The return of fluids would be thousands of feet below the water table or acquifers. Further, land usage would be only that required for the wellheads and the plant itself. And finally, since the reservoir is artificially created and restricted only by the availability of the hot rock at depth (without the coincident availability of water at depth) the location is more flexible, allowing location near power lines or away from environmentally sensitive locations.

The 1986 30-day closed loop flow test of the Phase II reservoir gave very encouraging results, but was not sufficient to determine energy draw down. Since that time we have been preparing for the Long Term Flow Test (LTFT).

The primary purpose of the LTFT is to demonstrate that energy at useful temperatures can be extracted from the Phase II HDR reservoir over an extended period of time, relevant to that required to make a power plant profitable at competitive energy prices. The physical plant will be completed by late summer of 1991, and the LTFT will begin subject to funding and the actions which must follow receipt of funding for the test.

But even successful conclusion of the LTFT doesn't let the HDR concept finally off the hook. Development and operation of a second site will be required to prove the generality of the Fenton Hill techniques and results. Additionally, the second site should accommodate what amounts to the pilot plant for the first generation of HDR commercially viable power plants. As such, not only will the geophysical factors be important, but also the marketing factors (the nearby need for power at the prices which can be justified) but also the political factors. Local acceptability and interest will be strong inputs as will the other political factors that weigh so heavily in R&D funding.

The California City of Clearlake and Mono County have shown substantial interest and are working toward answers to the questions that precede the selection of a second HDR site. Certainly they are working well with LANL, the State and the local authorities to demonstrate their interest and commitment, establishing the kind of situation that we can accept.

Advanced HDR systems will probably not be run entirely in the simplistic way that the R&D efforts have been conducted to date. With implementation of the first commercial plants there will arise the questions of multiple well and cyclic operation. Research on the reservoirs and their operations will not be complete, then, with the successful conclusion of the LTFT or even the completion of a second site.

Concurrent with this system engineering, research is continuing on the reservoir engineering, tracer fluids, microseismic techniques and other research required to help in the design and analysis of the future systems destined for utilizing this geothermal resource.

However, the above discussion of the status and future of the HDR program has breezed past the highly specific work that has had to be done in designing and constructing the Fenton Hill plant for the LTFT. The design of that plant to exploit the million-gallon reservoir has posed a number of unique technical challenges which we believe have been met. Among these were the needs to utilize the existing facilities and commercially available equipment.

The existing facilities included the two wells identified as EE-2A and EE-3A. EE-3A will be utilized as the injection well, and EE-2A will be used to bring the hot geothermal water to the surface, after it has been pumped through the rock fractures and thereby extracting heat from the surrounding rock. On bringing the water to the surface, however, it brings with it dissolved minerals, sediment and gases. Consequently, a separator is used to remove the gases and solids. The heat exchangers then remove a significant portion of the heat energy, as would happen in a generating system, the energy removed is measured and the fluid is returned via the injection pumps, along with makeup water, to complete the cycle.

The plant is designed and constructed in accordance with codes and standards applicable to a commercial power plant. The pressure boundary design of vessels and piping conforms to the ASME B & PV Code and the ANSI Power Piping Code.

This sounds simple enough until one notes that the injection pumping system alone weighs 70,000 pounds and each of the two units can provide a discharge pressure of 3900 psi with a flow ranging from 84 to 168 gpm, with the feasibility to be configured into even higher pressures. The units together provide over 1000 horsepower and are made with the required corrosion resistant materials.

The air-cooled heat exchangers are the oldest parts of the system, and had been used in the previous flow tests. After cleaning and inspection they were found to be free from significant degradation or pitting.

The makeup water mentioned earlier is necessary to compensate for losses via 1) migration outside the boundaries of the reservoir (estimated to be about 7 to 9 gallons per minute at 3900 psi) and/or 2) growth of the reservoir above 3900 psi (estimated to be about 60 to 70 gpm at a pressure of 4500 psi.) Two 50 hp pumps are available to provide this water at 1000 psi.

The separator removes free vapor and suspended solids from the geothermal fluid, aiming at providing a single pahse fluid, free of solids through the surface plant. Installed upstream of the heat exchanger, the separator can remove 130,000 cu ft of vapor and 170 pounds of solids per day.

If it still sounds simple, consider the valving, pressure and heat measuring equipment, and operational capabilities that have been designed in so that the system will operate smoothly and safely. It is nearing completion at this point and we're very proud of it.

But the fundamental reason for all this work is the HDR reservoir - a reservoir formed in 1983 by injecting 5.7 million gallons of water at pressures up to 7000 psi. The pressure opened several sets of pre-existing tight joints rather than fracturing previously unflawed crystalline rock. Today we have an ellipsoidal-shaped region of fractured rock with an accessible volume of 20 million cubic meters with a mean temperature of 240 degrees centigrade. It is about 400 m long by 350 m high by 150 m thick. Further, the unfractured boundaries of this large volume are very tight, with a fluid loss rate of less than 2.5 gpm at a surface pressure of 2200 psi. Rather like a watertight shopping bag full of hot gravel and fluid.

The tests that have been done indicate that we can expect a water loss rate of 8 or 9 gpm, at most, at an injection pressure of 3600 to 3700 psi, the injection pressure for the first four months of the LTFT.

Thus, the reservoir has been investigated in detail over the years by means of pressurization and flow tests, by means of microseismic studies, and by means of tracers in the fluids that are injected and measured for times of passage and absorption as they pass through the reservoir. The reservoir will be more fully characterized by the LTFT measurements and by the studies and experiments that will be done in parallel.

This is as it should be. For it is the reservoir and its characteristics around which the systems and operations are designed. It is the behavior of the reservoir which will in the long run determine the economic viability of the HDR concept. But it is a reservoir which human beings have constructed in the face of nature's reluctance to release the energy in Hot Dry Rock. It is a hard won but vital step in harnessing the geothermal energy of the Earth for the use of mankind.

Moving HDR Technology Toward Commercialization

by

David Duchane
Earth and Environmental Sciences Division
Los Alamos National Laboratory

Introduction

Conventional geothermal resources are currently being developed in many parts of the world where naturally occurring steam or hot water can be extracted from the earth. These hydrothermal resources, however, provide access to only a small fraction of the energy contained within the crust of the earth. In most regions, the heat of the earth is contained in hot rock at depth. The total amount of energy available in the form of hot dry rock (HDR) is extremely large. Estimates place the magnitude of the accessible HDR resource base worldwide at greater than 10 million quads (Armstead and Tester 1987) (1 quad equals 15 quadrillion BTU, or the energy content of about 180 million barrels of oil). For the past two decades, the Hot Dry Rock Program sponsored by the United States Department of Energy at the Los Alamos National Laboratory has been directed toward the development of methods to extract the vast amounts of energy which exist in HDR.

The stated Level I Department of Energy objective for the Hot Dry Rock (HDR) Heat Mining Geothermal Energy Development Program is to "...provide the technology to enable industrial hot dry rock projects to generate power at 5-8¢/kWh by 1997." (USDOE 1989) Fundamental to this objective is the ultimate goal of bringing HDR technology to commercial fruition. Indeed, all of the work done in this exciting research and development area will be for naught if we fail to move as rapidly as possible toward the utilization of this abundant and clean energy resource as one of the important elements in the future energy supply of the world. The purpose of this paper is to outline a path toward the commercialization of HDR heat mining technology, to discuss the potential obstacles in such a path, to propose techniques for overcoming those obstacles, and finally, to present a picture of what a commercial HDR facility may look like near the beginning of the next century.

The Economic Promise of HDR

Because drilling down to hot rock is the primary variable cost element in the development of an HDR system, the cost of production of electricity from HDR is highly sensitive to the local geothermal gradient (The rate at which the local temperature of the earth increases with depth). A number of economic analyses have shown that electrical energy could be produced from HDR at costs which are competitive with fossil fuel plants and which meet or approach the Level I objectives of the program. These studies were carried out at different times and relied on a variety of different assumptions regarding factors such as resource quality, drilling costs, and power plant efficiency, among others.

Results of all these studies were recently combined and integrated by the Energy Laboratory at the Massachusetts Institute of Technology (MIT) to produce a cost profile based on the quality of the resource as reflected in the geothermal gradient (Tester and Herzog 1990). Some of the results of the work by MIT are summarized in Table 1. It is clear that electric power from high grade HDR resources, at costs of 5-7¢/kWh, could be economically feasible today, but that for lower grade resources technical and operational advances are needed to lower the energy costs to competitive levels. Possible ways to achieve some of these needed improvements are discussed later in this report.

Table 1

Busbar Electric Power Costs (Current Technology)

Resource Grade	Electric Power Cost, ¢/kWh
High (80°C/km)	5-7
Medium (50°C/km)	8-12
Low (30°C/km)	>15

While the economic promise of HDR energy is bright, the uncertainties associated with some of the assumptions on which all of the HDR economic studies have been based are relatively high. No operating HDR facility exists at present. Thus there is no concrete example by which to confirm or refute the assertions used as the basis of economic calculations of the cost of energy from HDR. Therefore, inferences have been drawn from geothermal industry data, information from related industries, or extrapolations of findings from the tentative and fragmentary HDR experiments conducted to date. Long-term testing of the world's only viable HDR reservoir at Fenton Hill, New Mexico, should put more substance behind current favorable estimates of HDR economics and point the way to future development of the technology.

The Environmental Promise of HDR

In a world in which environmental concerns are becoming ever more important, HDR offers the promise of a clean and abundant energy source. Based on the demonstrated favorable environmental qualities of hydrothermal energy, together with environmentally sensitive plant engineering, HDR systems can be designed to have minimal environmental impacts which put this technology in a class with the best of the other alternative energy sources. When operated as a closed-loop, HDR systems release no atmospheric emissions except waste heat. Because HDR reservoirs are by design located thousands of feet below the water table, there are no problems with contamination of ground or surface waters.

Like hydrothermal plants, land usage for HDR facilities can be confined to the small space required for the wellheads plus the power plant itself. Plant siting, however, should be more flexible than for hydrothermal installations, since HDR reservoirs are fully engineered and thus not dependent upon the existence of hydrothermal anomalies. In the most optimistic scenario, commercial HDR plants could be sited essentially at the point of energy demand, thus eliminating the need for long runs of high voltage power lines together with the attendant land use and electromagnetic field concerns.

No long-term wastes accumulate as a result of the operation of an HDR power plant. There are no by-products of the process except waste heat, and shut-down of the facility at the end of its useful life can be accomplished by straightforward procedures already proven in the geothermal, oil and gas industries.

HDR Development to Date

The HDR Program grew from ideas conceived in the early 1970's by researchers at the Los Alamos National Laboratory. They reasoned that the vast store of energy contained in the crust of the earth could be extracted by employing drilling and hydraulic fracturing techniques already being used successfully in the oil industry. A patent describing the essence of the HDR process was issued in 1974, but has since expired (Potter, Robinson, and Smith 1974).

Also in 1974, work began on the construction of the world's first HDR reservoir at Fenton Hill. It was constructed at Fenton Hill, a site in northern New Mexico about 35 miles by road west of Los Alamos. The purpose of this effort was to demonstrate that thermal energy could be mined from the earth by drilling a pair of wells deep enough to penetrate into hot, crystalline rock, connecting the wells by means of hydraulic fracturing, and circulating water through the fractures to extract the heat from the rock and bring it to the surface (Tester, Brown, and Potter 1989). By 1977, this "Phase I" HDR system had been developed at a depth of 2,600 m (8,500 ft) in rock at temperatures of 185°C (365°F). This system was enlarged in 1979, and operated for about a year. It was clearly demonstrated that heat could be extracted from the earth at reasonable rates without insurmountable technical problems or serious environmental effects.

In 1980, work was begun at Fenton Hill on a larger, deeper, and hotter HDR system. Under the auspices of the International Energy Agency, Japan and West Germany became involved in the project both technically and financially. In developing this "Phase II" system, two wells were sunk, with the lower portion of each well drilled at an angle of 35° to the vertical. Fracturing operations were carried out in the lower well with the expectation that vertical fractures would be opened to form a connection to the upper well.

After numerous attempts, however, it became obvious that no connections between the two wells were likely to be achieved in this way. In fact, signals from the microearthquakes caused by the fracturing operations indicated that a large reservoir was being formed, but that it was tilted approximately along the trajectory of the angled portion of the lower wellbore and would never intersect the upper well. In 1985, a decision was made to redrill the lower portion of the upper wellbore into the region of microseismicity. Once this had been done, a connection was rapidly established. The Phase II reservoir as it appears today is illustrated in Figure 1.

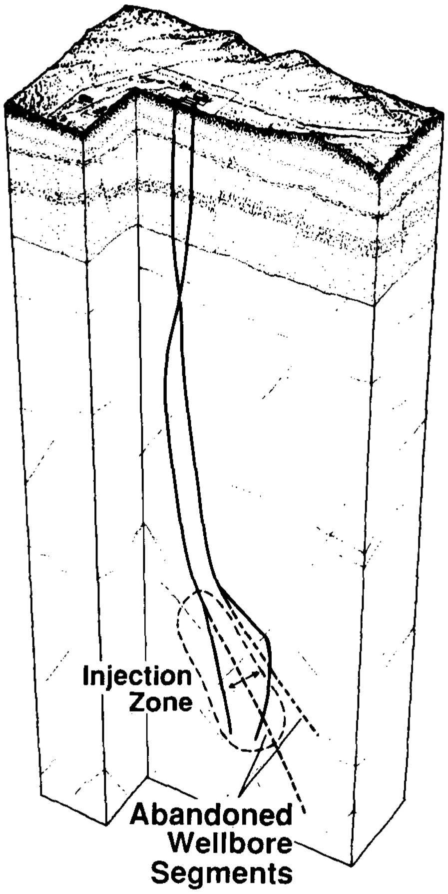

Figure 1. The Phase II HDR Reservoir.

During the late spring of 1986, a 30-day closed-loop flow test of the Phase II reservoir was conducted (Dash 1989). This test included numerous brief shutins, and other pressure and flow rate variations. It is possible, however to generalize the results in regard to some important system parameters as shown in Figure 2.

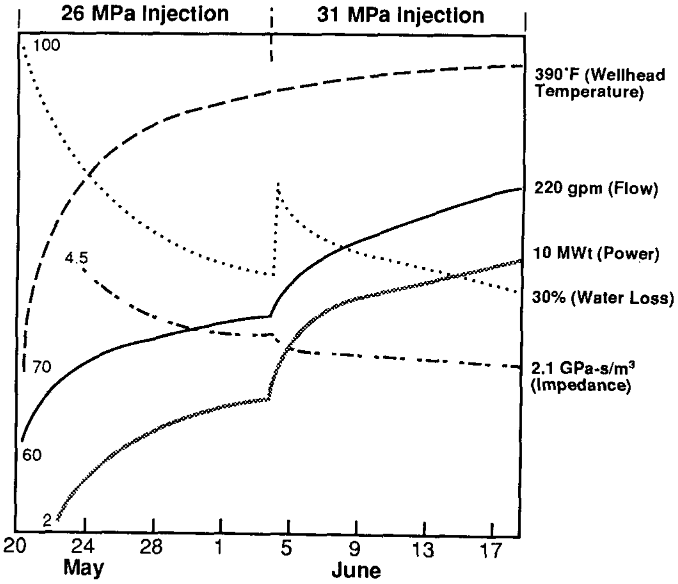

Figure 2. Results of the 30-day flow test of the Phase II HDR System.

The production flow rate, fluid temperature and, consequently, the thermal power increased throughout the duration of the test. By the end of the experiment, the power level had reached about 10 MWt, with water being returned to the surface at a rate of about 220 gpm and a temperature of 190°C (375°F). The flow impedance continually declined during each constant injection pressure phase, as did the rate of water loss. At the conclusion of the test, the flow rate at the production well was approximately 70% of the fluid injection rate.

Subsequent experiments have demonstrated that most of the "apparent" water loss in this reservoir is due to storage of water in the microcracks of the reservoir rock and at its periphery (Brown and Robinson 1990). As these fill up, water consumption declines under conditions of constant pressure, as illustrated in Figure 3.

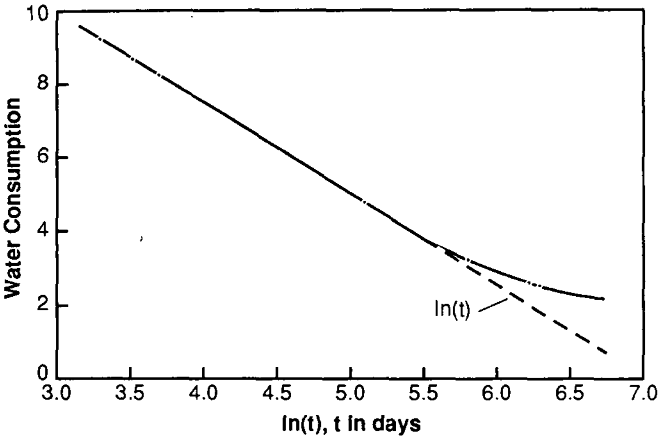

Figure 3. Water Consumption in the Phase II HDR Reservoir at 15 MPa Pressure.

During the period 1987-1991, preparations have been underway for a long-term flow test (LTFT) of the Phase II HDR reservoir. In 1987, repairs were made to the production wellbore to assure that it has the integrity to withstand extended circulation tests (Dreesen, et al., 1989). Since 1988, we have been building a surface plant for the LTFT. While the details of the design and construction of this plant are discussed in a separate paper, it is important to note here that it is being constructed to industrial standards which should permit continuous, reliable operation and assure that the plant itself does not become a stumbling block in the conduct of the LTFT.

Future Plans for HDR Development

The Long-Term Flow Test (LTFT)

The primary purpose of the LTFT is to demonstrate that energy at useful temperatures can be extracted from the Phase II HDR reservoir over an extended period of time. If successful, it will provide an example of the potential of HDR and a benchmark for the development of future HDR systems.

The objectives of the LTFT fall into three broad categories. Technical goals are associated with evaluating the useful thermal lifetime of the reservoir, quantifying water consumption rates, measuring production fluid flow and temperatures, and determining the power production of the reservoir. Operational goals are directed toward understanding the important operating parameters of the system including maintenance requirements, ongoing costs, and other relevant information. Finally, the scientific goals of the test are aimed at increasing our levels of understanding in seismology, tracer technology, and underground reservoir engineering.

The detailed protocol for the conduct of the LTFT is still being developed, but the general schedule of operations will include a short start-up/shakedown period to verify system operating parameters, an extended term of operation under conditions of constant injection pressure, and a series of short experiments toward the end of the test to explore the potential of some novel techniques for operating HDR systems. The term of the LTFT will be one to two years contingent upon the funding provided by the Department of Energy. While the physical plant needed to conduct the test will be in place by late summer of 1991, the actual start-up date of the LTFT will again be subject to funding considerations and time constraints imposed by the necessity to put in place contracts for operating personnel, services, and fuel.

Extensive monitoring, logging, and tracer programs will be mounted during the LTFT. Regular geochemical analysis and corrosion monitoring schedules will be maintained and automated recording will be employed to measure important operating parameters such as fluid temperatures, pumping rates, pressures, water consumption, etc. A continuous seismic monitoring effort will be carried out in shallow wells located at various points near the reservoir, with additional seismic observations in a deep-well station during periods of anticipated seismicity. Downhole temperature logs will be run monthly. Other logging schedules are still being worked out.

Two types of tracers will be employed on a periodic basis. A radioactive tracer will be used on a regular schedule to follow changes in fluid flow paths through the reservoir over the span of the test. A newly developed temperature sensitive tracer (Birdsell and Robinson 1989) will see its first field application during the LTFT. This tracer is an organic compound which reacts with the reservoir fluid at the high temperatures characteristic of the hot reservoir, but not at lower temperatures. It should allow us to study the thermal drawdown of the reservoir over the course of the LTFT, and even provide information which can be used to predict the useful thermal lifetime of the reservoir for many years into the future.

By the close of the LTFT, we should have sufficient information about operation of an HDR facility to permit critical decisions about a second HDR site to be made. If the Fenton Hill system operates as anticipated with limited thermal drawdown and minimal operational problems, then construction of the second HDR heat mine will be relatively straightforward although lessons learned in the LTFT may be applied to increase the efficiency and/or improve the economics of the second facility. In the event the LTFT is plagued by operational problems, these will be addressed prior to final design and construction of the second system.

If significant thermal drawdown of the Fenton Hill Phase II reservoir takes place during the LTFT, modifications in the design concepts and operational schemes for HDR reservoirs, as well as additional experimental work, may be required prior to building a second HDR plant. Rapid temperature decline or severe and prolonged operational problems during the LTFT are not anticipated based on all our experience with HDR heat mines to date. Were they to occur, it would force a rethinking of our basic ideas about HDR heat mining.

The Second HDR Heat Mine

The construction of a second HDR heat mine at another site is extremely important to prove that HDR can be developed in a variety of locations and that the success achieved at Fenton Hill represents the general case and not just a fluke of nature. In addition, the second site must be more oriented toward economic considerations than has been the case at Fenton Hill. While the next HDR facility does not have to be strictly competitive with fossil fuel power plants, it should clearly demonstrate that HDR can be an economic energy source. In order to do this it will be necessary to produce and market power on a regular and continuous basis over a period of years. In effect, the second HDR facility will be the pilot operation for commercial HDR plants of the future.

A number of factors of more or less equal importance must be considered in selecting the second HDR site. Resource quality is, of course, a paramount consideration. At this stage of its development, any hope for economic exploitation of HDR lies in reaching the resource at a reasonable cost, and this can only be done today in high gradient areas. The details of the local geology are also extremely important, and for the same basic reason. Insurmountable technical difficulties in drilling, completion, or reservoir creation could result in failure of the project and lead to a major setback in the acceptance of HDR technology by the energy community. Excessive water consumption could also make continuous operation impossible and cast the economics in an unfavorable light.

Political considerations will play a key role in the selection of the second HDR site. A receptive political climate will speed the process of obtaining the required permits and local cooperation will be needed to obtain the water to run the facility. Finally, marketing factors will be very important. Since the production and sale of electric power is primary consideration in the development of another HDR site, proximity to a market for such power is essential.

The Clearlake, California HDR Initiative;

At this time, perhaps the most promising location for development of a second HDR facility is the area of Clearlake, California. Located just to the north of The Geysers geothermal area, Clearlake has many of the qualities desired in a second site. Numerous dry geothermal wells have been drilled in the vicinity, and there is no doubt that a resource of extremely high quality exists there. Generally, thermal gradients are on the order of 100°C/km, among the highest in the country.

A significant amount of general information about the HDR resource potential at Clearlake has already been reported (Burns and Potter 1990). Los Alamos is currently working with the City of Clearlake, Lake County, and the California Energy Commission to investigate the HDR potential of the region in more detail. The relationships being developed in connection with this effort will provide a good basis for rapid solution of political questions regarding HDR at Clearlake as they arise. In addition, there is a potential market for power in the area. San Francisco is less than 100 miles away, and production declines at The Geysers may result in locally available transmission capacity.

The most important question regarding the Clearlake area is the local geology. The rock at depth is a mixture of greywacke, chert, greenstone and andesite, rather than granitic as at Fenton Hill, and the area is highly faulted. In addition, as in many parts of the west, water supply may be a problem. As part of the current effort at Clearlake, the local geological regimes will be documented and the most promising site for further investigation of HDR development selected. There is also a possibility of obtaining treated municipal effluent as a source of water for a commercial HDR facility. Pending the outcome of the current study, Clearlake may or may not be the ideal second site for an HDR plant.

Advanced HDR Systems

Profitable operation of commercial HDR plants will depend on implementing the most economic mode of operation that is safe, practical, and environmentally sensitive. Work to date has concentrated on simply demonstrating the HDR is technically feasible, but in the future enhanced modes of production must be developed to make the technology as efficient and reliable as possible. A number of techniques for increasing the efficiency of operation of an HDR plant have been conceived and evaluated in a preliminary fashion on paper (Robinson and Brown 1990, Robinson 1990) but none has yet been tested in practice.

Table 2 provides a synopsis of the important advantages and disadvantages associated with a number of possible ways of operating an HDR system. Running an HDR facility under conditions of reservoir stability represents the base case. This approach is technically the most conservative and it and minimizes water consumption. It may be far from the most economic method of operating an HDR reservoir, however.

Table 2

Possible HDR System Operational Modes

Operational Mode	Important Advantages	Signifcant Disadvantaqes
[illegible])	T[illegible]s [illegible]imal	
Reservoir Extension	[illegible] [illegible]cti [illegible]emonstrated	In[illegible] Use • Reser[illegible] Growth I[illegible]ea[illegible] Pumping C[illegible]t
[illegible]	[illegible]mpi[illegible]	Not Den[illegible]
t[illegible] [illegible]	G[illegible]ly Ir[illegible] Energy Production Minimal [illegible]es [illegible]h	Hig[illegible] Hig[illegible] p[illegible] Costs Not Yet De[illegible]
• Cyclic	• Eliminates Short Circuit Problems • Provides Peaking Power	• Intermittent Energy Production • Not Yet Demonstrated

[illegible] of [illegible] e [illegible] a[illegible] significantly [illegible] so [illegible] costs [illegible] ate[illegible] Mo[illegible] h[illegible] that applying high backpr[illegible] the p[illegible]tion wellhead sh[illegible] low pumping [illegible] en[illegible]luction, [illegible] in [illegible] consumption. [illegible] of [illegible]ese production [illegible]ime[illegible]lly investigated duri[illegible] the [illegible] [illegible]oir

P[illegible] promising [illegible] increasing [illegible] of [illegible] 3-well [illegible] In t[illegible] concept, two production wells are utilized, one on either side of the injector. Each well not only produces energy, but also functions as a pressure relief device to prevent seismic growth. The net effect is to increase production very significantly while virtually eliminating seismic growth of the reservoir and attendant water consumption.

Unfortunately, funds are not currently available to build a three-well HDR system, but experiments to simulate multi-production well systems will be carried out as part of the LTFT. While these will not fully demonstrate the potential advantages of multiple production wells they should provide enough information to determine whether or not further investigation of this concept is warranted.

Yet another technique for operation of an HDR heat mine entails a cyclic schedule wherein the production well is alternately flowed and shut in. During the shutin period the reservoir would be in a charging mode with an anticipated increase in temperature and pressure of the geofluid. In the production phase, this stored fluid would be brought to the surface and utilized. In a two well system, this mode of operation might be used for peaking power applications or to provide a continuous energy supply when used in conjunction with other intermittent energy sources such as solar or wind.

Short circuits, in which the bulk of the geothermal fluid flows rapidly from the injection well to the production well, are considered a major potential problem in HDR systems because short circuiting fluid will not remain in contact with reservoir rock long enough to efficiently extract its thermal energy. While no signs of short circuiting have been seen at in the Phase II HDR reservoir, they apparently have been observed in HDR circulation tests in a shallower reservoir in the United Kingdom (Parker 1989). During cyclic operations, the geofluid is stored in the HDR reservoir some definite period of time as an inherent part of the operating procedure. By employing cyclic operating techniques, it may thus be possible to eliminate the potential for production fluid temperature declines due to short circuiting without imposing significant operational penalties. No field tests of cyclic operation of an HDR system have yet been carried out, but we plan to investigate this concept near the end of the LTFT.

When fully developed commercially, HDR heat mines may consist of systems with multiple production wells, each operated in a cyclic mode but on schedules designed to provide a constant supply of energy. In this type of system, continuous injection could be coupled to steady production from a network of producing wells.

Summary

The technical feasibility of HDR heat mining has already been proven in field testing. The potential for future geothermal development of the HDR resource as an economically competitive source of energy with negligible environmental impact is extremely large.

A long-term flow test (LTFT) of the Phase II HDR system at Fenton Hill, NM, is scheduled to begin this year. Its primary purpose is to demonstrate that energy can be produced from HDR on a sustainable basis.

Development of a second HDR heat mine will be based on what is learned at Fenton Hill during the LTFT. The second facility will be designed to serve as a model for commercial HDR plants. A large number of operational strategies which may increase the production capacity and efficiency of HDR heat mines have yet to be investigated. These may have a significant impact on the design and operation of future HDR systems.

The national energy strategy predicts that by 2030, geothermal sources will account for about 3% of electric power production in the U.S. (USDOE 1991). It is difficult to conceive of this level being achieved without the development of HDR. The march toward orderly development of HDR technology must be strong and deliberate, and the necessary resources must be committed to do the job. Such an investment will yield substantial and timely returns both financially and in the form of national energy security.

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The Design and Construction of a Hot Dry Rock Pilot Plant

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The geothermal energy program at the Los Alamos National Laboratory is directed toward demonstrating the potential of the hot dry rock (HDR) technology as an alternate energy source. Since the inception of the program, scientists and engineers have perfected drilling and fracturing techniques to create underground reservoirs for the purpose of tapping the potential heat energy from the hot rock in the earth. One of the achievements to date has been the creation of a reservoir at the Laboratory's test site at Fenton Hill, New Mexico. This reservoir, located at a depth of 12,000 feet below the surface of the earth, has an estimated fluid capacity of one million gallons within the large volume of fractured rock. To evaluate the thermal power potential of this reservoir, preparations are currently underway to conduct a test which will entail the circulation of fluid through the reservoir by the injection of water at high pressures. A major part of the preparations involves the building of a demonstration pilot plant. The process concept poses a number of unique technical challenges with regard to the design and construction of the equipment and facilities. This paper reviews the system design and operating features of this plant.

INTRODUCTION

Encouraging results have been obtained in earlier circulation tests of HDR reservoirs at Fenton Hill. These tests however, have been short in duration and were conducted primarily to verify the circulation technique. As a result, there still remains the need to demonstrate that effective fluid flow rates can be produced from an HDR reservoir in an efficient manner.

The next step in bringing the HDR technology a step closer to commercial reality is to establish the reservoir characteristics. Preparations are underway to conduct a circulation test of the Phase II reservoir at Fenton Hill. This test, identified as the Long-Term Flow Test, LTFT, will entail the continuous circulation of fluid through the reservoir for a minimum period of one year. Through this test, reservoir engineers will be able to characterize long-term reservoir performance in terms of the rate of thermal drawdown, water loss, flow impedance, induced seismicity, and geochemical behavior.

In support of this test, a pilot plant has been designed and is currently under construction. The design presents several technical challenges in the areas of materials of construction and fluid handling. In developing the project, consideration was taken to allow for the use of existing facilities and commercially available equipment. The construction of the plant is scheduled to be completed in the summer of 1991.

While the primary objective is the characterization of the reservoir, the test will also provide operational, performance, and reliability information on the plant equipment.

System Description

Reservoir - The reservoir for the circulation test is identified as the Phase II reservoir. It is located at a depth of approximately 12,000 feet below the surface. The temperature of the rock at this depth is estimated to be about 460°F. From seismic analyses, the size of the reservoir is dimensionally estimated to be 1000 feet vertically, 1200 feet long in the N-S direction and 500 feet wide in the E-W direction. The reservoir is connected to the surface by two wells, identified as EE-2A and EE-3A. The reservoir and wells are illustrated in Figure 1.

In circulating water through the reservoir, EE-3A will serve as the injection well. Water to the reservoir will be channeled through a casing with a 3-7/8 inch inside diameter. EE-2A, the production well, will act as the conduit to bring the hot geothermal water to the surface. This well is constructed with a casing that has a 6 inch inside diameter.

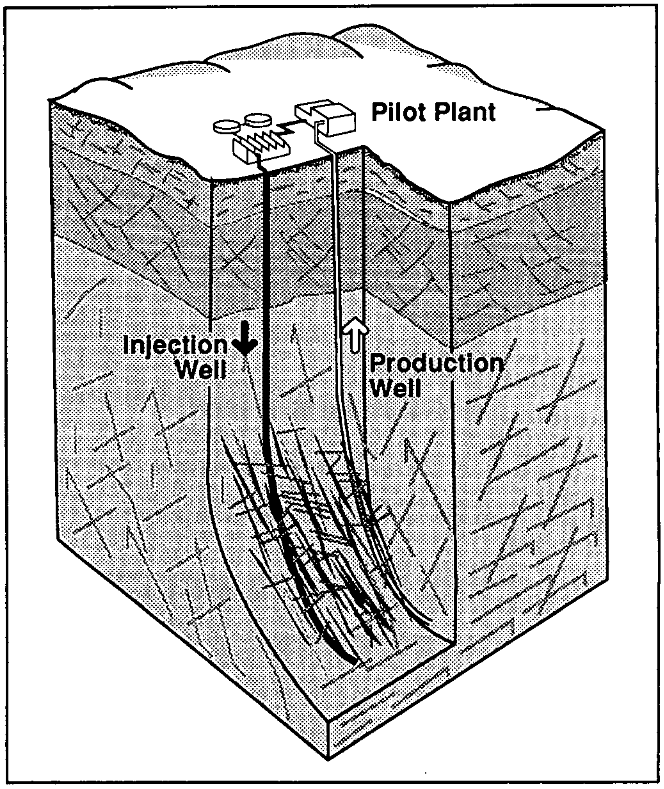

Figure 1. Phase II HDR Reservoir and Wells.

Pilot Plant - The process concept of the plant is illustrated in the basic schematic of Figure 2. Circulation of fluid through the reservoir is created and maintained by an injection pump which delivers water under high pressure to

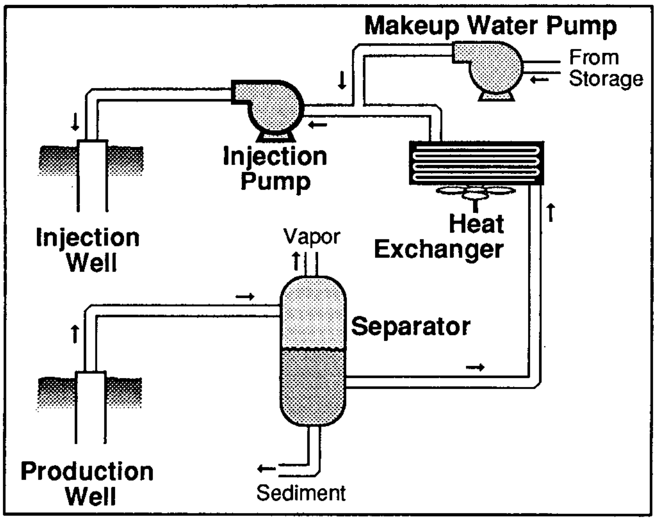

Figure 2. HDR Flow Diagram.

the reservoir through the injection well. After passing through the rock fractures and extracting the heat energy, the water is returned to the surface via the production well. At the surface, the hot geothermal water passes to a separator where any gas and solids are removed from the process stream. Production temperatures are expected to be in the range of 400° to 425°F. The hot fluid then flows to a heat exchanger where the temperature is reduced and the extracted heat energy is measured. After cooling, the fluid is returned to the injection pumps to complete the cycle. Previous tests have shown that some water loss will occur during the circulation process. For this reason, a makeup water facility is included as part of the plant to replace the lost water.

The plant is designed to handle the circulation of 336 gpm. Based on a production temperature of 425°F, the plant has the capacity to produce 15 MW of thermal power.

Design and Operating Features

From a mechanical design standpoint, the plant can be divided into two sections, namely the high pressure and low pressure segments. The high pressure side is comprised of the injection pumps and the piping to the injection well. The components within this portion of the plant are designed for a maximum allowable working pressure of 5000 psi. The materials of construction for this segment are austenitic stainless steels. The low pressure side of the plant is designed for a maximum operating pressure of 1100 psi. The major components include the heat exchanger, separator, makeup water pumps and interconnecting piping. This portion of the plant is constructed from carbon steel materials.

The plant is designed and constructed in accordance with codes and standards applicable to a commercial power plant. The pressure boundary design of vessels and piping conforms to the ASME B&PV Code and the ANSI Power Piping Code.

As will be discussed later, the injection pressure at start-up will be limited to a maximum of 3900 psi. Once started, the plan of operation is to circulate water through the reservoir continuously throughout the test period. To minimize plant interruptions, redundancy of critical components and auxiliary systems are part of the plant design. However, unlike a typical power plant which is designed for a defined power production, the equipment has been selected to provide the greatest flexibility to study the flow characteristics of the reservoir.

Injection Pumps

The pressure for injecting the fluid into the reservoir will be developed by two pumping systems. Each system is a self-contained, fully instrumented unit, consisting of a quintuplex reciprocating pump, diesel engine, and automatic transmission. The components are skid mounted and housed in a sound-attenuating enclosure. A complete system weighs 70,000 pounds. Each unit is capable of producing a discharge pressure of 3900 psi over a flow range of 84 to 168 gpm. The pumping systems have the flexibility to be configured to obtain higher discharge pressures.

The pumps are engineered products of the Ingersoll-Rand Company. They include materials of construction that are unique to the application. Those parts in contact with the geothermal fluid have been manufactured from corrosion resistant materials. The fluid-end, pressure boundary parts, are made from Nitronics 50 material while the valves are manufactured form Inconel. The pumps are shown in Figure 3.

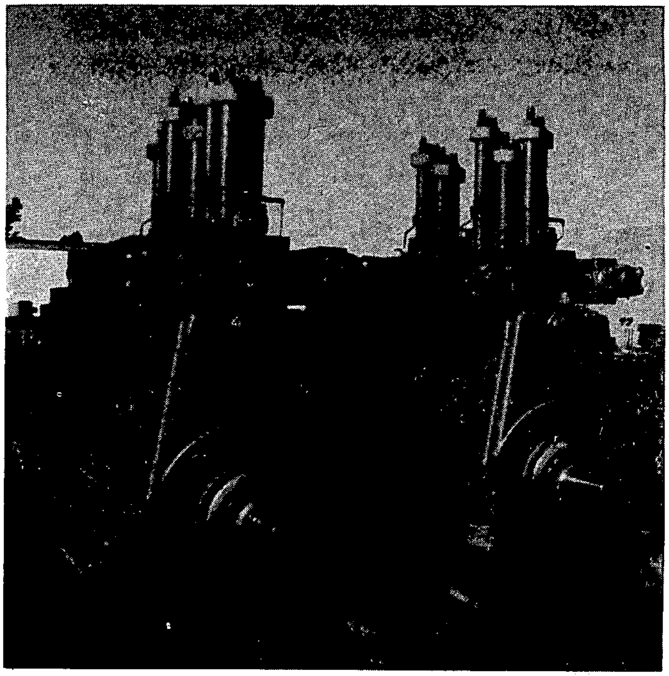

Figure 3. Injection Pumps.

The pumps are powered by turbo-charged diesel engines. Manufactured by the Caterpillar Company, each engine has a power rating of 520 horsepower.

Heat Exchanger

The heat energy will be removed from the hot geothermal fluid through an air-cooled heat exchanger. It is modular in design with four (4) separate tube bundles. Each has a duty rating of 20 MW.

The heat exchanger is the oldest component in the plant.

Manufactured by the Yuba Heat Transfer Company, it has been used periodically since 1976 to support other circulation experiments. The cooling tubes are constructed from ASTM A-214 carbon steel material.

Because of its age and the susceptibility of the material to corrosion, an internal inspection was made to evaluate the condition of the tubes. The inspection uncovered a large buildup of scale deposits which were identified as iron carbonate. After removing the deposits, the wall surfaces of the tubing were found to be free of any significant pitting or erosion effects. The results of the inspection concluded that there was no significant degradation in the thickness of the tubing wall to require the derating of the design working pressure of the heat exchanger.

Makeup Water pumps

There are two types of water losses that are associated with the pressurization of the Phase II reservoir. From previous experiments, a threshold pressure has been found at which reservoir extension due to hydraulic fracturing begins. This is estimated to be between 3700 and 3900 psi. At pressures below this point, water loss is due to diffusion at the boundary of the reservoir. Water loss for this condition is estimated to be in the range of 7 to 9 gpm at the threshold pressure.

At pressures above 3900 psi, hydraulic fracturing starts to occur and the reservoir begins to grow in size. The water consumption in this situation is a combination of diffusional loss and volumetric increase of the reservoir. From previous inflation experiments, the total water loss is estimated to be in the range of 60 to 70 gpm at a pressure of 4500 psi.

To compensate for these losses, the plant includes a makeup water facility. Water will be drawn from a 5 million gallon man-made reservoir and pumped into the low pressure side of the plant. The water will be supplied by two centrifugal pumps which will be connected upstream of the suction to the injection pumps. Depending on the demand, the pumps will operate singularly or in parallel to maintain a constant suction pressure to the injection pumps. Each pump is driven by a 50 hp motor via a belt drive arrangement and has the capacity of delivering 37 gpm at a pressure of 1000 psi. The pumps for this service were manufactured and packaged by the Roto-Jet Pump Company. The pumps are shown in Figure 4.

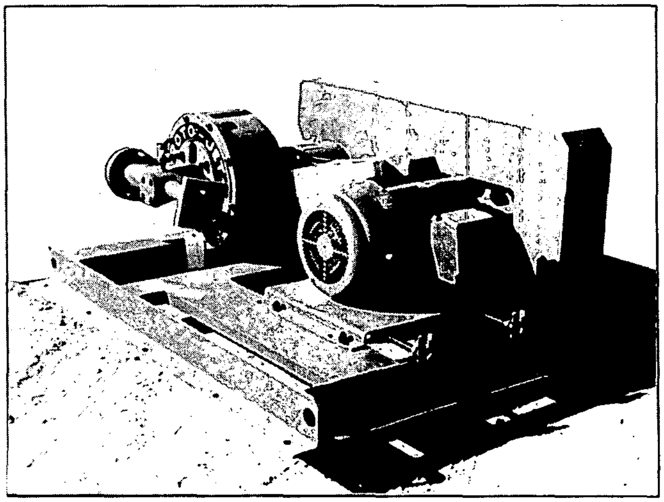

Figure 4. Makeup Pump.

Separator

From a process standpoint, the separator is designed to remove any free vapor and suspended solids from the geothermal water. Its purpose is to assure the circulation of a single phase fluid, free of solids, through the surface plant.

Previous tests have indicated the production of both gas and suspended solids in the hot geothermal water. The gas consisted primarily of carbon dioxide and water vapor. The solids were found to be silica sand and carbonate scale. If left in the process stream, these solids and gases will adversely affect the mechanical reliability of the plant equipment, in particular, the injection pumps.

The separator will be installed upstream of the heat exchanger to remove any vapor before the fluid is cooled. The separator has a capacity for removing 130000 scf/day of vapor and 170 lb/hr of solids at maximum flow capacity.

Summary

With the completion of the pilot plant in the summer of 1991, the HDR program at Los Alamos will be ready to take the next step in proving the commercial viability of the technology.

The construction phase of the project is proceeding on schedule. The return of warmer weather has enabled the resumption of normal outdoor activities. Efforts have been focused on the installation of the major components and piping construction. The pumping systems for injection as well as the makeup water have been installed and tested. The last milestone, with regards to the plant construction, is the installation of the separator. The separator is scheduled for delivery in early July.

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RECENT PROGRESS IN HDR RESERVOIR ENGINEERING

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ABSTRACT

In the past two years, three very significant advances have been made in our understanding of the behavior and properties of Hot Dry Rock (HDR) geothermal reservoirs. First, we have determined that the rate of water loss from such deep, engineered reservoirs -- previously thought to be a major problem -- is minimal in the absence of reservoir growth, even under considerably elevated operating pressures. Second, a new method has been developed for determining the volume of hot fractured rock accessible to circulating water; i.e., the size of the HDR reservoir. This technique, after appropriate verification, will allow operators to actually quantify the size of the available thermal resource **before** power plant design and installation. Finally, the partitioning of reservoir fluid storage between the matrix microcracks and the network of joints has been measured at two pressure levels, one above and one below the joint opening pressure for the most favorably oriented set of joints. The observed difference in the storage partitioning above and below this threshold pressure is quite pronounced, particularly for the microcrack fraction. For any given HDR site, the measurement of this pressure-dependent storage partitioning may provide guidance as to the optimal method of reservoir production.

INTRODUCTION

The creation, flow connection, and subsequent extension of the Phase II reservoir at Fenton Hill, NM, and its scientific interrogation and associated flow and pressure testing, have provided the major focus for the Los Alamos HDR Project during the past 8 years.

1. Steps in the Development of the Phase II Reservoir

The major portion of the Phase II reservoir was formed during the Massive Hydraulic Fracturing (MHF) Test in December, 1983. During this test, 5.7 million gallons of water were injected into a 70-foot openhole interval immediately below the casing shoe in the lower wellbore, EE-2. In 62 hours of pumping at surface pressures up to 48 MPa (7000 psi), a seismically determined stimulated region of about 0.3 cubic kilometers was formed. However, during the MHF pressure stimulation, considerable evidence now suggests that we did **not** create new fractures in previously unflawed crystalline rock as initially envisaged, but instead hydraulically opened several sets of pre-existing joints that had been previously sealed by secondary mineralization (i.e., the rock mass was pre-flawed, but almost pressure tight).

Unfortunately, the stimulated zone did not connect to the upper well as we had hoped -- apparently because the main fracture conduits were not vertical but inclined to the east at about the same angle as the directionally drilled upper target wellbore. After several additional attempts to establish a flow connection by high-pressure pumping, the upper well was redrilled, in the spring of 1985, diagonally through the main portion of the seismically determined stimulated region. By redrilling, we were able to successfully complete the Phase II reservoir flow loop, with a number of flow entrances over more than 1,000 ft of open wellbore.

Then, in mid-1986, we performed a successful 30-day reservoir flow test which involved extending the reservoir deep and to the south of the lower portion of the redrilled injection wellbore, now referred to as EE-3A. Finally in the fall of 1987, the lower portion of the MHF injection well was redrilled to both bypass damaged casing in the lower portion of the old wellbore and to access a much larger interval of the fractured reservoir for subsequent production. The redrilled lower well is now referred to as EE-2A.

2. The Physical Characteristics of the Present Phase II HDR Reservoir

As presently understood, the physical characteristics of the reservoir are:

a. An ellipsoidal-shaped region of fractured rock with an accessible volume of 20 million cubic meters.

b. Centered at a depth of about 3.6 km (12,000 ft) in granitic rock at a mean temperature of about 240°C.

c. Very tight unfractured boundaries, with a current measured permeation loss rate from this large pressure-stimulated region of less than 2.5 gpm at a surface pressure of 15 MPa (2180 psi).

d. Equivalent rectangular dimensions for the fluid-accessible reservoir region of 400 m long by 340 m high by 150 m thick. The longest dimension is in the north-south direction with the region dipping to the east at about 15 to 30 degrees from the vertical.

e. A multiply interconnected region of hot crystalline rock created by high-pressure hydraulic stimulation of a previously very tightly sealed -- but jointed -- rock mass. This region now appears to contain a large number of highly impeded flow paths that in aggregate result in an overall low flow impedance between the injection and production wellbores. Based on previous flow testing, however, there are apparently no directly connecting joints --i.e., short-circuiting flow paths -- between wellbores.

3. Reservoir Pressure Testing During the Past Two Years: Experiment 2077

The objective of this long series of pressure tests was to determine: (1) the time-dependent reservoir water loss rates at several pressures and, (2) the reservoir fluid storage volume as a function of pressure (i.e., its inflation volume). These pressurization tests began on March 28, 1989, and continue today. In this noncirculating mode of testing, the shut-in production well (EE-2A) has been used only to measure the reservoir pressure away from the injection well.

In this present paper, the primary emphasis will be on the results from Experiment 2077, and the implications of these results as regards the commercial development of the HDR concept. In Figure 1, a smoothed pressure profile for Experiment 2077 is shown through December 1990. Of particular note are pressure plateaus at 7.5, 15, and 19 MPa (1090, 2180, and 2760 psi). Further, it should be noted that plateaus at 15 MPa have been repeated several times during this series of tests to determine the temporal variation in reservoir water loss rate at this pressure level. Finally, note the long reservoir shutin in mid-1990. This interval has provided significant information on the partitioning of fluid storage between the

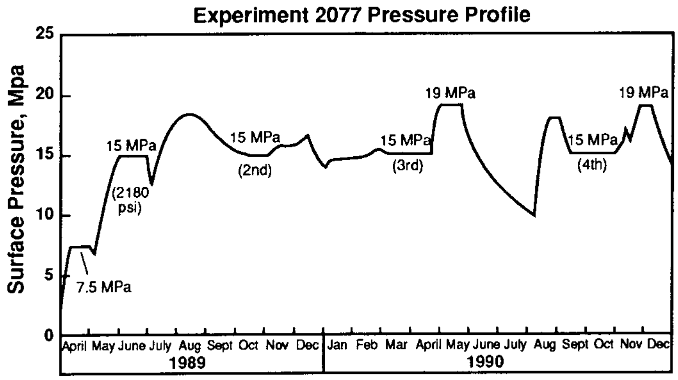

Figure 1. Phase II Reservoir Pressure Profile during Experiment 2077

interconnected microcrack fabric of the rock and the pressure-stimulated joints.

RESERVOIR BOUNDARY WATER LOSS RATES

The results from Experiment 2077 have clearly shown that water loss rates from deep, pressure-dilated regions of hot crystalline rock can be very small. Figure 2 shows the reservoir water loss rate at a pressure of 15 MPa plotted vs the natural logarithm of time. The straight line shows the expected diffusional behavior for flow from a two-dimensional pressurized region (i.e., assuming no significant water loss in the vertical direction). Figure 3 shows the early-time water loss behavior at this same pressure, indicating that there was an early period, lasting about 14 days, in which water was still being stored within the reservoir in both the joints and microcracks. Referring again to Figures 2 and 3, during almost two years of reservoir pressure maintenance, the boundary permeation outflow at 15 MPa has continuously declined from an initial value of about 15 gpm to a recently measured value of 2.5 gpm, essentially negligible in the overall scheme of things. However, the measured water loss rates for the third and fourth 15-MPa pressure plateaus (the lowermost three data points in Figure 2) show a leveling off of water loss. This behavior would suggest that with increasing time beyond about 9 months [ln(t) = 5.6], the water loss rate is approaching that for three-dimensional diffusion from a point source -- i.e., a constant value.

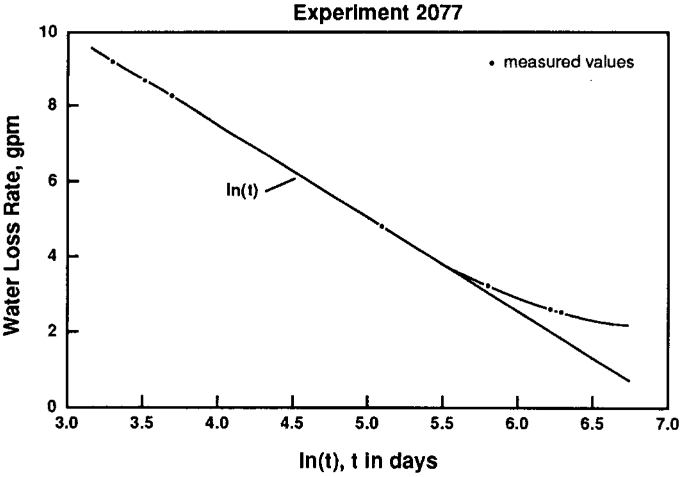

Figure 2. Phase II Reservoir Water Loss vs. Time at 15 MPa Pressure.

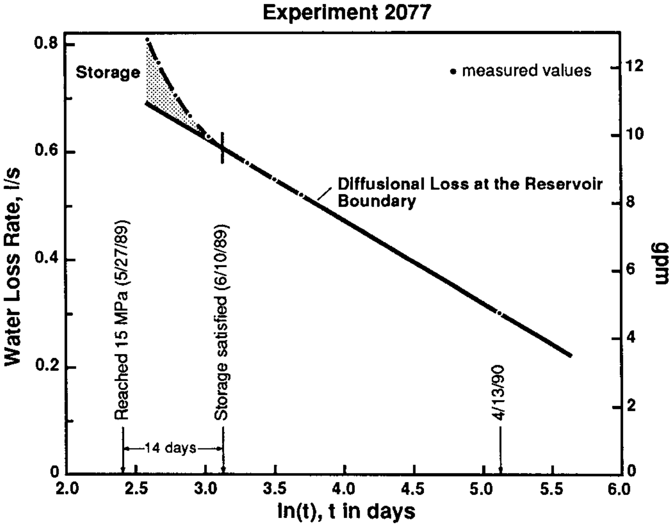

Figure 3. Temporal Variation in the Phase II Reservoir Water Loss Rate at a Pressure of 15 MPa.

Measurements at two successive 19-MPa (2760 psi) pressure plateaus have shown that at this even higher reservoir pressure, but below the threshold pressure for additional reservoir growth by fracture extension at the reservoir boundaries, the water loss rate increased to only 8.5 gpm and 7.5 gpm, respectively. The data for these two periods of pressure maintenance is shown in Figure 4. The water loss rate at 19 MPa represents the expected upper bound for nonextensional reservoir water loss at an injection pressure of 25.5 MPa (3700 psi), the planned injection pressure for the first four months of reservoir flow testing during the upcoming Long-Term Flow Test. Of further note is the fact that at this pressure, which is above the first joint-opening pressure of 15 MPa, it only takes 7 days to satisfy the internal reservoir storage, half that observed at 15 MPa.

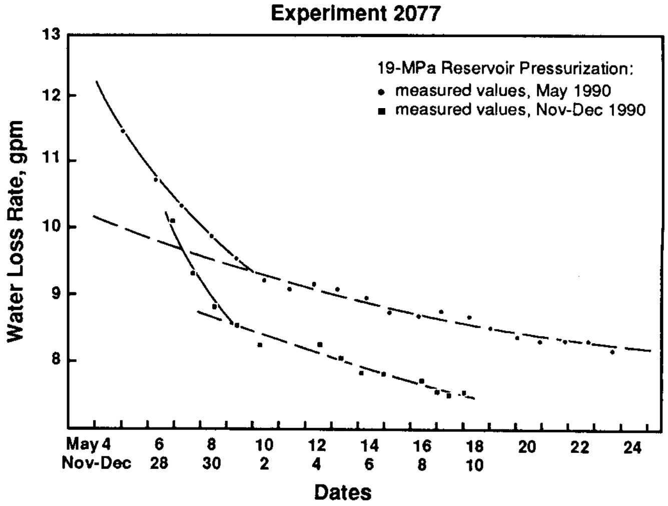

Figure 4. Reservoir Water Loss Rates During Two Periods of Pressure Maintenance at 19 MPa.

THE RESERVOIR VOLUME ACCESSIBLE TO PRESSURIZED FLUID

Recent advances in our understanding of the pressurized deformation of fractured HDR reservoirs has provided us with a new method to quantify the volume of the pressure-affected region. This method is a consequence of reservoir pressure testing during Experiment 2077, and appears to provide a direct measure of the fractured rock volume available for heat transfer to the pressurized circulating fluid prior to actual reservoir power production. If at that time, the size of the accessible fractured region were determined to be too small for the planned use, further reservoir extension could easily be accomplished by additional high pressure pumping -- the same technique used to create the initial reservoir.

Let us postulate a region of microcracked and jointed crystalline rock of very low porosity but with a finite fluid permeability on all scales (i.e., where all the cracks of whatever size are interconnected). From all that we have been able to learn in the past 8 years, this apparently represents an accurate description of our present Phase II reservoir. If this region were to be pressurized in such a way that all the contained fluid (in whatever size cracks) was in pressure equilibrium at the beginning and end of the pressure rise, then the only material that would be compressed would be the mineral constituents of the rock matrix between cracks (i.e., the quartz, feldspar and biotite crystals, among others), but **not** the cracks themselves. (Obviously, the compressibility of the water is being ignored, but for a rock with a measured porosity of 0.01 percent or less, there is such a relatively small amount of contained water that this is a reasonable assumption.)

Table I gives the resulting calculation of the pressure-affected reservoir volume using the above model for the rock mass under hydrostatic, linearly elastic compression.

Table I

Determination of the Pressure-Affected Reservoir Volume

Pressure Range:	7.5 to 15 MPa (ΔP)
Change in Reservoir Volume:	2715 m^3 (ΔV)
Bulk Modulus for Rock:	55 GPa (K)
Reservoir Volume:	$(V = K\frac{\Delta V}{\Delta P})$
	V = 20 x $10^6 m^3$
Seismically Determined Volume:	16 x $10^6 m^3$ (1σ distribution)
	130 x $10^6 m^3$ (2σ distribution)

The bulk modulus (K) was determined from the seismically measured compressive and shear wave velocities for the rock mass in the reservoir region. This bulk modulus value compares very favorably with laboratory measurements on dry granite samples under high confining stress. Also listed in Table I is the reservoir volume as determined from the envelope of the locations of the microseismic events produced during the MHF and subsequent reservoir extension testing, with two different Gaussian distributions of events: 1-sigma which includes 67% of the events, and 2-sigma which includes 95% of the events. As can be seen, these two very different methods of determining reservoir volume show good agreement.

Of particular note is the fact that we have developed a purely mechanical method for measuring the fluid-accessible reservoir volume **before** flow testing and reservoir thermal drawdown. Until now, the reservoir volume accessible to the pressurized circulating fluid had to be calculated from measurements made **after** extended operation of the reservoir.

THE PARTITION OF FLUID STORAGE BETWEEN JOINTS AND MICROCRACKS

I. Analysis of the Long Shutin Following the First 19-MPa Pressure Plateau

As previously mentioned, the Phase II reservoir was shut in from late May to Early August of 1990, immediately following the first 19-MPa pressure plateau (refer to Figure 1). During this 11-week shutin, the reservoir pressure decayed from 19 MPa to 9.8 MPa, mainly in response to a venting of the reservoir through a well-documented annulus leak in the EE-3A wellbore.

Figure 5 shows the reservoir pressure profile during the last five weeks of this shutin and the early portion of the subsequent rapid repressurization. During the last three weeks of the shutin, the reservoir pressure was dropping at a mean rate of 8.86 psi/day in response to an annulus outflow of 2.58 gpm. However, during the subsequent rapid represssurization, the reservoir pressure rose at an initial rate of 201 psi/day; a factor of over 20 greater than the previous rate of pressure decay.

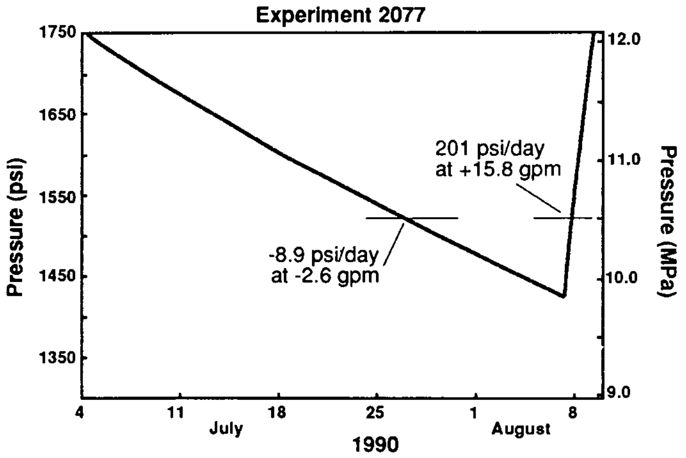

Figure 5. Reservoir Behavior at 10.5 MPa During Slow Deflation and Rapid Inflation.

Recognizing the following conditions, one can use these data to separately determine the volume fractions of fluid storage in the microcracks and dilated joints within the reservoir (at a mean pressure of 10.5 MPa):

a. During the very slow reservoir depressurization, stored fluid was flowing from both the matrix microcracks internal to the rock blocks comprising the reservoir, and the joints between these blocks, in a very nearly pressure-equilibrated manner.

b. However, during the first few hours of the subsequent rapid reservoir repressurization, fluid was being stored almost completely in the interconnected set of stimulated joints, with only a very small amount being stored in the microcracks. This would be expected due to the very large contrast (at least several orders of magnitude) between the matrix and joint permeabilities, and the short time available for microcrack pressure saturation.

Under these conditions and using the above data, the calculated fraction of reservoir fluid stored in the microcracks is 0.73 and that in the joints is 0.27, which is counterintuitive for a **fractured** HDR reservoir. As a check on the validity of these fluid storage results, one can compare the microcrack storage fraction to the measured rock porosity values for deep cores from Fenton Hill.

These porosity measurements average 0. 013% for cores from a depth of 2.9 km. (These core measurements were made under in situ conditions of stress by Gene Simmons at MIT using his differential strain analysis (DSA) approach.)

Using the flow-connected reservoir volume of 20 million cubic meters determined above, and a microcrack volume fraction of 0.73, the calculated volume-averaged microcrack porosity at this mean pressure level of 10.5 MPa would be 0.010%, quite close to the core porosity data obtained from DSA measurements.

2. The Partition of Reservoir Storage Above 15 MPa

Based on previous reservoir inflation results from Experiment 2077, it is apparent that a significant change occurs in the nature of the inflation above 15 MPa. From an analysis of pressure inflection data, this corresponds to the pressure at which the first set of joints starts to jack open within the Phase II reservoir (i.e., 15 MPa appears to be very close to the internal pressure required to just balance the normal joint closure stress for the most favorably oriented set of joints.) Therefore, the reservoir pressure performance during a recent pumping interval, shown in Figure 6, was carefully analyzed to determine if there was a marked change in the nature of the reservoir storage above 15 MPa as compared to the results obtained at 10.5 MPa.

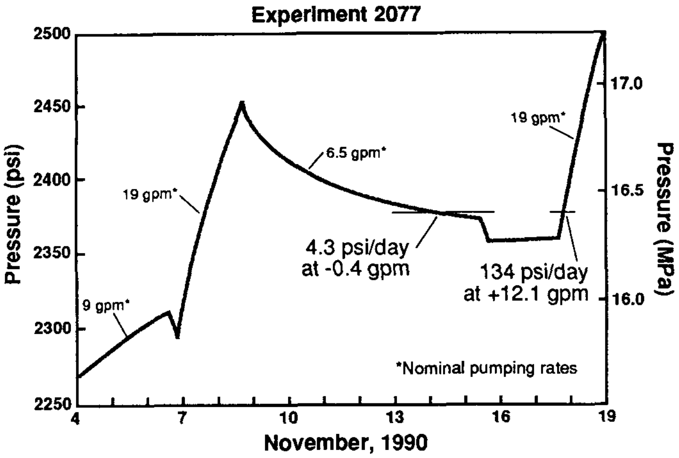

Figure 6. Reservoir Behavior at 16.4 MPa During Slow Deflation and Rapid Inflation.

A comparison was made between the initial rapid inflation behavior of the reservoir on the afternoon and evening of Nov. 17, 1990 and the previous slow deflation behavior during the last two days of the low pumping rate interval from noon, Nov. 13 to noon, Nov. 15, 1990. The relevant data for the slow deflation and subsequent rapid inflation of the reservoir are given in Table II.

Table II

Reservoir Pressurization Behavior at a Mean Pressure of 16.4 MPa

	Slow Deflation	Rapid Inflation
Rate of pressure change, psi/day	4.3	134.4
Net fluid inflow or outflow, gpm	0.42	12.12
Pressure change/ fluid storage change, psi/day/gpm	10.2	11.1

These experimental results imply that at an average reservoir pressure of 16.4 MPa, there is no longer any appreciable difference in the slow vs rapid reservoir pressurization behavior. This indicates that almost all the pressure-dependent change in fluid storage is now occurring in the open joints comprising the primary reservoir flow paths. This is in marked contrast to the results obtained at a reservoir pressure of 10.5 MPa, where the slow deflation pressure drop per unit outflow was one third that of the rapid inflation pressure rise per unit inflow, indicating an appreciable amount of fluid flowing from the microcracks during slow deflation in this pressure range. This significant change in pressurization behavior strongly suggests that the matrix microcracks are no longer contributing to additional reservoir storage at pressure levels above 15 MPa. That is, microcrack storage appears to "saturate" at a reservoir pressure of about 15 MPa.

Other experimental results as well as mechanical deformation models support the above conclusion. Table III shows the measured reservoir inflation data for three pressure intervals during Experiment 2077.

Table III

Reservoir Differential Volume Increases Measured During Experiment 2077

Pressure Range MPa	Differential Volume m^3(gallons)	Volume Change per Unit Pressure Change m^3/MPa
0.0 to 7.5	2140 (566,000)	285
7.5 to 15.0	2715 (717,000)	362
15.0 to 19.0	618 (163,000)	155

The data given in Table III show that as the reservoir is pressurized to 15 MPa, the differential storage volume increases with pressure. This is a result that we have observed before, and is a direct consequence of nonlinear pressure-dependent joint and microcrack dilation. However, when the reservoir is further pressurized above 15 MPa, this trend is not continued. As shown in the third column of Table III, only about one third of the fluid storage anticipated from the trend of the data up to 15 MPa actually occurred between 15 and 19 MPa. Therefore, the data given in Table III also indicates that there is a marked change in the the reservoir inflation behavior above 15 MPa.

Further experimental evidence for this change in storage partitioning has been mentioned previously -- the time required for pressure saturation at and above 15 MPa. As shown in Figures 3 and 4, it required 14 days of constant pressure operation to fill the reservoir at 15 MPa, but only about 7 days to do the same thing at 19 MPa. This is a further indication that the slower-filling microcracks are not contributing to incremental fluid storage at 19 MPa.

SUMMARY

Based on a two-year sequence of pressure tests of the Phase II reservoir at Fenton Hill, we have:

Measured a very low rate of water loss from the reservoir periphery: 2.5 gpm at a surface pressure of 15 MPa (2180 psi) after 21 months of pressurization. This is a very important result from the standpoint of commercializing HDR geothermal energy, since water loss was once thought to be a major impediment for the adoption of this technology.

- Developed a new method for determining the pressure-affected reservoir volume. For our present Phase II reservoir, this volume is 20 million cubic meters, which is smaller than we had previously thought, but within the range of the seismically determined reservoir volume (16 to 130 million cubic meters). From the standpoint of a potential developer, this is an important result, since it would provide an early measurement of the actual exploitable HDR thermal resource, which otherwise might take many years to determine based on thermal drawdown.

- Determined the partitioning of fluid storage between the joints and microcracks for two levels of reservoir pressurization, one above and one below the 15-MPa joint opening pressure for the most favorably oriented set of joints. At a reservoir pressure below 15 MPa, about 3/4 of the fluid storage is in the interconnected microcrack fabric of the rock blocks, and only about 1/4 in the array of pressure-dilated, but not yet open, joints separating these rock blocks. In contrast,essentially all of the additional fluid storage is in the joints at pressures greater than 15 MPa. This storage partitioning may influence the preferred method of reservoir production for any particular HDR site.

GEOPRESSURED-GEOTHERMAL TECHNOLOGY

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

PROGRESS IN GEOPRESSURED - GEOTHERMAL TECHNOLOGY

Ken Taylor
U.S. Department Energy - Idaho Operation Office

The goal of the Geopressured-Geothermal Program is two-fold. First, it must be proven that the resource can be produced over a period of time necessary for utilization. Second, effective methods for producing, handling, and utilizing the geopressured-geothermal fluids must be developed. To obtain these goals, three geopressured-geothermal wells are being tested. These wells are the Pleasant Bayou Well in Texas and the Hulin and Gladys McCall Wells in Louisiana. To date, much progress has been made toward achieving the program goals. Two wells (Pleasant Bayou and Gladys McCall) have endured flow testing in excess of 3 years. Additionally, researchers have developed methods to curtail sanding, scaling, and corrosion during these long term flow tests. Finally, a 1 MWe Hybrid Power System was tested at the Pleasant Bayou site. This test was quite successful. However, electrical production from the Geopressured-geothermal resource at a development cost of between 12 to 18 cents per kw-hr, is still not economically viable. The most efficient use of this resource presently is in the direct use arena, i.e. thermal enhanced oil recovery (TEOR). An Industrial Consortium for the utilization of the geopressured-geothermal resource has been developed and includes many individuals and companies very interested in these direct use opportunities, in particular TEOR.

This session had three presentations discussing various aspects of the Geopressured-Geopressured Program

Richard Campbell, The Ben Holt Company, presented the results from the operation of the Pleasant Bayou Hybrid Power System. This project, which was funded by both DOE and EPRI, utilized both the gas and the brine to produce 1 MWe. The plant operated very successfully for 9 months. This was the first time that power had been produced from the geopressured-geothermal resource.

Phillip Randolph, Institute of Gas Technology discussed the lessons learned from operating geopressured-geothermal surface facilities. Scaling and corrosion problems have been greatly reduced. Additionally, much has been learned about design considerations.

Finally, Jane Negus-de Wys, Idaho National Engineering Laboratory discussed utilization options for the resource and the Industrial Consortium which has been developed to investigate these options. This has been an extremely successful consortium since it provides an excellent pathway for technical transfer between the government and industry.

Overall, the program has advanced the technology needed to exploit this energy resource. These accomplishments may allow successful direct projects to take place in the next few years and will allow economically viable electrical conversion to take place in the future.

OPERATION OF A GEOPRESSURED HYBRID POWER SYSTEM

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The Ben Holt Co.
Pasadena, California

ABSTRACT

The U.S. Department of Energy (DOE) and Electric Power Research Institute (EPRI) co-funded a demonstration of the hybrid cycle power concept on the Pleasant Bayou geopressured resource in Texas. This one megawatt power plant provided valuable data over a range of operating conditions. In addition, an extended run at maximum power production demonstrated that power can be produced reliably with no serious operating problems. This paper presents an overview 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 was burned in a gas engine to generate electricity directly. Exhaust heat from the gas engine was then combined with heat from the brine to generate additional electricity in a binary cycle. Heat from the gas engine was 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 at 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 were under a separate contract funded by DOE. Management and technical support for the program was provided to DOE by Idaho National Engineering Laboratory. For this work, Holt teamed with Eaton Operating Company (Houston, Texas) and Institute of Gas Technology (Chicago, Illinois).

The primary objective of this project was to demonstrate the hybrid concept for electricity generation. Other objectives included 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 was designed to operate on 10,000 BBL/day of geopressured brine containing 22 SCF of gas/BBl. This flow was approximately one half of the total flow from the Pleasant Bayou well. The gas was 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 a 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, were used at Pleasant Bayou.

The final form of energy recovered is heat. The high temperature engine exhaust gas and the hot geothermal brine provided heat to a binary cycle.

Design power generation from the system without the pressure reduction turbine was:

Gas Engines	650 kW
Binary Cycle Turbine	540 kW
Parasitic Power	(210 kW)
Net Power	980 kW

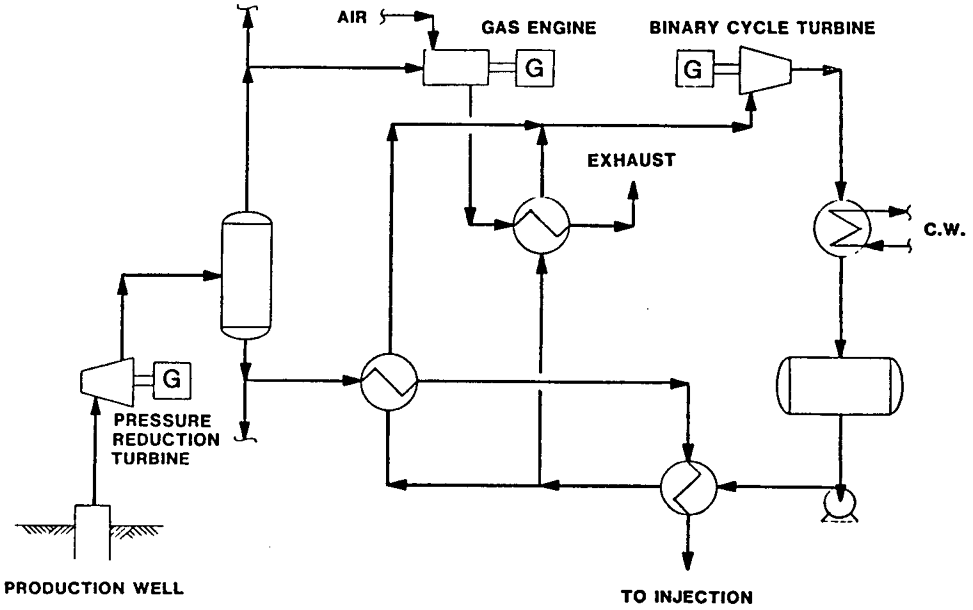
DESIGN AND CONSTRUCTION

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 also selected for use in the hybrid

FIGURE 1

HYBRID CYCLE FLOW DIAGRAM



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.

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 occurring 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.

SYSTEM PERFORMANCE

System check-out was performed in September and October of 1989, and performance tests were conducted in November and December of 1989. From the start of 1990 until the well was shut in on May 30, 1990, the Hybrid Power System ran at or near design power output except for an occasional outage. Over the course of the test, 1,443,250 STB of brine and 39,250 MCF of gas flowed through the plant. The plant achieved an availability of 97.5% and a capacity factor of 80.2% for the five-month continuous operation test.

Typical power generation from the system at design flow was:

Gas Engines	690 kW
Binary Cycle Turbine	535 kW
Parasitic Power	(270 kW)
Net Power	955 kW

The gas engines and turbine met their predicted design performance at design conditions. However, parasitic loads were higher than predicted due to higher pumping power and higher incidental power loads.

Maximum net power was generated at maximum isobutane flowrate. The brine flow required to heat the isobutane did not change significantly over the life of the test. At 60°F, 3.8 kW were produced by the turbine for every 1000 lb/hr of brine circulated. This was greater than the design value of 3.2 kW per 1000 lb/hr of brine. The primary reason for this high performance was that the brine temperature at 297°F was 19°F higher than the design temperature of 278°F.

COMPONENT PERFORMANCE

Gas Engines

The engines operated at their rated output over 4,500 hours each with only routine maintenance. Gas utilization remained constant at approximately 1.32 kW each per lb/hr of gas flow. Gas utilization was optimized at maximum gas flow. Gas utilization per engine decreased at lower gas input to that engine.

There were no operational difficulties associated with operating on impure wellhead gas. Periodic analysis of the engine oil showed that contaminant concentration was within normal levels. Visual inspection of the valves and cylinders was conducted at the completion of the test. No scoring was evident on the cylinders or valves.

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.

The turbine accumulated 2902 hours of operation with a single rotor. This was a significant improvement over the DCHX test in which five turbine rotors operated for a total of only 1074 hours.

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 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 was produced by the turbine. Since an evaporative condenser was used in this system, the isobutane condensing temperature and consequently the turbine back pressure were set by the wet bulb temperature.

Heat Exchangers

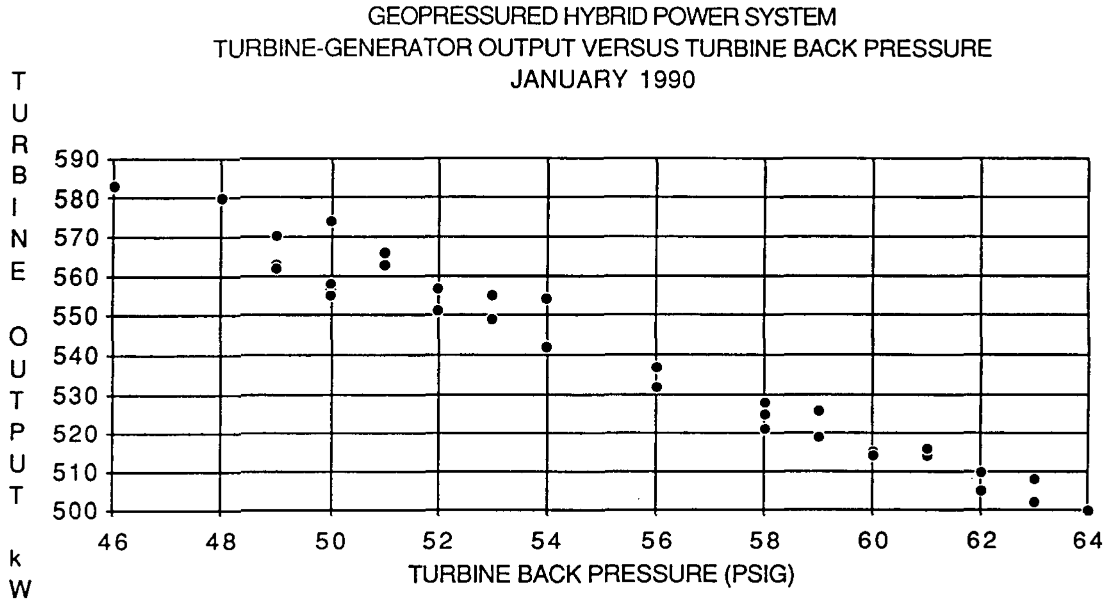
Geopressured resource utilization requires that problems due to corrosion and scaling be overcome. The brine had approximately 130,000 ppm of total dissolved solids and had shown severe scaling tendencies when untreated. In addition, carbon steel in untreated brine had been corroded at rates as high 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 were successful at production temperatures with heavy-walled carbon steel pipe. This combination was also effective at preventing scaling and corrosion at lower brine temperatures in thin-walled carbon steel heat exchangers.

Heat transfer coefficients were closely tracked to monitor scaling. Isobutane was heated to its bubble point in a brine-to-isobutane heat exchanger. This was a shell-and-tube exchanger with single tube and shell passes with true counter current flow. 90% of the isobutane was vaporized in the brine-to-isobutane boiler. This heat exchanger was a reboiler with isobutane on the shell side and brine on the tube side. Exhaust gas from the gas engines was used to vaporize the remaining portion of isobutane.

No appreciable fouling with time was noted in either of the brine-to-isobutane exchangers. At design flow, the overall heat transfer coefficients were consistently slightly better than design.

Fouling in the exhaust gas to isobutane exchanger was significant. Fouling increased uniformly while the engines were running. Black carbon powder deposited on the inside surface of the tube, thereby degrading performance. As

FIGURE 2


GEOPRESSURED HYBRID POWER SYSTEM
TURBINE-GENERATOR OUTPUT VERSUS TURBINE BACK PRESSURE
JANUARY 1990

operation continued, the deposition layer became thicker and heat transfer continued to degrade. Each time the engines shut down and were restarted, soot was blown out of the exchanger and heat transfer improved dramatically.

Excessive fouling in this exchanger has several possible solutions. A gas turbine may be installed instead of a gas engine to reduce particulate emissions. A blower which periodically removes the soot could be provided. A low pressure drop filter may be all that is required. Environmental concerns have prompted engine manufacturers to develop low-NOx natural gas diesel engines. Since these engines also have a low level of particulate emission, exhaust gas fouling will be reduced.

CONCLUSION

The hybrid power system demonstration at Pleasant Bayou was successful in all respects. Design power output was achieved, and 3,445 MWh of power were sold to the local utility over the course of the test. Plant availability was 97.5% and the capacity factor was over 80% for the extended run at maximum power production. Scale and corrosion inhibitors were shown to be effective throughout the operating range of brine temperatures. Heat exchanger fouling due to scaling from high salinity brine was not a problem. The hybrid cycle power plant demonstrated that there are no technical obstacles to electricity generation at Pleasant Bayou.

NATURAL GAS RECOVERY & BRINE DISPOSAL FOR GEOPRESSURED-GEOTHERMAL WELLS

Philip L. Randolph
Institute of Gas Technology

Introduction: Geopressured-Geothermal wells provide energy in three forms: hydraulic, thermal, and hydrocarbon. The hydraulic energy is in the form of high wellhead pressure and, if utilized, would be recovered in the first surface facilities after the wellhead. This is because the pressure drop greatly reduces the required pressure rating, and therefore cost, of hardware for recovering the other energy forms.

Natural gas is exsolved from the brine due to reduction in pressure. Although the gas content of reservoir brine was less than saturation for some of the wells, pressure always dropped below the bubble point pressure for the gas in solution before the brine reached the surface. Pressure below the bubble point is accompanied by gas coming out of solution. The lower the pressure, the greater the volume of gas liberated per unit of pressure reduction.

For the one experiment to date in which thermal energy was utilized to generate electricity, natural gas energy was recovered upstream of the heat exchangers for recovery of thermal energy from the brine. A pressure controller in a brine bypass line provided an upstream pressure of 550 psi on the heat exchangers. The injection pressure for the brine disposal well provided a back pressure of up to 450 psi on the flow control valves downstream of the heat exchangers. This pressure was sufficient for disposal of about 15,000 BPD of brine. With this configuration, about 80% of the natural gas was recovered. The rest was either vented to the atmosphere or injected into the brine disposal well.

Separation of natural gas from brine, and disposal of the brine are inevitable aspects of any energy recovery from the geopressured-geothermal resource. This paper focuses on these topics, including actions to avoid problems due to scale and corrosion.

Background: Prior to 1984, testing of a dozen Geopressured-Geothermal wells confirmed that an enormous energy resource existed in the form of hot high pressure brine containing dissolved natural gas. These early experiments provided important data on properties of the resource and the problems that had to be solved. On the other hand, they all had a short duration. For the well-of-opportunity tests, planned duration was at most a few weeks. The early tests of three design wells each ended in less than a year due to unanticipated problems.

Since that time, multi-year flow tests have been conducted on two of the design wells. These are the Gladys McCall well in Cameron Parish, Louisiana and the Pleasant Bayou well in Brazoria County Texas. The long term flow test of the Gladys McCall well began at the end of 1983 and the well was shut-in for buildup testing in the fall of 1987. Flow testing at Pleasant Bayou was resumed in 1988 and is still in progress.

The testing of these two wells has involved multiple years of flow and implementation of solutions to many of the practical problems that must be faced in conjunction with any scheme for utilization of the produced energy. This paper is primarily based on those experiments. As such, we are talking about energy that we know can be produced and actual field experience with such production.

It is important to recognize that our experience base of multi-year production involves two wells with fairly similar characteristics. This is apparent from the table which follows:

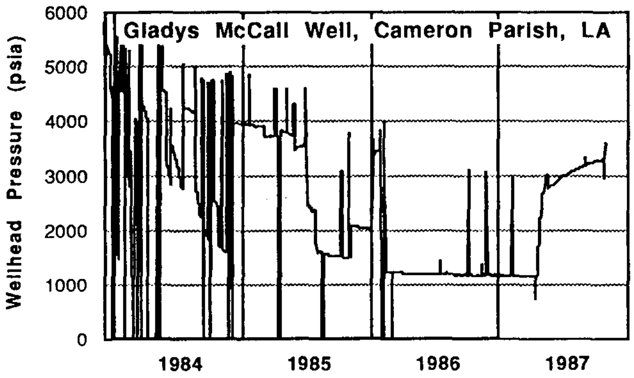
Characteristic	Gladys McCall	Pleasant Bayou
Depth to Perfs (feet)	15,160	14,600
Sand Thickness (feet)	300	60
Initial Pressure (psia)	12,800	11,200
Brine TDS (mg/l)	94,000	134,000
Temperature (Deg F)	298	306
Gas Content (SCF/STB)	29	24
CO_2 Content of gas (%)	11	13
Max Brine Rate (STB/d)	29,000	24,000
Cum Prod (Millions of STB)	25	20
Lowest Flowing BHP (psi)	8605	9015

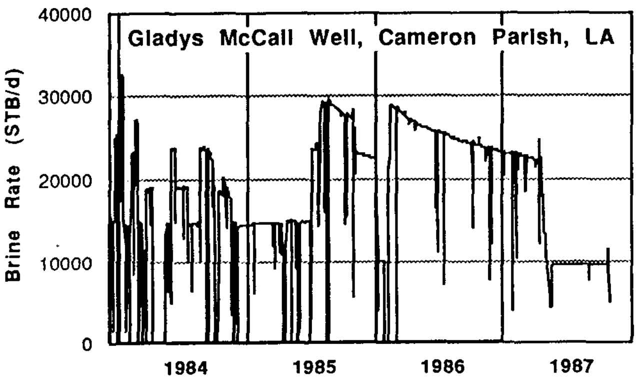
Both wells are completed with 5-1/2 inch tubing set in a packer a few hundred feet above the perforations. At both locations, all of the produced brine has been disposed of by injection into a single salt water disposal well.

Neither of these reservoirs was saturated with natural gas at original conditions. Production to date has not drawn the pressure down far enough for a significant amount of gas to come out of solution in either reservoir.

Production from the Gladys McCall Well: The facilities at this well were designed for long term production at a brine rate in excess of 40,000 Stock Tank Barrels per day (STB/d). A "stock tank barrel" is the volume occupied by 42 gallons of liquid at atmospheric pressure and a temperature of 60 Deg F. In practice, production rates were substantially below the design value for the surface hardware.

The brine rates and flowing wellhead pressures for almost four years of production from this well are shown in the plots below:





During the first year of production, flowing wellhead pressure was in excess of 4000 psia for brine rates less than 15,000 STB/d. However, for higher brine rates, flowing wellhead pressure declined anomalously fast. This was due to formation of calcium carbonate scale inside the 5-1/2 inch production tubing and the associated higher pressure loss due to friction with the smaller inside diameter. The scale was removed twice during 1984 by dissolving it with hydrochloric acid.

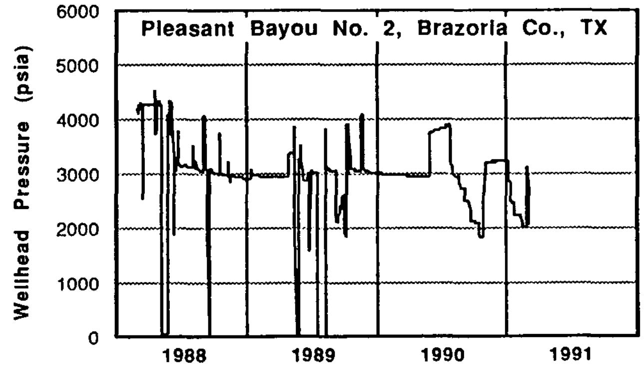
Through the middle of 1985, brine rate was kept below 15,000 STB/d to avoid scale. In mid-1985, after two unsuccessful attempts, a "pill" of phosphonate scale inhibitor was successfully pumped down the tubing and out the perforations to the formation. Brine rate was then increased to nearly 30,000 STB/d with a flowing wellhead pressure of about 1500 psi.

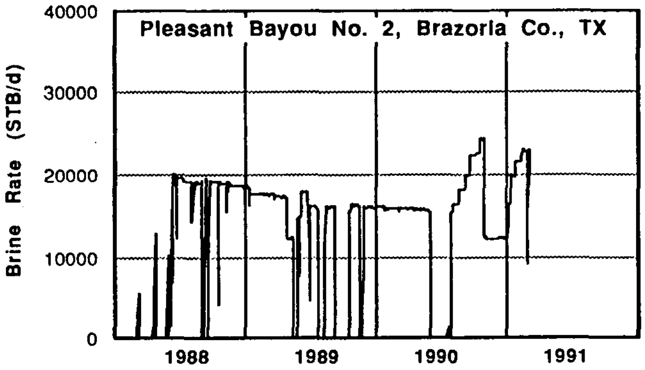
Near the end of 1985, the disposal well injection pressure after a brief shut down was found to be so high that the previous high flow rate could no longer be used. After rework of the disposal well early in 1986, maximum production was resumed. The decline in brine rate for the next year was due to depletion of the reservoir with the wellhead pressure at the lowest value that could deliver the sales gas to the line pressure of about 1000 psi.

In the spring of 1987, brine rate was reduced to a little below 10,000 STB/d. After allowing several months for the reservoir pressure profile to stabilize, a downhole pressure sensor was run into the well. Then, the well was then shut in for buildup pressure recording, which is still in progress. The pressure is up to within 700 psi of the original value of 12,800 psia that existed before the start of production testing.

Production from the Pleasant Bayou Well: This was the first of the design wells. It was drilled in 1979. A total of 1.05 million of barrels of brine were produced during several production attempts in the next two years. Each of these ended due to problems with wirelines or scale. An additional 3.49 million barrels were produced during 6-1/2 months of continuous production in 1982-1983. This test ended when the tubing parted. The shallowest 12,000 feet of tubing was found to be lined with scale up to 1/2 inch thick.

Production testing was resumed during 1988 and is continuing at the present time. The brine rates and flowing wellhead pressures for this most recent production testing of this well are shown in the plots below:





A phosphonate inhibitor pill was pumped before the start of continuous production in 1988. Then, brine rate was increased stepwise to assure that the wellbore was cleaned out and to determine the operating characteristics of the wells and surface hardware. A slug of about four cubic feet of sand was produced two hours after increasing brine rate from 22,000 to 25,000 STB/d. An upper limit of 20,000 STB/d was then put on brine rate to provide high confidence in the integrity of the source of gas and brine for the planned test of the hybrid power system.

After about three months of production, two sections of old separator inlet piping developed leaks and had to be replaced. Unacceptably high rates of metal loss were also seen on corrosion coupons. Injection of corrosion inhibitor was then started upstream of the choke. The rate of corrosion was reduced to such an extent that no new leaks have developed.

From mid 1988 through mid 1990, brine rate was kept low enough to avoid pressure in excess of the 600 psi rating of the heat exchangers in the hybrid power system (HPS). Rate was reduced as the injectivity of the disposal well declined. There was no problem keeping the brine rate well above the 10,000 STB/d required for the HPS.

After the HPS experiment was concluded in the summer of 1990, the disposal well was reworked and stepwise increases of brine rate were commenced. About three cubic feet of sand were suddenly produced twelve days after the brine rate reached 24,000 STB/d. Rate was then reduced to a level low enough for running a wireline bottomhole pressure sensor for a short shut in buildup test. Delay of funding for the fiscal year precluded that test and brine rate is again being increased in steps.

Brine production from the Pleasant Bayou well during the time shown on the plots has been 15 million STB. The gas/brine ratio has remained constant and the bottomhole pressure has not yet been drawn down to the bubble point for the gas in solution in the reservoir brine.

Hydraulic Energy Recovery: The initial shut-in pressure is high for geopressured-geothermal wells. At Gladys McCall it was about 5800 psi and at Pleasant Bayou it was about 4300 psi. Such pressures have resulted in some focus of attention upon the possibility of recovering hydraulic energy. However, the actual production data has been somewhat sobering in this regard.

At McCall, drawdown of pressure was found to be the only fundamental limitation upon production rate. At the peak brine rate of 29,000 STB/d, wellhead pressure was drawn down to 1200 psi. This was the lowest practicable value because the pressure in the gas sale line was 1000 psi. During a little over a year of flow at minimum wellhead pressure, brine rate declined from the peak of 29,000 STB/d to a little below 24,000 STB/d, or about the same as the current rate at Pleasant Bayou.

The maximum sustained brine rate at Pleasant Bayou has been limited to 24,000 STB/d by production of slugs of sand at higher rates. At this rate, flowing wellhead pressure is a little below 2000 psia and is declining at a rate a little over one psi per day due to depletion of the reservoir. In contrast to McCall, gas sales line pressure is only about 400 psi. But, the lowest practical production wellhead pressure is about 1000 psi due to the pressure required for brine injection into the disposal well.

Visual examination of the data plots for these two wells suggests that a brine rate of about 20,000 STB/d would provide a lifetime in excess of four years for facilities to extract natural gas and utilize the thermal energy. The pressure drop available for hydraulic energy recovery would decline to zero from an initial 1500 to 2500 psi on that same time scale.

A portion of the hydraulic energy is recovered if the pressure drop is taken with a choke. The brine is heated about 2.5 Deg F for each 1000 psi of pressure drop. Heating at the choke was observed during the hybrid power system (HPS) experiment at Pleasant Bayou. It resulted in the brine temperature, and the HPS efficiency, being a little above design.

Scaling and Corrosion: Both scaling and corrosion are of major significance. Pleasant Bayou testing in 1983 terminated when the tubing in the production well parted, in part due to the heavy load of scale therein. The Gladys McCall brine rate was kept below 15,000 STB/d in late 1984 and early 1985 because experience had revealed scale deposition in the production tubing for higher brine rates. Since mid 1985, scale has been controlled with inhibitor "pills" at both locations.

An inhibitor "pill" consists of pumping a pad of water with a very low calcium content, then concentrated phosphonate inhibitor, and finally a second pad of water with a very low calcium content, through the perforations and into the formation. The phosphonate then returns with produced brine with a concentration in the range of 0.02 to 0.10 mg/l. Each pill has prevented scale upstream of the choke for production of several million barrels of brine.

Starting about 3 million barrels after an inhibitor pill, injection of additional scale inhibitor at the wellhead has been needed to avoid scale in surface facilities. The first indication of the need for more inhibitor has been low readings from brine turbine meters due to scale formation in the bearings. We have found that injecting polymaleac anhydride to provide a concentration of 0.25 mg/l in the brine is effectve at Pleasant Bayou. Use of this inhibitor has the advantage of not masking analysis to determine the concentration of phosphonate from the inhibitor pill.

Corrosion of production well tubulars was found to be a problem when adjacent joints of tubing were screwed into a collar with a gap between the ends of the two joints of tubing. Premium joints that provide a smooth interior across the joint has removed this problem.

Corrosion has been much more severe in surface piping downstream of the choke -- particularly in areas where flow velocity is in excess to 10 feet per second or where high turbulence is induced by discontinuities or valves that throttle brine rate. Stainless steel lining of choke bodies has been essential at both wells. In addition, dump valve bodies and pipe spools downstream of chokes and dump valves were fabricated from stainless steel at Pleasant Bayou.

High corrosion rates still persisted in mild steel, particularily near weld beads, at diameter changes, and in elbows. Corrosion inhibitor containing Quaternary Alkyl Pyridine has been found to be effective. It is injected upstream of the choke to provide a concentration of 8 ppm of purchased inhibitor per barrel of brine.

The cost of corrosion control is about 0.25 cents per barrel and the cost of scale control is about 0.5 cents per barrel, of which 80% is for the inhibitor pills.

Brine Disposal: The spent brine is disposed of by injection into unconsolidated miocene sands at shallower depth than the geopressured sands. These sands initially contain high salinity brackish water and are at greater depth than those containing potable water.

Some of the earlier DOE field tests had substantial problems in disposing of the produced brine. But, the problems have been less severe at Gladys McCall and Pleasant Bayou. We now understand that there are real reasons for these differences. Four of the common reasons for disposal problems are:

1. Produced solids with grain size too small to settle out in the separator and too large to pass through the pore throats in the disposal sand.

2. Hydroxides of iron that form when oxygen form the atmosphere enters the brine.

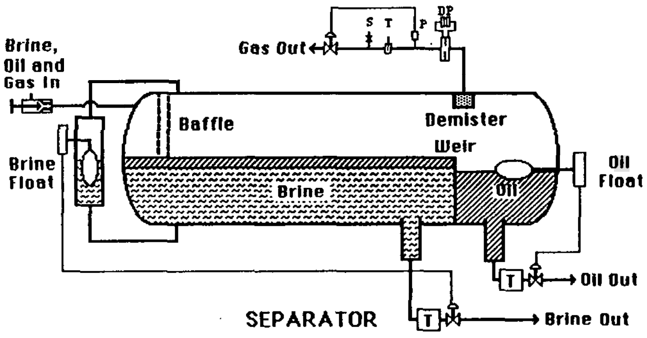
These form flakes that plaster over the pore throats in the disposal sand.

3. Calcium carbonate that forms when the pressure on high temperature brine is dropped to the point where scale inhibitors are no longer effective.

4. Produced oil that reaches the disposal well. This is particularly troublesome when the oil wets precipitating calcite to form a sludge with a density near that of the produced brine.

The lack of problems on current wells is fortuitous good luck. Solids production is so small that use of polishing filters is practical. The density of the hot brine is less that of the native fluid in the disposal sands. As a result, there is always a pressure high enough to avoid oxygen entry into the brine or precipitation of calcite. No oil is produced at Pleasant Bayou. The separator at Gladys McCall is so large that residence time is adequate for separation of the small amount of oil that is produced.

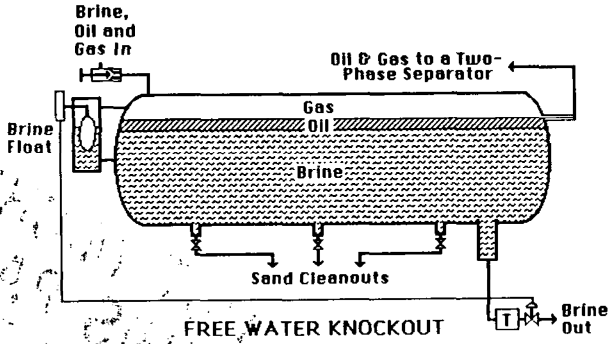
Separator Design & Controls: Separation of gas and brine from geopressured-geothermal wells involves much lower gas/brine ratios and much higher temperatures than conventional production of oil and natural gas. In addition, formation solids may well be produced with the high brine rates characteristic of geopressured-geothermal production. The tests to date have used conventional horizontal separators with the configuration shown below:



Use of an external float chamber has been found to be essential to sufficient stability of level control. For the low gas rates characteristic of geopressured-geothermal wells, level changes translate to gas rate changes A rising liquid level displaces gas out of the separator. On the other hand, a dropping the liquid level reduces the rate at which gas leaves the separator.

None of the wells tested to date have produced enough oil for use of a level controller. This is in part because the temperature of gas leaving the separator is about 275° F. Hydrocarbons in the gasoline range, as well as the produced aromatics, are in vapor form.

Another limitation of the conventional separator is that the vessel is large is relation to brine volume, or to brine residence time. The same residence time can be achieved at lower cost by use of a free water knockout such as shown below:



The gas and oil leave the free water knockout through the same pipe. This stream would then be cooled to maximize condensate production. Then, the condensate would be separated from the gas in a small vertical separator.

Definitions of Unusual Abbreviations:

HPS	Hybrid Power System
SCF	Standard Cubic Foot -- The amount of gas in a cubic foot of space at atmospheric pressure and a temperature of 60 Deg F.
STB	Stock Tank Barrel -- The volume occupied by 42 gallons of liquid at atmospheric pressure and a temperature of 60 Deg F.
TDS	Total Dissolved Solids

THE INDUSTRIAL CONSORTIUM FOR THE UTILIZATION OF THE GEOPRESSURED-GEOTHERMAL RESOURCE

J. Negus-de Wys, Ph.D.
Idaho National Engineering Laboratory

Summary

In January 1990, the first meeting of the Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource was held with 75 participants at Rice University in Houston, Texas. A second meeting was held in September 1990, at The University of Texas at Austin, TX. The mailing list is now over 300 and the next meeting is planned to be held at Louisiana State University Rural Life Museum at Baton Rouge, Louisiana on May 16, 1991.

This technology transfer activity has resulted in increased industrial interest in the Department of Energy Geopressured-Geothermal Program activities. A Request For Proposals will be put out in FY-92 for a thermal enhanced oil recovery (TEOR) project using geopressured-geothermal fluids. Industry has supplied data for collocation studies of hot brine and medium to heavy oil in Texas and Louisiana. The California Energy Commission has now initiated a collocation study focussing initially on Kern County in the San Joaquin Basin and on the Los Angeles Basin.

Four feasibility studies have been developed by the Idaho National Engineering Laboratory (INEL): TEOR, Use of Supercritical Fluid Processes for Detoxification of Pollutants, and Hydraulic Conversion to Electricity, and Direct Use. The studies provide information bases for potential industrial partners. A joint proposal from Los Alamos National Laboratory (LANL) and INEL on supercritical fluid processes is going forward. Western Resources Technology has begun development of a dozen geopressured well projects. British Gas Exploration America has leased 4000 acres around the Hulin Well and plans to spud their first well 3/4 mile northeast of Hulin, March 1, 1991. Additionally, they are proposing a cooperative effort on the Hulin testing and will share a new N-S seismic line with DOE. An hydraulic turbine test will be conducted at Pleasant Bayou in the summer of 1991. Dr. Wayne Steele of Anglewood, TX, is proposing to raise fresh water Australian lobsters in the Pleasant Bayou Well fire-water pond. Additional projects such as catfish farm, crayfish farm, desalination plant and agricultural greenhouse use of the resource heat are "waiting in the wings" for the DOE wells to become available for pilot projects.

The first industry cost-share project, with the Electrical Power Research Institute (EPRI), was a 1MWe hybrid power system successfully tested for eight months in 1990, at the Pleasant Bayou Well. Interest in the resource and its use is now being shown by China, Iceland, Canada, and Japan.

Potential collaboration is being examined with the Solar Energy Research Institute (SERI), Fossil Fuel, and several industrial components. The U.S. Department of Energy document for industry participation has been developed to assist and streamline cost sharing and protection of intellectual property when private industry, government, and universities work together. For more information please contact Consortium Director,
Dr. J. Negus-de Wys, (208) 526-1744.

Introduction

In the Fall of 1989, a meeting was convened with thirty-five interested representatives from industry, academia, and government at the Eaton Operating Company offices, Houston, Texas, to discuss the formation of an industrial consortium for the utilization of the geopressured-geothermal resource. The first meeting of the new consortium was held in January 1990, at Rice University, Houston, Texas, with 75 attendees. The second meeting was held in September 1990, at the University of Texas at Austin and drew 50 attendees, despite travel curtailment in many programs and industries. The next meeting is planned for May 16, 1991, at the Louisiana State University Agricultural Conference Center, Baton Rouge, LA. The mailing list of interested persons and companies now exceeds 350. Proceedings are prepared following each meeting to enhance the technology transfer of science, technology and applications related to utilization of the geopressured-geothermal resource.

Proposed Utilization

At the top of the list for proposed uses of the geopressured-geothermal resource is recovery of medium and heavy oil using the hot geopressured fluids for field flooding. The appeal of this project at this time is several fold.

TEOR

Thermal enhanced oil recovery (TEOR) using geopressured-geothermal fluids is a unique concept for recovering heavy and medium oils that are bypassed during conventional production processes. The successful implementation of this technology would provide an environmentally clean and less expensive method of thermal recovery as opposed to the burning of crude oil or natural gas used widely by industry at the present time in oil recovery projects employing steamflooding (Negus-de Wys et al, 1990).

The geopressured-geothermal fluids are under high pressure in their parent reservoir and when linked to shallow oil reservoirs by suitable plumbing will provide a self-propelled method of heat transfer to a target reservoir existing at shallow depth. The geopressured-geothermal fluids will heat the reservoir as in conventional TEOR. This will reduce the residual oil saturation by lowering the viscosity of the oil so that it can be moved more easily and in greater amounts. The method is similar to hot water flooding and thus the basic technology already exists. However, the major difference is the usually high total dissolved solids present in geopressured-geothermal waters. The exact effect of the brine on the target reservoir is uncertain but may have a beneficial effect not only on viscosity and oil extraction but also on permeability and porosity. The operational and mechanical problems associated with piping the geopressured-geothermal fluids into shallow reservoirs also are uncertain but probably can be readily overcome. The important point is that an enormous amount of additional domestic heavy and medium oil will be recovered if the concept works. Geopressured-geothermal fluids combine the temperatures and propulsion into a technology that would be comparatively clean environmentally.

The U.S. heavy oil resources show California, Alaska, Arkansas, Louisiana, Texas, and Wyoming as major states from which considerable quantities of additional production is possible (Fig. 1). The cumulative production of U.S. heavy oil as of December 31, 1987, was 12.3 Bbbls with 3.3 Bbbls produced by TEOR. The distribution of heavy oil resources shows 42 Bbbls in California, 25 Bbbls in Wyoming, and 2 Bbbls in other states. The leading basins for application of the technology in the United States include the Gulf Coast Basin, the San Joaquin Basin, and the Los Angeles Basin. Totals for these basins are 8.134 Bbbls of medium oil and 4.239 Bbbls of heavy oil (Negus-de Wys et al., 1990). See Figures 1. The San Joaquin Basin alone has 2.5 Bbbls of recoverable heavy oil.

The present status of geopressured TEOR is as follows: An industry cost-shared proposal has been received to apply the process to a field in South Texas. An economic evaluation of the pilot study, included in a feasibility study by the Idaho National Engineering Laboratory (INEL), estimates a cash flow of $6,270,928 per year, based on an assumed recovery of 1,000,000 Bbbls of South Texas crude (Negus-de Wys et al., 1990).

The Geopressured-Geothermal Program has proposed that a Request for Proposals (RFP) to be issued later in FY-91 to solicit industry to proposals for geopressured TEOR projects. The intent is to initiate a TEOR project in FY-92.

Supercritical Fluid Processes

Supercritical fluid processes have been proposed and investigated over the past few years by a number of laboratories and industries for the detoxification of a wide variety of organic wastes. The M.I.T. Energy Lab, Modar, Modelle, Modec, Stone and Webster, Los Alamos National Engineering Laboratory (LANL), S.R.I. International, the University of Texas at Austin (UTA), and the INEL are among the key players.

Supercritical conditions occur at 705.4°F and 3208 psia in the fresh water system. Both pipe and vessel reactor systems have been designed and tested. In a matter of seconds a water carrier with 10% organic waste can be converted to carbon dioxide, salts, and water. It may be possible to go as high as a 30% waste stream. Subcritical processes are also being investigated and show promise (Propp et al, 1990; Shapiro et al., 1991).

In FY-90 the INEL developed a feasibility report on the use of supercritical fluid processes with the geopressured-geothermal resource. An outgrowth of this study was a collaboration with the Los Alamos National Engineering Laboratory in developing a joint proposal for a test processing unit to be evaluated at a geopressured-geothermal site (Figure 2). While developing this proposal S.R.I. International expressed interest in working with INEL, using an hydrolysis process with the hot pressured brine. This concept is under study. M.I.T. has expressed an interest in developing and evaluating additional chemical/engineering processes with supercritical processing. This area of utilization is, thus, rapidly gaining interest, effort, and support.

Desalination

Fresh water can potentially be removed from geopressured-geothermal fluids to meet critical freshwater needs in California, the lower Rio Grande Valley of Texas, and other areas, both nationally and internationally. Following are some of the activities that are currently underway.

G. S. Nitschke and J. A. Harris, Wichita State University, proposed a system that will use the pressure gradient of the reservoir to produce electricity by way of a pressure reduction turbine and generator combination. The natural gas would be separated for sale or on-site use, and the thermal energy would be used to produce potable water through a multi-effect distillation unit. In turn, the remaining saturated brines could be sold. The brine is ideal for solar ponds that utilize binary power generators, a method effectively proven in Israel. Solar pond power could be used for further water production in a conventional reverse osmosis desalination scheme fed with seawater. It is suggested that such a scheme could produce as much as 40% of the total water load in California (Nitschke, 1990, private communication).

F. J. Spencer (International Management Services) has identified six areas for utilization of geopressured-geothermal resources, particularly in the entire lower Rio Grande Valley, South Texas, in the coming decade. The proposed areas are: 1) Recover dissolved methane and sell it as pipeline gas, 2) Use the geopressured-geothermal fluid and/or gas pressure to drive turbines for power production, 3) Use the steam content of the geopressured-geothermal fluid to drive conventional turbines for power production, 4) Use the heat in the fluid for industrial processes, 5) Desalinate the fluid, or use as is (depending on salinity) for both aquaculture and industry, and 6) Use the salts contained in the fluid as starting points for chemicals (Spencer, 1990).

Conversion of Thermal and Hydraulic Energy to Electricity

In 1990, a 1 MW hybrid power system was tested successfully for eight months. This pilot plant demonstrated the potential for generating electricity from thermal energy in the geopressured-geothermal fluid using heat exchangers and getting a thermal boost from the exhaust gases from gas engines run on the methane in the resource. A study by INEL on the economics of converting the thermal energy to electricity concluded that economic viability was still in the future and possibly tied to diversity in use.

In FY-91, a Pelton turbine test will be conducted at the Pleasant Bayou site to evaluate the conversion of hydraulic energy to electricity. With a flowing wellhead pressure of 2200 psia and a turbine exit pressure of 200 psia (this would be dependant on other uses of the fluid), a 500 kW generator could be run with a flow of around 24,500 bpd. The installation of this type of device at the Pleasant Bayou Well would result in a decrease in the break even cost of electricity to between 2 and 2-1/2 cents per kWh. With the conversion of thermal energy to electricity, the breakeven cost was 9 to 17 cents per kWh, hardly competitive in an area where the going price is about 3 cents per kWh. However, as more efficient means of conversion are developed and all energy forms of the resource are used, the economic viability begins to appear feasible (Thurston et al., 1990).

Fresh Water Australian Lobsters

Dr. Wayne Steele, has investigated the potential for raising "fresh water Australian lobsters" in the fire-water pond at the Pleasant Bayou site. Dr. Steele was introduced to these fresh-water lobsters in Australia and followed up with meetings in Georgia with experts on the subject. Dr. Steele has proposed this unique project and will be presenting the topic at the May 16, 1991, meeting of the Industrial Consortium (Steele, private communication, 1991).

Availability of DOE Wells

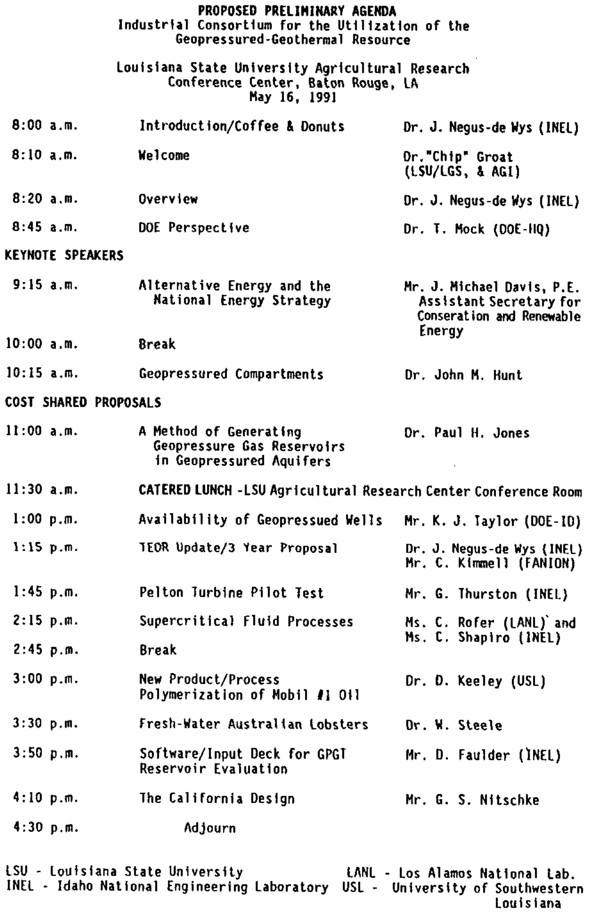
It is planned to make the Pleasant Bayou and Hulin wells available for selected industry cost shared evaluation projects, following flow testing and other tests that preclude parallel efforts. The Gladys McCall Well was successfully flowed for over four years and has been shut in while the pressure build up is monitored. This well will be plugged and abandoned or turned over to industry this year after final testing. The Pleasant Bayou Well was the site of the successful HPS test and is being tested at higher flow rates. The Hulin

Well will be flow tested in FY-92. The DOE will announce to industry more specific plans on well availability.

May 16, 1991, Consortium Meeting Plans

The next meeting of the Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource will be held at the Louisiana State University, Agriculture Conference Center, Baton Rouge, Louisiana. A registration brochure was mailed out in March, followed by phone contacts to over 350 persons on the mailing list. As in the past, proceedings will be compiled and made available to the participants and interested parties.

The agenda is shown in Figure 3. Copies of the last proceedings are available by calling me at (208) 526-1744. Copies of the registration brochure will be sent on request.



PROPOSED PRELIMINARY AGENDA
Industrial Consortium for the Utilization of the
Geopressured-Geothermal Resource

Louisiana State University Agricultural Research
Conference Center, Baton Rouge, LA
May 16, 1991

8:00 a.m.	Introduction/Coffee & Donuts	Dr. J. Negus-de Wys (INEL)
8:10 a.m.	Welcome	Dr."Chip" Groat (LSU/LGS, & AGI)
8:20 a.m.	Overview	Dr. J. Negus-de Wys (INEL)
8:45 a.m.	DOE Perspective	Dr. T. Mock (DOE-HQ)
KEYNOTE SPEAKERS		
9:15 a.m.	Alternative Energy and the National Energy Strategy	Mr. J. Michael Davis, P.E. Assistant Secretary for Conseration and Renewable Energy
10:00 a.m.	Break	
10:15 a.m.	Geopressured Compartments	Dr. John M. Hunt
COST SHARED PROPOSALS		
11:00 a.m.	A Method of Generating Geopressure Gas Reservoirs in Geopressured Aquifers	Dr. Paul H. Jones
11:30 a.m.	**CATERED LUNCH** -LSU Agricultural Research Center Conference Room	
1:00 p.m.	Availability of Geopressued Wells	Mr. K. J. Taylor (DOE-ID)
1:15 p.m.	TEOR Update/3 Year Proposal	Dr. J. Negus-de Wys (INEL) Mr. C. Kimmell (FANION)
1:45 p.m.	Pelton Turbine Pilot Test	Mr. G. Thurston (INEL)
2:15 p.m.	Supercritical Fluid Processes	Ms. C. Rofer (LANL) and Ms. C. Shapiro (INEL)
2:45 p.m.	Break	
3:00 p.m.	New Product/Process Polymerization of Mobil #1 Oil	Dr. D. Keeley (USL)
3:30 p.m.	Fresh-Water Australian Lobsters	Dr. W. Steele
3:50 p.m.	Software/Input Deck for GPGT Reservoir Evaluation	Mr. D. Faulder (INEL)
4:10 p.m.	The California Design	Mr. G. S. Nitschke
4:30 p.m.	Adjourn	

LSU - Louisiana State University
INEL - Idaho National Engineering Laboratory
LANL - Los Alamos National Lab.
USL - University of Southwestern Louisiana

Figure 3. May 16 Consortium Agenda

Acknowledgements:

Work supported by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy Office of Utility Technologies, Under DOE Contract No. DE-AC07-76ID01570.

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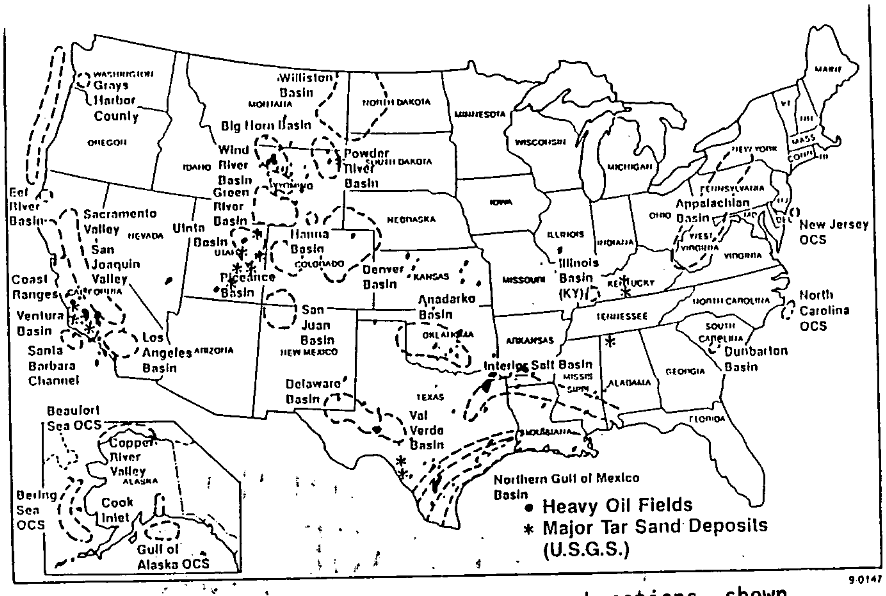

Figure 1. Index Map of Geopressure Locations, shown by dash lines. (Negus-de Wys, 1990)

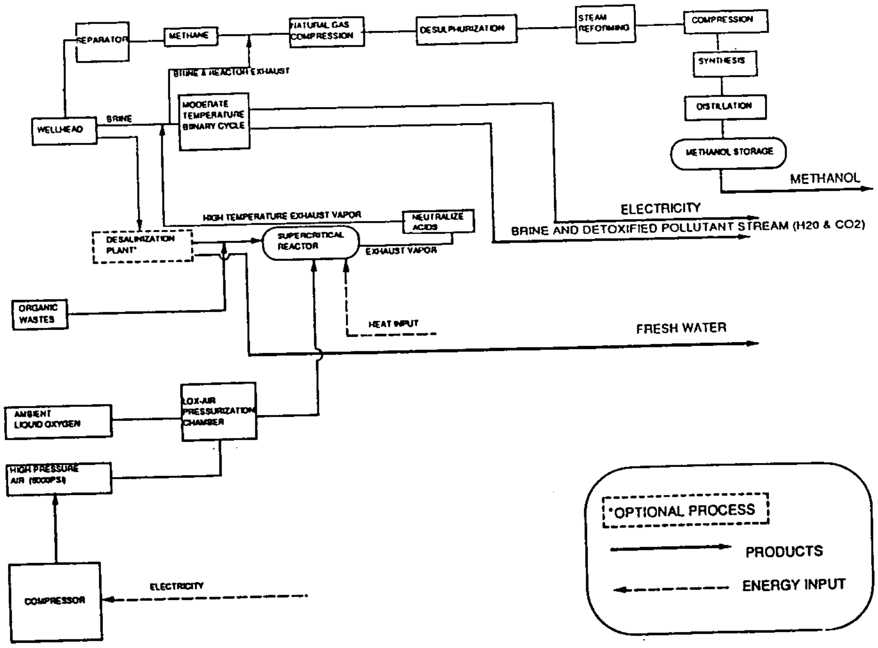

Figure 2. Interface Option Between Geopressured Well and Supercritical Reactor.

LONG VALLEY EXPLORATORY WELL

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

SUMMARY - LONG VALLEY EXPLORATORY WELL

George P. Tennyson, Jr., Session Chairman
U. S. Department of Energy, Albuquerque Operations Office

The Magma Energy Program represents the most exotic of the DOE geothermal energy programs. Certainly magma is the most omnipresent of the resources being considered, since the entire earth is essentially magma with a relatively thin crust insulating life as we know it from the vast source of heat energy below.

The program was initiated in 1985 to determine the engineering feasibility of extracting useful power from crustal magma bodies. Since that time, researchers have reached promising conclusions with regard to drilling, materials, and our ability to extract energy. But the nature of the crustal magma resource is elusive. Shallow crustal magma is necessary for the existence of hydrothermal and hot dry rock systems as well as providing a potential for magma energy extract. However, predicting the location and characteristics of the magma bodies with sufficient accuracy to warrant drilling is extremely difficult at this stage of the technology's development.

The Long Valley Exploratory Well is a major effort to test theories and explore the mysteries of crustal magma. It is a four phase effort, with the first phase having been completed to a depth of 2500 feet in the summer of 1989. Phase II drilling will begin this coming summer and continue the drilling to approximately 7500 feet. This second phase is being cost shared by DOE and the California Energy Commission through a grant to Mono County.

However, the cost sharing aspect of the second phase illustrates again the vitality of the partnerships between industry and two levels of government. The results from this and the other joint efforts are being looked forward to for more than the data output. They represent an affirmation of the selection and priority process for the geothermal programs of the future.

The drilling plans approach the shallow crustal magma issue by aiming to drill the world's deepest well in an active volcanic system. The Long Valley caldera was chosen after substantial research and airing of viewpoints because it is typical of the major magma resource as estimated by the U. S. Geological Survey, it is one of three major active U. S. calderas, and it is a location where present-day magmatic activity is present.

Because of the unique location and the scientific interest it has generated, the Long Valley exploratory well has been designated a Continental Scientific Drilling Program well where add-on scientific experiments will be funded. These Phase II activities were described in some detail in one of the papers in this review.

Also, it should be noted that the Long Valley exploratory well provides data of value beyond the magma program. Its hydrothermal system has long presented a significant problem in analysis. Shallow exploratory wells drilled there have been disappointing even though its location, age and current activity point to the strong possibility of there being a major resource located there. The new data from the Long Valley Exploratory Well could be the key to this mystery and perhaps lead to pinpointing a major geothermal field for exploitation.

However, the main scientific issues to be addressed in the drilling program, as described in this review, include direct assessment of the significance of the observed anomalies, investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor, determination of the amount of collapse and subsequent resurgence of the central portion of Long Valley, determination of the intrusion history of the central plutonic complex beneath the caldera, and establishment of the relationship of intrusive to eruptive events. It is planned that data relative to these issues will be taken during a series of scientific experiments in the well.

The plan described those observations most likely to provide the relevant data, and aims toward developing or eliciting coordinated proposals which will provide the optimum amount of data from Phase II of the drilling program. It is hoped that this data, taken together can provide a very meaningful test of the hypothesis that magma is still actively present beneath the confines of the Long Valley caldera.

Also, during the review, the Phase II drilling operations to be carried out at Long Valley were described in some detail. In that description, it was pointed out that the overall drilling plan will include the objective of testing high-temperature drilling technology under rigorous and realistic conditions. However, during Phase II, it is not expected that the formation will exceed 150 degrees Celsius.

The drilled depth for Phase I was 2568 feet, which meant that the borehole was about 500 feet into the Bishop Tuff. In Phase II, drilling is expected to continue in that formation to below 6000 feet. It was reported that while the Target Depth (TD) is 7500 feet, "the most important criterion is to drill far enough into the Mt. Morrison formation for a secure casing anchor when the 13-1/2 inch liner is cemented in place." Further, with the possible exception of the transition from the Bishop Tuff to the Mt. Morrison formation, it is not expected that the significant lost circulation problems encountered in Phase I will be found in Phase II. Data will be obtained after reaching TD, but before the setting of the 13-1/2 inch casing, using wireline logs and sidewall coring. After the casing is in place, cores will be drilled to depths of approximately 300 feet below the casing shoe.

Not counting the coring effort, the Phase II drilling operation will last approximately 54 days and cost about $2.2 million. We are pleased that the State of California is joining DOE in funding Phase II and supplying about half the funding by means of a grant from the California Energy Commission.

This second of four phases will bring us significantly closer to the magma body that has been estimated by the U. S. Geological Survey to contain 1200 quads of thermal energy. When compared to a total US annual energy consumption of 80 quads, it is apparent that exploitation of this one magma body could supply the entire US energy requirements for 15 years! If the problems are great and the remaining effort to exploit the thermal energy of magma appear daunting, it is well to remember that the potential is even more enormous.

ADVANCED ENERGY SYSTEMS INCLUDING MAGMA

James C. Dunn
Sandia National Laboratories
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ABSTRACT

The Magma Energy Program was initiated in DOE's Geothermal Division in 1985 to determine the engineering feasibility of extracting useful power from crustal magma bodies. Since that time a number of studies have led to promising conclusions in the areas of drilling, materials compatibility and energy extraction. Probably the most critical remaining issue at this time is the nature of the crustal magma resource. The existence of shallow magma in the crust influences not only potential magma energy extraction, but also is necessary for the existence of hydrothermal and hot dry rock systems.

PROGRAM SUMMARY

The current magma energy effort is focused on drilling and completing the Long Valley Exploratory well. However, it is important to remember that the advanced energy systems of Geopressured, Hot Dry Rock and Magma offer the promise of an extended and expanding future for the geothermal industry. The estimated U. S. resource base for these three systems far exceeds the fossil resource and comprises over one-third of the total estimated renewable energy base.

Highlights of the Magma Energy concept include: (1) The potential resource is very large - up to 500,000 Quads; (2) Power produced from a single well is estimated by analysis and experiment to fall within the range of 25 to 45 MWe; (3) A wellhead temperature of 500 °C is predicted; and (4) Fluid circulated as a heat transfer medium through solidified magma at depth is naturally confined by plastic rock regions surrounding a crustal magma body, therefore, fluid loss should be negligible.

Major accomplishments in the magma program have occurred in each of the project areas of magma location and definition, energy extraction, geochemistry and materials, and drilling. Considerable evaluation of geophysical and geological data led to the selection of Long Valley caldera as the site for verification of the crustal magma resource. The expected silicic magma at Long Valley has been characterized and compatible materials have been selected. The important thermal processes of magma convection, thermal stress fracturing during cooling, fluid/rock heat transfer, and overall concentric flow energy extraction have been evaluated both analytically and experimentally. The surface power generation cycle has been designed and evaluated based on dual fluid loops which allow a closed fluid loop circulating through the solidified magma. Drilling methods for penetrating magma are based on our earlier work at Kilauea Iki where water-jet augmented bits and high cooling rates were used. For these procedures to work at great depth, insulated drill pipe and surface cooling of the mud flow is necessary. The insulated drill pipe has been analyzed and designed with industry.

The remaining key question to answer in order to assess engineering feasibility is, Does magma exist in large quantities at drillable depths beneath U. S. silicic calderas? This issue is being addressed by drilling the Long Valley Exploratory well. A deep well in this active caldera can verify the existence of magma at drillable depths in a location that is a major contributor to the large magma resource estimate.

The Magma Energy Program recently received an independent review by Mine Development and Engineering Corp (MDEC) that was funded by the California Energy Commission through Mono County. Mdec concluded that engineering feasibility was successfully addressed for source location, energy extraction, geochemistry and materials. They pointed out that more development was needed in the drilling technology area to finish the work on insulated drill pipe which would include procurement and testing. Also, complete design of the bottom-hole-assembly is needed. MDEC completed an economic assessment of the magma energy concept and concluded that previous cost estimates used for magma wells were too high. The resulting estimate of magma based power, therefore, was very favorable (5 to 10 cents per KWHr). MDEC also agreed that the Long Valley well is essential to evaluate the magma concept.

The primary objective of the Long Valley well is to verify the existence of magma at drillable depth. There are also other important goals which include determining the structure beneath the resurgent dome in order to refine geophysical modeling and improve geophysical techniques for magma location. As the well probes beyond the Bishop Tuff, new data in the form of geological samples of formation and fluids and downhole geophysical measurements will be used to constrain hydrothermal models of the caldera. We will obtain a history of hydrothermal activity as well as current thermal and fluid states.

John Finger will describe the planned Phase II drilling which is scheduled to begin in July of 1991. Funding of this phase is shared by three agencies: DOE/ Geothermal Division, California Energy Commission, and DOE/ Office of Basic Energy Sciences.

PHASE II DRILLING OPERATIONS AT LONG VALLEY

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The Long Valley Exploratory Well is designed to be drilled in four phases (see Figure 1), with scientific experiments in the intervals between drilling operations. We completed Phase I drilling, with 26" hole to a depth of 2568 feet and 20" casing to 2559 feet, in September 1989. Special drillpipe from the Ocean Drilling Program was then used as a bushing, or "artificial wellbore", (see Figure 2) to continuously core approximately 200 feet below the 20" casing (Ref. 1).

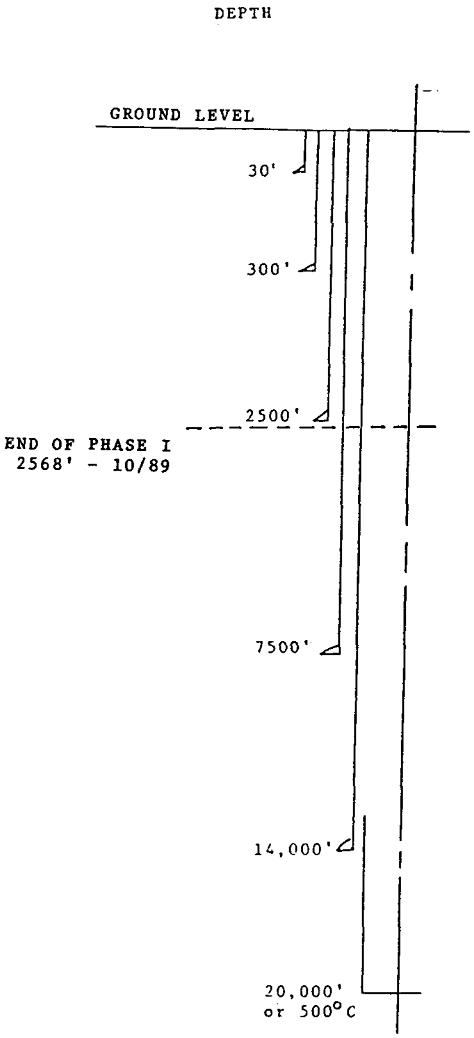
The primary stimulus for this drilling project is the belief that a relatively shallow magma body underlies Long Valley caldera. There is overwhelming evidence, including seismic anomalies, recent magmatic activity, geologic setting, and large-scale surface uplift, for the presence of such a body. This phenomenon is of great economic and scientific importance, because the USGS estimates that magma beneath Long Valley alone contains approximately 1200 quads of thermal energy (compared to <u>total</u> US annual energy consumption of 80 quads), and scientists' opportunity to penetrate a young caldera and examine its evolutionary history is unique. Goals of this exploratory well include the following: (1) to aid potential hydrothermal development with better definition of the deep fluid circulation in the central caldera structure; (2) to verify the presence of a magma body beneath the resurgent dome; (3) to test high-temperature drilling technology under rigorous and realistic conditions; and (4) to provide a unique scientific opportunity for observation of the near-magmatic environment in a young caldera.

Phase II drilling, designed to reach 7500 feet, will begin in early July 1991. Phase I target depth (TD) was approximately 500 feet into the Bishop Tuff, and we expect that Phase II will continue in that formation to below 6000 feet. Although the nominal Phase II TD is 7500 feet, the most important criterion is to drill far enough into the Mt. Morrison formation for a secure casing anchor when the 13-1/2" liner is cemented in place. Based on the 500 feet of Bishop Tuff that we have already drilled, we believe the Phase II drilling, with the possible exception of the transition between Bishop Tuff and Mt. Morrison formations, will escape the massive lost circulation problems that plagued Phase I. After reaching TD, wireline logs and sidewall coring in the open hole will precede the setting of 13-1/2" casing to that depth. Once casing is in place, we will core drill approximately 300 feet below the casing shoe, possibly using the same ODP drillpipe technique as in Phase I. The open core hole will remain for scientific experiments. The drilling and coring operations will not be significantly affected by high temperature, since the formation is expected to be cooler than 150°C at the end of Phase II.

We estimate that the Phase II drilling operation, excluding coring, will last approximately 54 days and cost approximately $2.2 million. The state of California provides about half this money, by virtue of a grant from the California Energy Commission, and the DOE provides the other half. Data from the drilling operation, available before the subsequent scientific work, will comprise the drilling records, mud logger's reports of lithology and fluids, contract wireline logs (temperature, caliper, gamma, dual induction, and acoustic), any logs done by Sandia with our own equipment, and samples of core, cuttings, and fluids.

<u>References</u>

1. "Phase I Drilling Operations for the Magma Energy Explorator Well", J. T. Finger, Proceedings Geothermal Program Review April 1990



DEPTH	HOLE DIAMETER	CASING SIZE	I.D.
30'	48"	40"	
300'	36"	30" .625 wall	28.75"
2500'	26"	20" 133#	18.73"
7500'	17-1/2"	13-1/2" 81.4#	12.37"
14,000'	12-1/4"	9-5/8" 53.5#	8.54"
20,000' or 500°C	8-1/2"	OPEN HOLE	

Figure 1 -- Diagram of well design, showing hole and casing sizes

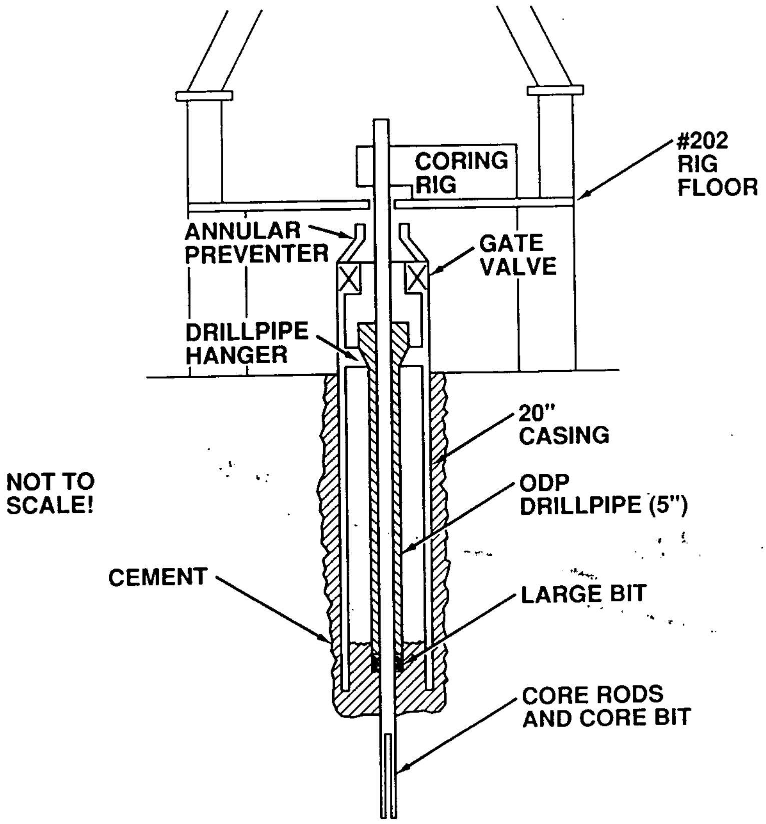


Figure 2 -- Schematic of core rig operation. Core rig is placed on large rig's floor; core rods travel inside ODP drill pipe, which acts as an "artificial wellbore".

SCIENCE PLANS FOR PHASE II OF THE LONG VALLEY EXPLORATORY WELL

by

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ABSTRACT

The Geothermal Division of the United States Department of Energy began drilling a deep exploration well in Long Valley Caldera in August 1989. Drilling is to be carried out in a series of four phases. Phase I drilling was completed to a total depth of 782.7 m in October, 1989. Location of the well is in the central part of the caldera, coincident with a large number of shallow (5 - 7 km depth) geophysical anomalies that may signal the presence of magma. Scientific results from the well will enable a direct assessment of the significance of the observed geophysical anomalies, investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor, determination of the amount of collapse and subsequent resurgence of the central portion of Long Valley, determination of intrusion history of the central plutonic complex beneath the caldera, and establishment of the relationship of intrusive to eruptive events. The answers to these questions will be obtained by a series of scientific experiments in the well. The purpose of this Plan is to describe which observations are most likely to provide answers to these questions, and to develop coordinated proposals for carrying them out in Phase II of the drilling program. If, as seems likely, these experiments can be carried to successful conclusions throughout all phases of drilling, the well will indeed provide a stringent test of the hypothesis that magma is still actively present within the Long Valley caldera.

1. Introduction

The US Department of Energy, Geothermal Division (GD) has begun drilling a deep exploratory well within Long Valley caldera to test the hypothesis that magma exists at shallow depth. The ultimate goal is to evaluate the engineering feasibility of magmatic heat as an energy source. The well is being drilled in four phases with primary funding provided by GD/USDOE. A recent supplement to the Interagency Accord on Continental Scientific Drilling designates the Long Valley exploratory well as a CSDP project. Participating agencies have agreed in principle to fund approved scientific measurements in the well that address the following areas of interest: (1) geophysics; (2) geology/petrology; (3) hydrothermal systems; (4) stress, rock mechanics and physical properties of core; and (5) science - related tools and equipment. To carry out these measurements, a set of high priority experiments have been proposed for Phase II of the drilling program. Proposals have been submitted to the Office of Basic Energy Sciences of the US Department of Energy.

2. Background

The Long Valley - Mono Craters volcanic complex in eastern California (Figure 1) is presently the most active major silicic system within the conterminous United States. The most recent major eruption associated with this system occurred only 550 years ago, with a possibility that a minor eruption may have occurred beneath Mono Lake in 1890. Beginning in October, 1978, a series of tectonic events occurred which may be a consequence of major intrusive activity beneath the caldera (see, e.g., Rundle and Hill, 1988). A sequence of moderate earthquakes initiated the activity northwest of Bishop, California, which has since encompassed both the Long Valley caldera, and the Sierra Nevada mountains to the south. Eleven of these events had magnitudes close to 5 or larger, and four had magnitudes larger than 6. Since 1980 in particular, Long Valley

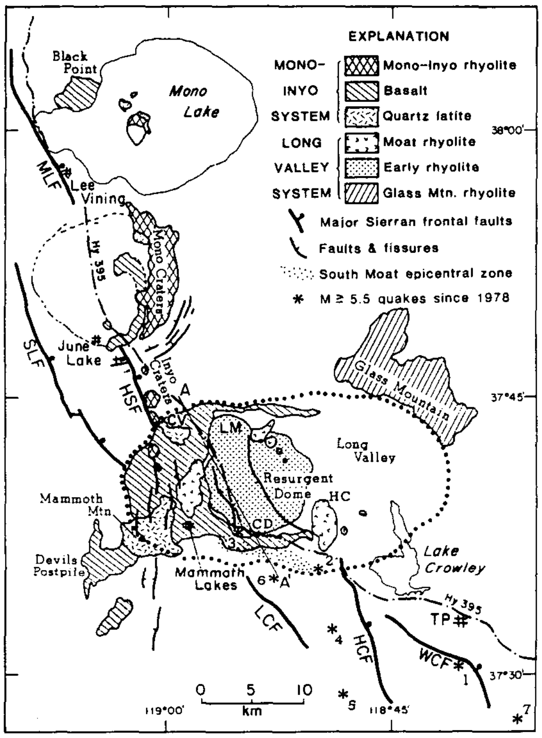

Figure 1. Regional geologic and tectonic setting of the Long Valley caldera (after Rundle & Hill, 1988). Dots indicate the boundary of the caldera. HCF = Hilton Creek fault; HC = Hot Creek; LCF = Laurel Canyon Fault; MLF = Mono Lake Fault (also known as Lee Vining Fault); WCF = Wheeler Crest Fault; HSF = Hartley Springs Fault; SLF = Silver Lake Fault; CD = Casa Diablo; LM = Lookout Mountain; TP = Tom's Place; CV = Crestview. Numbers refer to major earthquakes (larger than magnitude 5) that have occurred in the area (see, e.g., Rundle & Hill, 1988).

has experienced substantial ground uplift of at least half a meter, and horizontal extension rates of geodetic lines spanning the caldera have exceeded several ppm/year. In fact, beginning in September 1989, horizontal extension accelerated to rates as much as 9 ppm/yr, before subsiding to lower rates of 5-7 ppm/yr in late spring, 1990 (Langbein *et al.*, 1990). An increase in the associated seismicity began somewhat later, in November 1989.

Regional volcanic activity associated with the Long Valley caldera began about 3 million years ago, culminating in the caldera - forming Bishop Tuff eruption of 700,000 yr. B.P. (Bailey et al., 1976). Additional, smaller eruptions since that time include the Mono Craters eruption of the last 50,000 years (Wood, 1983), the Inyo Domes dike eruption at 550 years B.P. (Miller, 1984), and numerous other intrusive and extrusive events throughout that time (e.g., Bailey et al., 1976; Hill et al., 1985). A variety of recent investigations have led to the conclusion that present activity within the caldera is the result of the injection of 150 to 200 million m^3 of magma beneath the central part of the caldera since 1980.

Given the extensive efforts which have gone into modeling the uplift in terms of magmatic sources (e.g., Rundle and Hill, 1988), the most reasonable inference is still that the horizontal location associated with the peak of the uplift most likely overlies the site of active magma injection. This area of maximum uplift has thus been chosen as the site for the Magma Energy exploratory well (Figure 2). The principal goals of the drilling program are to confirm the existence of magma at drillable depths, to assess possible drilling problems associated with magma energy production wells, and to examine materials compatibility problems in the high temperature regime. Supporting scientific and technological research is therefore of value to the project if it serves to meet these goals.

The Magma Energy program of the US Department of Energy, Geothermal Division (GD), began Phase I drilling activities in August 1989. The Phase I segment of the well was completed to a depth of 782.7 m, with subsequent wire-line core drilling to 839.4 m. Bottom hole diameter of the cased well at 782.7 m was 20" (50.8 cm) inside diameter. Unfortunately, the drilling rods for the corehole became stuck in the well, preventing a number of the planned experiments, those that required an open hole, from being carried out. As described previously, the well was designed as a stringent test of the hypothesis that magma is still present within the central plutonic complex and to provide engineering data needed for the design of future magma-energy production wells. The furloughs between the four phases of drilling are a scientific boon as they allow important and otherwise unobtainable scientific measurements to be collected at a number of depths. Because the well provides the opportunity for a large number of scientific studies in an area of great interest, it has been identified as a Continental Scientific Drilling Program "Well of Opportunity" in which the USGS, NSF and DOE will consider supporting additional scientific studies. A complete description of the well design, the program timetable and constraints, and the objectives and scientific opportunities available can be found in Rundle *et al.* (1989); Finger and Eichelberger (1990); and Chu *et al.* (1990).

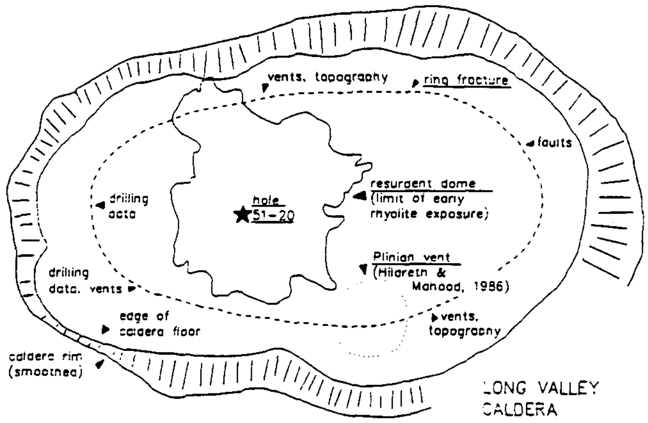

Figure 2: Location of well within the caldera.

3. *Summary of Results from Phase I Drilling*

The corehole drilled at the termination of Phase I drilling was funded by the Office of Basic Energy Sciences, Division of Geosciences. Original plans calling for a suite of experiments including seismic, electromagnetic, hydrothermal and other investigations had to be limited after the core drilling rods became stuck in the corehole (this presents no significant problems for Phase II drilling). However, logging and analysis of the core, together with temperature logging observations were completed. The results of these investigations are reported in McConnell and Eichelberger (1989); Shearer *et al.*(1990); and Sass *et al.* (1990).

Briefly, the core and cuttings revealed that the well began in Early Rhyolite and ended in Bishop Tuff. The top of the Bishop Tuff was encountered about 200 m deeper than expected on the basis of stratigraphy provided by nearby wells. The rhyolite is thick and rich in tephra that is for the most part aphyric, glassy, and generally perlitic, pumicieous, and lithic poor. The hole apparently followed the contact between Bishop Tuff and an Early Rhyolite intrusion, sampling varying proportions of the wallrock, the intrusion, and its obsidian margin.

The temperature logs indicate that the uppermost 200 meters or so are dominated by a shallow hydrologic regime overlain by transients from the drilling operation and cementing. The gradient is about 53 °C/km, and there are examples of what appear to be major circulation loss zones, for example at about 825 m depth.

4. *Experiment Objectives*

The primary objective of this well is to achieve a deeper understanding of the physical properties of basement rocks at near magmatic conditions at depths of 5-7 km. Extensive surface experiments and shallow drilling programs have examined the volcanic section overlying the caldera basement. It is evident from those investigations that the shallow caldera fill strongly influences the surface and near-surface geophysical data which has been used to identify magma drilling targets. However, the Phase II well will be the deepest drilled to date within the caldera, and is expected to bottom in basement. For the first time, it will be possible to direct sensing experiments at active crustal magmatic processes in Long Valley caldera without the obscuring effects of the caldera fill intervening. Experiments of most interest to the Magma Project will be those which ultimately have the capability of detecting, locating, and characterizing the active magma chamber. Specifically, these experiments include passive and active seismic observations, electromagnetic profiling, stress and deformation measurements, and temperature logging. Due to the engineering nature of the drilling program, these experiments are highly time - constrained, and must be carried out during the furlough periods separating episodes of drilling.

While the specific types of experiments identified in the following sections represent information of maximum interest to the Magma Project, there are many other kinds of experiments as well whose results would nonetheless be of considerable interest at a more general level. These include studies of hydrothermal alteration, stable and unstable isotope studies, secondary minerology, fluid and gas sampling, pore pressure monitoring and additional properties of cuttings and core. Addtional experiments may be proposed as the well progresses, and many of these investigations become more important as the well approaches its target depth. Because this well represents a unique opportunity to study the nature of the caldera's magmatic and deep hydrothermal systems, these independently funded experiments should be considered for the period between drilling episodes.

In addition to these experiments, there is a distinct need to develop the capability of conducting observations of various kinds at temperatures in the range of 250 °C - 500 °C, conditions that will be encountered as magma is approached during the drilling program. Given the physical constraints imposed by high temperatures and pressures, the only possible way of obtaining these observations is with the use of a dewared pressure vessel, in which the electronics needed to operate downhole are cooled to keep them within their operating specifications. Rather than each experimenter custom-designing a container to his own specifications, it makes most sense to develop a dewared facility which can accomodate many different kinds of experiments. Conceptually, a versatile dewared vessel might be likened to a NASA - designed general use satellite platform, hence the name "Inner Space" capsule. The design specifications would include the ability to maintain a low temperature (< 150 °C), atmospheric pressure environment for a hypothetical trip from the surface to 6 km depth, with a planned residence time in the bottom of the hole of 6 - 7 hours, at an ambient temperature of 500 °C. The tool would be sized to fit through a standard lubricator and valve at the wellhead. Plans for the capsule, to be developed by Magma Project personnel for general use, provide for on board power and memory or communications link. The individual investigator would supply the sensor, amplifiers, and signal conditioning of analog signals to a stadardized interface at a standard level of + 5 volts. Sensors might include 3 - component geophones, or three component ring-core fluxgate magnetometers, or televiewers, etc. An additional advantage of this approach is that workers on the rig need only be familiar with one type of dewared tool, thus minimizing potential problems with operations. In fact, the logic of the inner space capsule approach has been recognized by the Magma Energy Project, and plans are currently being made to develop such a facility (J. Dunn, personal communication, 1989). It can therefore be anticipated that a dewared vessel of this type will be available later in the drilling program.

5. *Experiments Proposed for Phase II*

At the conclusion of Phase II drilling, a standard suite of logs will be taken prior to casing. Following emplacement of casing, a short corehole will be drilled out of the cased section. If all goes well, it will be left uncased until the next phase of drilling, nominally a year later, for a variety of experiments. Many of these experiments will be carried out by a variety of national laboratory, university, US Geological Survey, and other agency personnel. The following experiments are of the highest priority.

A. Coring, Logging and Lithology

A short (100 meter long) HQ corehole will be drilled out of the 13.5" diameter cased well at the end of Phase II drilling. In addition, 30 sidewall cores will be obtained from the main wellbore prior to casing. Core retrieved will be analyzed for lithology, fracture density, and physical and chemical properties. Core obtained from sidewall coring, and from the corehole at termination of the first phase of drilling will principally be of value for measurement of stress by anelastic strain recovery, for verifying lithologic information, and for obtaining data on fracture density. The principal value of the well will be in allowing in situ measurements of electromagnetic and seismic wave fields, and for observations of in situ stress via hydrofracture.

B. Well Logging

Upon completion of the main well section to 2286 meters, and just prior to casing, a suite of logs will be obtained. Some of these logs are required by the permitting agencies, while others will allow interpretation of the subsurface lithology, and will aid in modeling and understanding data from other experiments. Logs required by the permitting agencies include a deviation survey to measure well inclination every 500 feet; a directional survey in the case that deviation exceeds 5° ; a mud log consisting of temperature, gas content, pump pressure and cutting lithology; and any other lithologic information which can be obtained. Additional logs which are desirable include a dual induction survey to infer porosity and fluid content; a gamma log to use for lithologic inferences; a density log; an oriented caliper log; and a vector sonic log. Consideration is also being given to obtaining a cement bond log, which may or may not be taken at the same time as the vector sonic log.

C. Temperature Logging

A variety of activities will be carried out to determine the *in situ* thermal state of the well environment. These activities will include:

1. A time series of temperature logs during rig furlough (ideally at 1 week, 1 month, 2 months 4 months, and 6 months after completion of phase 1 drilling).

2. Heat flow estimates using the corehole as a flux - plate during furlough. Detailed temperature measurements combined with thermal conductivity measurements on preserved core will be measured at ambient pressure and temperature.

3. Estimations of equilibrium temperature profile obtained by extrapolation of temperature time series to long times after completion of drilling.

4. Thermal conductivity measurements on drill cuttings, with corrections for grain conductivity and porosity at each depth, and comparison of these with measurements obtained from core in the corehole.

D. Active and Passive Seismic Experiments

The total and interval seismic velocities from the surface to 2286 meters depth will be determined for use as constraints on interpreting seismic velocity structure along and in the vicinity of the hole, and ultimately, of the magma body. Reflected wave fields will also provide a "look ahead" capability to help plan further drilling strategies. The experiements are of two types, active and passive. The minimal passive experiment for Phase II involves cementing two, 3 - component borehole seismometers at the bottom of the corehole. Two surface shots will be fired to calibrate the installation, and data from local earthquakes would be recorded by the seismometers in a passive mode for 3 - 4 months. These seismometers would be installed after all other measurements in the corehole were completed. Of course, drilling activities in Phase III would destroy the instruments, so they would have to be constructed in such manner as to minimize problems with drilling.

The complete active experiment involves, in addition to passively recording local earthquakes, performing a P, S, and acoustic Vertical Seismic Profile (VSP) in the cased portion of the well, from the surface to 2286 meters, and in the uncased corehole. Vector wavefield information from the P and S profiles would be obtained using a standard, 3 - component clamped, movable instrument, whereas acoustic information can be obtained by means of unclamped hydrophones. The advantage of using hydrophones is that their sensitivity to high temperatures is far lower than conventional seismometers, hence they can be used even at the high temperatures (500 ^oC) anticipated at near magmatic conditions in the later stages of the drilling program. Experience suggests that explosive surface sources may be more effective than vibrator trucks.

E. Active and Passive Electromagnetic Experiments

Similarly to the seismic experiements, passive and active observations of the electromagnetic wave field will be carried out to determine the electromagnetic structure of the caldera, both near the borehole and in the surrounding medium, horizontally out from the well and below it. With passive ovservations, far field sensing of conductors to the side and below the borehole can be accomplished by monitoring transient fluctuations in the earth's magnetic field using a 3 - component magnetometer emplaced in the corehole. Because natural source fields are much more spatially uniform than artificial source fields, and do not suffer from the $1/r^3$ geometric attenuation with distance that artificial sources at the surface experience, natural EMT methods appear to be an effective means to complement other geophysical studies such as VSP and borehole gravimetry. These studies can be readily accomplished using available 3 - component ring - core fluxgate magnetometers operating in the pulsation band from 5 to 300 s. Employing signals in this band provides the greatest depth of penetration and uses a relatively rich spectrum of natural energy.

Controlled - source (active) EMT measurements are those in which a large - moment magnetic dipole is activated at the surface. An example of such an experiment would include an in - hole instrument consisting of a high - sensitivity, dewared borehole detector using a 1.3 meter long coil magnetometer and associated amplifier. The energy source would be a large diameter horizontal loop antenna laid out around the well and energized by a generator over a frequency range of .1 to 100 Hz. These active - source methods have the advantages that the radius of investigation into the formation is much larger than can be achieved with conventional logging methods, the method can be used to look ahead of the drilling, and the technology can be used in cased holes. Thus, the active source method can be used to obtain a vertical electromagnetic profile in much the same way as one can obtain a vertical seismic profile.

F. In Situ Stress Measurements

\Measuring the stress at shallow depth in the caldera will answer two important and interesting questions:

1. What is the relationship between the depth dependence of stress in the caldera, the regional tectonic and volcanic history, and the current presence or absence of magma within the caldera?

2. Will boreholes in pressure and temperature regimes above an active magma reservoir be stable?

The preferred method for stress measurements is hydraulic fracturing, which is a well - known, widely used technique to obtain stresses from pressure - time signatures following fluid injection in isolated sections of a drillhole. If the drillhole axis is parallel to one principal stress, and if the rock permeability is low, then it is generally easy to determine the magnitude of the minimum principal in situ stress from the shut - in pressures immediately after pumping into the fracture intervals has ceased. In many cases, particularly in hard rock, it is also possible to ascertain the direction of the minimum principal stress from the trace of the hydraulically induced fracture or fractures at the borehole wall.

Other methods to be used for obtaining data on the state of in situ stress are:

1) Anelastic strain recovery and acoustic emission immediately upon extraction of oriented core.

2) Borehole televiewer observations of fracture density and orientation.

3) Caliper logging to obtain orientation of borehole breakouts.

6. Priorities

Of all the experiments described here, the most critical to successful completion of the project are the thermal and other logging, and the coring. *Funding of these experiments should have the highest priority.* Of the remaining experiments, seismic and EMT data are relevant to the question of reservoir evaluation, and depth to magma. The *in situ* stress data are relevant to the issue of borehole stability and well design. More generally, seismic and EMT experiments can answer questions about the overall structure and evolution of calderas, whereas stress measurements can provide important data on the active mechanisms for injection of magma into the caldera magma chamber.

Based on the above considerations, it can be seen that the seismic and EMT experiments both provide information, in principle complementary and overlapping, on the structure of the caldera beneath the well. *Therefore, if budgetary constraints are severe, it may be necessary to select a subset of the proposed investigations to determine caldera structure.* Moreover, the *in situ* stress observations are planned for both FY 92 and FY 93, in hopes of observing stress changes within the formation related to injection of magma. *Again, if budgets dictate, it may be necessary to limit stress observations to only one field campaign during a single fiscal year.* These decisions should be made at the appropriate time by the project Science Panel in consultation with project personnel.

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PROGRAM REVIEW IX WRAP-UP

CLOSING REMARKS

Roland R. Kessler
Director, Office of Renewable Energy Conversion
U.S. Department of Energy

Communications is the word that seemed to highlight this conference. Speakers such as Darcel Hulse made us think both in terms of communicating to promote geothermal benefits and to correct misconceptions. When I came to Washington, D.C., in the mid-70's, one of my main assignments was to develop communications regarding the promise and benefits of emerging technologies in solar, wind, ocean, geothermal; to encourage understanding and applications by state and local governments and the public. We continue to have work to do in this regard. Our speakers have told us something of the needs.

We had a large amount of R&D money in those days -- in fact, too much in some research areas; but we did not have enough people. Some things don't change. Many things have changed, however, especially the funding.

There have been important changes in just the past couple of years. We have an Assistant Secretary, Mike Davis, who knows and advocates our programs. We have encouragement for our programs; but at the same time, always two critical questions are being asked by our boss in the Administration and, in fact, by Congressional staff, regardless of party, at briefings on our programs:

1. What specifically will be accomplished with the funds requested and why does it matter?

2. What important accomplishments have been made with the funds you have spent?

Usually, an associated or follow-on question is, "what additional investments were encouraged or leveraged by these accomplishments?"

All of you need to keep those questions in mind. We may face those questions, but you are answering them with us. I think most of you realize that by what you have said here.

Now, with regard to this, my first Geothermal Program Review, may I first congratulate you on a successful and enjoyable program. In fact, although "program review" is our DOE term for a conference to review the various elements of a program -- where they have been and where they are going -- I believe an even more appropriate term for this particular conference would be "progress review." This is true, I think, because we have heard one speaker after another report on progress in research results and progress in industry achievements, all directed toward the goal of greater geothermal use and benefit.

For example, I was pleased to hear that Fenton Hill is on the doorstep of the Long Term Flow Test. And, I enjoyed hearing that electricity has been generated -- on an experimental basis -- with geothermal-geopressured resources for the first time anywhere in the world. Jane Negus-de Wys said we'll be hearing much more about geopressured. Her consortium is rolling now.

As a newcomer, or "returnee," to the geothermal field, I also have another observation to make of the attendees here based on your reports and our side discussions. I am impressed with your enthusiastic commitment and your optimistic attitude about achieving the goal of increased use of geothermal energy. However, I do remind you of a question that Mr. Lipman of Unocal raised last year at Program Review No. 8. Is the story of geothermal accomplishments reaching those in control of our energy agenda? While Mr. Lipman placed the responsibility for achieving a prominent role for geothermal energy squarely on the shoulders of industry, I believe every member of the geothermal partnership represented here today -- DOE, state agencies, national laboratories, and participating universities -- shares that job of advancing the appreciation of geothermal energy. This resource is one of the most, if not the most, reliable and cleanest alternative fuel economically available today, and probably the best buy R&D can make, but this message must be carried to decision-makers on a national, state and regional level -- in the Executive and Legislative Branches -- and by more than a few spokesmen.

Beyond the impact this message may have on the general image and acceptance of geothermal energy, the message also has critical implications specific to industry's immediate and future competitive interests. Industry holds real influence and power if it cares to use these assets in public decision-making, particularly regarding this Administration and its expenditure of R&D dollars. The stack of real dollars is finite, and those who can crisply make their case for visible accomplishments and are willing to put their resources alongside their words will "carve up" most of the stack.

In addition to stretching available federal R&D dollars, another major benefit of cost-shared R&D is that it encourages more immediate technology transfer, a function described by the National Energy Strategy as a "fortifying foundation" to the nation's energy future. In fact, Secretary Watkins says technology transfer is "one of DOE's key missions." We are urged to emphasize support for cost-shared programs that help prove the feasibility of technologies that have potential for a broad range of government and commercial industrial applications. I look upon the Department's enunciated support for technology transfer and the importance of government, industry, lab partnerships to that end as one of the strongest policy statements DOE has made in the National Energy Strategy.

The reports given here indicate very forcefully that the geothermal industry appreciates the potential reward of this policy. To list only a few examples: The industry's financial contributions to The Geysers research have been larger than federal funds made available by Congress, though as you heard, ours have been increased last year over the previous one. The activities of the reservoir technology research are carried out jointly with industry and labs, technology transfer and commercialization of high-temperature materials is continuing under Geothermal Drilling Organization (GDO) sponsorship, and industry lends its facilities for testing of materials and equipment at various stages of development. All these are important means of technology transfer. The National Academy of Sciences found the GDO, and the similar industry-driven Geothermal Technology Organization, to be model mechanisms for technology transfer. The Department in its analysis of technology transfer methods, which I participated in, agreed with the NAS conclusion.

To its credit, as well as to its benefit, the geothermal industry's recognition of the value of cost-shared research is not new. It has participated since the outset of the federal R&D program. Thus, my brief remarks are intended only to emphasize once more that, in today's dollar-short climate, we should all be even more vigilant in identifying the highest priority areas for the expenditure of the dollars of both government and industry. I can and do assure you that we at DOE will continue to encourage and solicit industry guidance in formulating our programmatic objectives and strategies.

In the sum, key words to me over the past two days describing the essence of this meeting have been: communications, partnerships, technology transfer, accomplishments.

Bob San Martin challenged us to let decision-makers know -- we are the ones with the solutions. He said geothermal opportunities will be growing and our collective responsibility is to tell people what has been and can be accomplished.

Jack Motter said our theme is utilities and partnerships. He said communication is key and called for adding regulators to the partnerships of industry, government, utilities.

Ted Mock listed a half dozen major technology transfer accomplishments in FY90 alone... stories that need to be told repeatedly! And, he reminded us that NES does clearly state support for geothermal development; an accomplishment for the program too.

But, Ray Alper brought back some reality. The outlook is rosy, he said, but we do have some public image issues. And, NIMBY will impact renewables as it has non-renewable technologies. Attend to political influences, at all levels, he said, so they see geothermal's great promise!

Finally, what I heard over these two-plus days was about the benefits of the "geothermal resource," the heat of the earth or, as Mike Wright called it, "earth energy" -- not about wet earth energy, or dry earth energy, or earth energy containing methane -- but all of that. The resource that is widely available, is reliable, is clean, is all of those. Geothermal energy needs to be recognized in its totality as well as its parts.

In addition to all I have pointed out, and perhaps above all, this meeting tells me -- tells those of us on the other U.S. coast -- our ability to respond effectively to changes that may occur, new circumstances, new problems, new opportunities, new participants, and new knowledge, is dramatically enhanced by the level of communication between you people in the field, out on the firing line, and those of us in DOE headquarters. We look forward to hearing from you.

I want to thank you for your participation here. Your reports send us home with a clearer understanding of the status of geothermal development, and with a renewed commitment to and confidence in our ability to support your goals effectively. Thanks again for your presentations.

OBSERVATIONS ON THE DOE GEOTHERMAL PROGRAM

Myron Tribus
Exergy, Inc.

It has been a pleasure to attend this review of the geothermal activities of the Department of Energy. I have had about 49 years of experience with Federal attempts to influence technology. My experiences are pretty much in agreement with the conclusions of Professor Squires in his book, "The Tender Ship", in which he reviews technical projects undertaken by governments from 1640, when King Gustaf of Sweden ordered the ill-fated ship, Wasa, to put to sea, even though the shipwright knew it was topheavy, to the Challenger disaster of recent times. From these experiences, one rule is clear: The quality of the work goes inversely as the funding!

The geothermal activities of the DOE seem to fall on the curve. By any measure it is under-funded and, by the same token, by any measure it is a well-run program. I think its budget might be increased, somewhat, without endangering the quality and hope that comes to pass.

It was a pleasant surprise to hear a dramatic change in attitude on the part of at least one representative of the utilities. When the speaker from Nevada finished speaking, I turned to a fellow next to me, who happened to be from PG&E and asked him, "If it had been a speaker from PG&E up there, would we have heard the same message?" He replied that it would have been the same message. Within PG&E he had watched a video from management taking the same line: The geothermal producers are our friends.

Another pleasant surprise was the degree to which I could detect a shift to a greater emphasis on systems. Most of the speakers were able to relate their work to the larger aspects of geothermal systems. I believe this is a reflection of better program management.

I suppose these developments all reflect the effects of tight budgets. When money is tight, people do pay more attention to what is important.

In considering what has been presented to us in the last few days, I find it helpful to categorize the contributions in one of four ways:

1. Contributions to knowledge. Knowledge enables us to understand what we see and hear and put it into a relationship with what we already know.
2. Contributions to know-how. Know-how teaches us how to do something. Knowledge without know-how is sterile. Know-how without knowledge prevents us from learning from experience. Instead of 30 years experience, we have 1 year repeated 30 times!
3. Contributions to infrastructure. Whenever we set out to apply our knowledge, we need help from an infrastructure. We require organization of knowledge and data in useful form. We require people and services upon which we can call. We require an agreed set of procedures, so we may work together. We get these from an infrastructure.
4. Reports of achievements. From time to time, someone announces a genuine breakthrough in some part of the geothermal chain of necessary events. In my judgment, there was only one such achievement at the conference, and since it concerns my company, I shall make no further remarks on it at this time.

There were, in my opinion, several important contributions to our knowledge that came out of this review. I would especially cite the work at UURI, where data are being gathered in a useful format and relationships are being established to bridge among academia, the government and industry. These will form the basis for an important infrastructure.

An example of a contribution to knowledge and know-how was the work of Professor Weare on the chemistry of fouling and precipitation. Not only did he provide a theory, but he also provided computer programs which may be put to work on practical problems.

Certainly we have to notice the work of Jane Negus-de Wys, whose efforts to form teams of people from industry have led to important commitments in support of geothermal-related R&D.

The work on hot dry rock also deserves a comment. Just as we have progressed from being hunters to farming, I think that soon we must progress from hunting for geothermal sources, only to find they are never where we need them, to creating them where needed. HDR methods permit us to engineer these resources. I am confident that we shall learn much about naturally occurring geothermal resources from the HDR work.

As we look ahead, it seems to me that there are several areas in which more work needs to be done. In order of priority, I would put these tasks as follows:

- Methods to assess the life and productive capacity of a given site.

  Today bankers are aware that although geothermal resources may have a history measured in geological times, they do not have similar futures. Moreover, geothermal wells now have lives which, today, seem unpredictable. We cannot expect geologists to develop an adequate theory which will tell us, in advance, how long a given well will last at what production rate. However, it seems to me possible to develop methods of assessment which will enable us to tell how long a particular well will last. Furthermore, we ought to be able to trade off well life against production rate. We need instrumentation and methods which will enable us to do so in a predictable way.

  Because we now cannot do this, the trend is towards highly modular units which can be sled mounted and quickly moved from one site to another. This is a clever solution to a problem we ought not to have.

- Resources should be identified and classified according to their economic potential.

  Insofar as we can do so, we should identify resources according to the potential flow rates and temperatures. Admittedly, this is not an exact process. However, we now make maps which show areas in which high and moderate temperatures are to be expected. Given the recent advances in which we attain approximately 75% of the second law limit, it is now possible to translate these maps into electrical energy potential. Each year these maps should be updated and overlaid with the current purchasing price of electricity for the region in which the geothermal resource occurs. In that way, we shall have a much better understanding of the economic potential in various areas. Information presented in this way will be much more meaningful to potential developers and area planners.

- Develop metrics of meaningful progress.

  Insofar as possible, translate progress into a uniform measure. For example, the geopressured resource should be defined in terms of its electric potential and as we improve various aspects of the technology of dealing with these resources, the measure of progress will be the decrease in the cost of the resultant electricity. Thus, scale removal can be related to cost of electricity. It will not be easy to develop these measures, but they will be of great value when it comes time to justify what has been done.

I have introduced this last item because it seems to me that the geothermal program of the Department of Energy has done very well with the limited funds it has been given. With better measures of accomplishment, perhaps the Congress and the Administration will better appreciate the value of what has been accomplished.

NGA PERSPECTIVES ON GEOTHERMAL TECHNOLOGY DEVELOPMENT

Moderator: Dennis Nielson
University of Utah Research Institute

NGA Perspectives on Geothermal Technology Development
Exploration/Reserve Development

Dr. Jim Combs
Geo Hills Associates

During the past two and one-half decades, the subject of geothermal exploration/reserve development, although I would prefer to call it geothermal exploration and reserves confirmation, has had an interesting history. Let's look at the past and consider what the future has to offer.

EXPLORATION AND RESERVES CONFIRMATION IN THE 60s AND 70s

During the late 1960s and throughout most of the 1970s many geothermal developers and operators (e.g., Union Geothermal, Chevron Resources, Gulf Oil, Phillips Petroleum, Shell Oil, Aminoil, Sun Oil, Getty Oil, Occidental Geothermal, Hunt Energy, Hunt Oil, Geothermal Resources International, Thermal Power, Magma Power, Magma Energy, California Energy Company, Anadarko Geothermal, Geothermal Kinetics, Amax Geothermal, Steam Reserves Corporation, U.S. Geothermal Corporation, Intercontinental Energy Corporation, Earth Power Corporation, Yankee Geothermal, Republic Geothermal, Geothermal Power Corporation, Thermogenics, etc.) were carrying out geothermal exploration and development programs in the western United States.

During this same time period several geothermal service companies emerged, including GeothermEx, Geonomics, ThermaSource, Inc., Microgeophysics Corporation, GeoThermal Services, Inc., Teledyne Geotech, Senturian Sciences, to execute the exploration programs that were funded at the level of many tens to hundreds of millions of dollars. These exploration dollars were being spent on geological investigations, geochemical surveys, isotopic studies, DC electrical resistivity surveys, seismic noise surveys, microearthquake surveys, magnetotelluric surveys, TDEM soundings, temperature gradient drilling, and heat flow surveys. Fortunately, these exploration efforts culminated in the drilling of several successful exploratory geothermal wildcats in California, Nevada, Utah, and New Mexico. Unfortunately, however, the geothermal developers and operators found that there was no one who was willing to buy this newly found steam and hot water under long-term contractual relationships and build the necessary power plants to utilize the geothermal fluids to generate electricity.

We, as geothermal developers and operators, while merrily carrying through our exploration/reserve confirmation programs, had neglected to develop our customer, i.e., the public, investor-owned, cooperative, and federally-owned utilities, who would purchase the geothermal resources and build the power plants to use the geothermal steam that was being developed.

EXPLORATION AND RESERVES CONFIRMATION IN THE 70s AND 80s

During the late 1970s and early 1980s, in order to encourage the development of geothermal resources, to stimulate exploration and reserves confirmation, and to ensure that some actual exploration data and exploratory drilling results were available in the public domain, the DOE/Division of Geothermal Energy initiated the so-called Industrial Coupled Program. This federal R&D program was initially viewed as another attempt by the federal government to dictate the direction of the geothermal programs of private industry; however, several of the geothermal developers and operators in private industry did eventually take advantage of the program. At Roosevelt Hot Springs, Utah, Phillips Petroleum, Thermal Power, Getty Oil, and Geothermal Power Corp. had formed a federal geothermal exploration unit, and they determined to take advantage of the cooperative R&D program to further their knowledge of the geothermal reservoir that was being developed. Similarly, at Cove Fort, Utah and Stillwater, Nevada, Union Geothermal released exploration data to the public domain and drilled cost-shared exploratory wildcats with the DOE geothermal research program. Chevron Resources at San Emidio, Soda Lake, and Beowawe in Nevada; Phillips Petroleum at Beowawe, Desert Peak and Humboldt House in Nevada, and Earth Power Corp. at Baldazor in Nevada were also geothermal developers and operators that took advantage of the industrial coupled program.

In his presentation on Tuesday entitled Hydrothermal Opportunities and Challenges in the Basin and Range, Dave Faulder of INEL did an excellent job of pointing out the potential geothermal reservoirs that were identified by the industrial coupled program. Some having been confirmed and developed to date, while many others have still not been developed.

During the late 1970s and early 1980s, the primary reason for not developing many of the geothermal resources that had been discovered by private industry, with or without federal cost-sharing, was that their base temperature was less than 200°C (400°F). The conventional wisdom at that time was that any geothermal resource below this temperature could not be economically developed. However, during the 1980s, the conventional wisdom of the day was disproved by Magma Energy Company at the East Mesa KGRA in southern California with the Magmamax Process, by Barber-Nichols Engineering Company at Wendell and Amadee Hot Springs in California as well as at Cove Fort in Utah, and by Ormat Energy Systems, Inc., with their initial facilities in Nevada and at the East Mesa KGRA in southern California.

With the development of the binary cycle power technology and the passage of the PURPA legislation of 1978, we have seen throughout the later part of the 1980s and into the 1990s that the fruits of the exploration efforts of private industry as well as the results of the DOE-Industrial Coupled Program are being reaped.

EXPLORATION AND RESERVES CONFIRMATION IN THE 90s

We are now moving into the 1990s. Contrary to the late 1970s and early 1980s, there are not thirty or forty geothermal exploration and development companies in existence with tens to hundreds of millions of dollars to spend on exploration for and confirmation of new geothermal reserves. More specifically, as we move into the 1990s, there is essentially only one multidisciplinary geothermal service company. Similarly, there are only about ten or so geothermal developers and operating entities. Furthermore, most of them, with the exception of Unocal Geothermal, are so-to-speak cash-short entrepreneurs who can not afford to do the exploration and reserves confirmation that is necessary to obtain the next round of long-term power sales contracts from utilities which are the cornerstone of the financing of each new geothermal power generation project.

Although much of the electrical power development from geothermal resources in the near future will most likely be concentrated in the Basin and Range Province, and in fact, will probably necessitate the acquisition of little or no additional exploration data, there is a desperate need for low cost reserves confirmation techniques to provide the level of comfort that is necessary to obtain the long-term power sales contracts from utilities.

Another pitfall for the geothermal industry is that it appears that the next two major geological provinces that will be developed are Hawaii and the Cascades of the Pacific Northwest. Both of these areas have proven over the last several years to be difficult geological environments in which to explore for geothermal resources. For example, we have identified the existence of the so-called rain curtain in the Cascades and have noted the difficult and expensive drilling that is encountered because of the extremely hard rocks and the ubiquitous loss circulation problems that exist in the igneous terrains of both Hawaii and the Cascades.

With the use of corehole drilling technology which has been developed over the past 30 or 40 years in the mining industry, the geothermal industry has been able to overcome some of these drilling and cost problems in order to establish that a particular area has elevated subsurface temperatures; and therefore, may have potential recoverable geothermal fluids. Drilling costs for these coreholes with depth ranges of 1,200m (4,000ft) to 1,800mm (6,000ft) typically are from 250 to 500 thousand dollars each. However, at present as was indicated above, geothermal developers and operators are still not able to determine whether there are producible geothermal fluids located at economically drillable depths without completing and testing at least one expensive, rotary-drilled, big-diameter, geothermal wildcat. Over comparable depth ranges as those for the coreholes, these wells can cost from 1.5 to 3.5 million dollars.

Additionally, the areal extent and definition of the boundaries of the possible geothermal reservoirs cannot be established without drilling and testing several of these expensive geothermal wells. Therefore, industry finds itself in the geothermal catch-22 of needing to prove a viable geothermal reservoir without spending much money in order to acquire a long-term power sales contract with a utility which can be used to finance the project in order to drill and test the wells that are needed to prove the efficacy of the geothermal power generation project.

DEFINITION OF A FEDERAL GEOTHERMAL EXPLORATION AND RESERVES CONFIRMATION R&D PROGRAM

In the 1990s, because of the present tenuous status of geothermal developers and operators, as outlined above, there is a definite need for an aggressive and well funded exploration/reserves confirmation effort in the DOE geothermal R&D program which will promote the continued development of geothermal resources. The strategy of DOE participation in cost-shared research with industry that was initiated in the early 1980s should be continued and stressed in order to gain the most from available funding. The cost-shared federal exploration and reserves confirmation R&D research program should contain the following elements:

1. Proof of concept experiments to demonstrate that low cost, small diameter, coreholes can be flow tested to provide comparable deliverability data and reservoir parameter estimates that are obtained from conventional rotary-drilled wells. These experiments would consist of drilling and testing of coreholes adjacent to drilled and tested production wells of industrial partners in producing geothermal fields such as The Geysers in northern California or at Steamboat Springs in Nevada, and possibly redirecting the exploration program in Hawaii to include testing of the coreholes that are being drilled and completed;

2. High-temperature hardening of diamond corehole drilling equipment to provide reliable service in the geothermal environment;

3. Development, improvement, and high-temperature hardening of slimhole geophysical logging tools to obtain reservoir parameters in the coreholes;

4. Development of borehole-to-surface, surface-to-borehole, and borehole-to-borehole electrical resistivity and/or seismic techniques to be deployed in small diameter coreholes to establish and confirm the areal extent and define the boundaries of the potential geothermal reservoirs;

5. Better define and improve tracer technology to be used in the exploration phase, as well as the exploitation phase of geothermal reservoir development, in small diameter coreholes and standard production and injection wells to establish, confirm, and monitor the areal extent of geothermal reservoirs and the interaction of fluids between production and injection wells;

6. Better define and improve geochemical and isotopic methods and techniques to be used in exploring for, confirming reserves of, and monitoring the production from geothermal reservoirs; and

7. Develop systems and techniques to lower the costs of drilling geothermal production and injection wells, for example, methods to control loss circulation, better and low-cost loss circulation materials, high-temperature directional drilling equipment, and high-temperature down-hole packers.

This recommended program should be funded at the level of 15 to 20 million dollars per year and should be carried out through partnership relationships between academia, government, and private industry. If this effort is not funded and executed immediately, specifically, in the next few years, it will be too late to provide the stimulus to sustain a viable geothermal industry that is needed to see the timely development of this economically attractive, renewable, environmentally advantageous, indigenous energy resource.

The geothermal industry continues to have the basic need for more reliable techniques to locate and adequately characterize geothermal reservoirs, to define the areal extent and boundaries of these reservoirs, to assess fluid movement and recharge paths, and to understand the complex reservoirs that continue to be identified from our exploration efforts. Additionally, geothermal developers and operators need the ability to predict the total available energy and the useful productive lifetime for each geothermal reservoir in order to convince the utility customers to provide the long-term power sales contracts that are necessary to encourage the development of geothermal resources and to maximize the benefit from this attractive alternative energy resource for society.

CRITIQUE OF DRILLING PROJECTS

MARC W. STEFFEN
CALPINE CORPORATION

The cost of drilling and completing economic wells represents a major portion of geothermal resource development. As we continue forward in our efforts to develop new areas and maintain existing drilling programs, reducing or minimizing these drilling costs will become absolutely vital to ensure the economic viability of future projects. It goes without saying that the actual commercialization of a project can be greatly impacted by initial development costs of which drilling is a significant contributor. Therefore, it is fundamental to continue to identify problems that directly affect drilling costs, develop and enhance the technology to mitigate these problems, and to coordinate the timely implementation of this technology to its practical conclusion in the field. It is vital that if we are to effectively meet these challenges, the geothermal partnership of Industry, Utilities, and Government must continue to work closer than ever.

This partnership has to be flexible enough to identify concepts, technologies, and innovations that have a practical use in the field and that can be developed and tested in a timely manner that is still beneficial to the industry user. One of the principal advantages of drilling over other elements of resource development is that the application of new technology and methodology can easily be field tested under actual operating conditions where performance and results can be monitored and assessed in a relatively short time frame. As a result, the process of commerciality and availability to the industry is expedited.

The Geothermal Drilling Organization (GDO), which was founded several years ago, is a good example of how the partnership of industry and government has joined together in identifying problems unique to geothermal drilling and developed technologies and products to overcome these problems. An illustration of how this partnership can work is the development of high temperature elastomers, particularly stripper rubbers for rotating heads, that are more durable and reliable under the extreme conditions of geothermal drilling. By identifying a need for a product through the GDO, development was undertaken through the efforts of Brookhaven National Laboratories and A/Z Grant Int., and the finished product is now being field tested in the Geysers. The GDO provides a forum for the flow of information from and to the people that are integral to identifying and solving a problem related to geothermal drilling. This kind of communication is imperative in developing new technologies and products that will significantly impact drilling performance and provide a practical benefit to the industry.

Another noteworthy industry/DOE cost shared project, also under the sponsorship of the GDO, is the development of a pneumatic positive displacement drilling motor. This tool will provide a dramatic improvement in directional control in fractured, vapor dominated reservoirs such a the Geysers and in other areas that demand the use of compressed air as their medium of drilling. As fields mature and well spacing becomes more critical, the need for precise directional control when drilling with mud or air becomes increasingly important. The development of this tool is being done by Eastman Christenson and it's parent Baker-Hughes, Inc. In an area like the Geysers, where a substantial amount of the well's total footage is drilled with air, the potential benefit to an operator is enormous. This also is an example of a project that may not have materialized if it weren't for the assistance of the DOE and a sponsoring body like the GDO. Even though the project will provide an immediate and valuable benefit to geothermal drilling in the Geysers, the market and industry demand for such a tool would, in all likelihood, have been inadequate to justify the necessary research and development to bring the tool to commerciality.

From my perspective, I think a great deal of progress has been made identifying projects that can directly benefit the Geothermal industry and continue to produce needed advances in technology. Addressing problems associated with excessive or abnormal drilling costs, such as lost circulation control, is essential to future economic resource development. The biggest obstacle, in my opinion, facing industry and government is to prioritize projects and place the necessary focus into areas that can provide an immediate and measurable cost benefit to reducing drilling costs. Assessing these cost benefits has to originate with people directly involved in the geothermal drilling industry and then communication channels have to be established between industry and the researchers to allow for a timely development process. Developing the technology to properly cope with some of the special problems posed by exploratory and developmental geothermal drilling is critical to the evolution of future geothermal projects.

It is unfortunate that geothermal drilling is a relatively small market compared to oil and gas, however, one of the advantages of drilling technology is, that in some cases, such as lost circulation detection and control, pneumatic drilling motors, and high temperature elastomers, are examples of areas where technological advances can be used in a wide variety of drilling applications. As a result, a greater incentive may exist for the partnership of industry and government to meet these technological challenges.

I believe that the focus on short term projects should continue to be concentrated on areas that are being actively drilled for several reasons: 1) problem areas can be identified through actual experiences, 2) changing conditions can be monitored and communicated to researchers; and 3) timely field testing can be achieved under actual operating conditions. I feel that a regular dialogue between industry and the DOE sponsored researchers is absolutely essential to identifying beneficial programs and accomplishing the desired objectives in a timely manner. Meeting the challenges of the 90's can be accomplished but only if the geothermal partnership of Industry, Utilities, and Government function as a cohesive unit with well defined goals.

Critique Panel Comments on DOE Reservoir Engineering

Gerald Niimi
ThermaSource, Inc.

To place my comments in perspective, I would like to point out that we have not received any DOE contracts nor are we working on any Federal government contracts. Therefore, I might have some misconceptions as to the exact objectives and results that the DOE programs are achieving.

Roland Horne presented some results of the effect of adsorption on the graywacke reservoir in The Geysers Field. Research work in The Geysers should be supported and continued. There is a huge amount of heat stored in the rocks and research efforts should be aimed at extracting this heat. The Geysers is a relatively easy place to work as the infrastructure in terms of roads, wells, and power plants are already in place. Marcello Lippmann talked about The Geysers and research into injectivity. This is an extremely important area of investigation as my experience with on-going projects suggest that many companies are finding that injectivity is one of the major problems facing geothermal development.

I believe that Field Case Studies is not an appropriate area for DOE research unless there are particularly unique behavior problems. I think this should be left to the private sector. There is an interest on my part to find out what geophysical techniques have worked in various geothermal areas. This would entail performing geophysical studies in known areas of success to calibrate geophysical tools.

In terms of computer codes, I think that the emphasis should be placed on tools that will work on the PC level so that field level implementation can occur. Most problems do not require reservoir simulation.

I was glad to hear David Faulder's talk on Basin and Range geothermal resources. The more resources are identified, the more development can occur since many fields are relatively small and a large number might provide economies of scale particularly when it comes to transmission lines.

Joe Moore talked about injection tracers and the results of these studies. Again I believe that research into injection technologies should be continued.

There is quite a bit of geothermal activity in foreign countries. In my contacts with people, it is evident that the United States is the technological leader in geothermal drilling, tools, and resource analysis. We should make every effort to remain the leader. We must also promote the industry if we are to keep the geothermal business vital. The industry has much to offer and these aspects should be played up, we cannot compete solely on a price basis.

Thank you for the opportunity to be here.

Critique On
Geothermal Fluid Handling

Harry Veizades, P.E.
Veizades & Associates, Inc.

I am pleased to participate in this panel and present my views on the fluid handling element of the Geothermal Program Review. As an active member of the geothermal industry, my views are limited to those items of the fluid handling element that I am aware as a design consultant.

You may have noticed, however, that very little has been presented in this conference on the subject of fluid handling. This lack of presentations may give the impression that all is well and all problems associated with fluid handling have been solved.

While this is true to a large extent, there are still problems requiring innovative solutions. The industry welcomes the participation of the research and development organizations in providing these solutions.

Up to now, the technology of fluid handling in geothermal fields has received little attention from researchers. This is primarily due to the fact that most geothermal fluid handling systems are perceived as systems that are not so unique as to require special attention. After all, geothermal steam is just a compressible fluid, and condensate is just water with some dissolved gasses and solids.

The design concepts of piping systems to handle such fluids are well developed. In fact, geothermal fluids do present special handling problems, and the industry to a large extent has solved most of these problems. Essentially the industry, mostly, through a process of trial and error has developed and implemented methods to solve most mechanical and process problems associated with geothermal fluid handling facilities. Through this process the present cost-effective design concepts of piping systems have been developed.

A possible contribution of the geothermal industries would be the preparation and publication of a comprehensive design manual that compiles all the design concepts and gives guidelines for the design of piping systems for handling geothermal fluids. This information now is scattered amongst several papers and in the files of various geothermal developers.

There are still several problems with the fluid handling systems that require further investigation and research. I will briefly outline some of these problems, hoping that some of you may undertake the task of finding solutions.

A persistent problem with geothermal piping systems is corrosion. This is an old problem that has plagued many geothermal systems for years. The problem may intensify as geothermal reservoirs are depleted and concentrations of corrosive constituents increase.

The industry has tackled this problem and I believe has developed successful corrosion abatement systems for surface piping systems. The corrosion is either abated by selection of piping materials or by neutralizing the corrosive elements through scrubbing and injection of chemicals. Further work is required to optimize the various processes and make them cost effective.

Another related problem is corrosion of downhole casing. Considerable work is under way to solve this problem by either selecting casing materials or by downhole injection of chemicals.

If the mechanical problems associated with downhole injection can be solved economically, this method would be the best method to employ as it would tackle the problem at its source, abating corrosion of both downhole casing and surface piping. A possible research and development project therefore, is to develop a cost-effective integrated casing system that would allow downhole injection of corrosion inhibitors.

The performance of most fluid handling systems, particularly systems for handling steam and two-phase flows, is analyzed on the basis of empirical formulas. Very little work has been done to correlate the empirical formulas to the actual performance of operating systems. Such correlation will be invaluable in order to optimize the design of such systems. This correlation is particularly important in order to better understand the flow characteristics of two-phase flow in large diameter piping.

A problem that will be facing the industry in the not too distant future is the decommissioning of piping systems as each power plant is retired.

At this time all surface piping systems are considered contaminated by scaling and deposits of hazardous materials. As such, all piping materials and components are not salvageable and must be disposed of on approved disposal sites. Methods of safe removal and disposal could prove to be very expensive.
It would be desirable, therefore, to develop cost-effective methods for on-site scrubbing of piping materials so that they can be safely removed and salvaged.

I have outlined only a few subjects that merit some research and development effort. The industry would be interested in offering assistance in solving some of these problems by making available, existing operating systems for testing and proving proposed solutions.

COMMENTS ON THE DOE POWER CONVERSION TECHNOLOGY R&D PROGRAM

John Brugman
The Ben Holt Co.

I am indebted to Ted Mock, Dennis Nielson, Dave Anderson and Ben Holt for this opportunity to present a few comments regarding the DOE Geothermal Energy Program. My comments will be restricted to the area of power conversion technology R&D and fall into four categories:

- The historical trend of DOE R&D efforts
- The philosophical aspects of Government Industry relations
- A reaction to current programs from an industry perspective
- A wish list for future R&D projects

The Historical Perspective

The FY 1980 federal geothermal budget was $149.4 million. One decade later, this had fallen to $18.0 million. A discussion of the reasons for this alarming trend is, at this point, academic but the consequences to the industry have been profound. Not only have worthwhile projects been curtailed but also new and innovative lines of research have been forestalled. Many of the important research projects carried out over the past two decades have been done in cooperation with other funding agencies, public and private, notably, the Electric Power Research Institute, and as federal funding has dried up, so also has matching funding. This has served to magnify the negative impact of federal cutbacks.

While geothermal energy provides about 0.5% of the nation's electric energy needs, only about 0.1% of the DOE budget is devoted to furthering the development of this emerging alternate energy source. We should examine the past with an objective and critical eye so that we can husband our limited resources and apply them to the best effect in the future.

Towards this end, I offer my personal assessment of some past big ticket programs, restricting myself to only those programs which are directly or indirectly associated with power conversion technology.

In the category of successful programs, I would place at the top of the list the Geothermal Loop Experimental Facility. This combined effort of the federal government and private industry led to the development of hypersaline brine technology which has allowed the exploitation of our country's largest hydrothermal resource. The Material Selection Guide lines by Ellis and Conover have contributed to the successful design of geothermal power plants in a variety of geothermal environments. However, it should be noted that this work is now ten years old and needs to be updated to incorporate new materials and additional operating experience. The investigation of hydrocarbon thermodynamic properties by several researchers as well as the refinement of our understanding of the physical and thermodynamic properties of geothermal fluids has been invaluable to the effective design of power conversion facilities. In the realm of future technology, the geopressured energy conversion work at Pleasant Bayou has demonstrated the practicality of near term exploitation of this energy source.

In the category of mixed success, fall two programs which were successful from a technical point of view but did not lead to economically viable commercialization. The first of these is the Heber Binary Demonstration project. Problems with the resource prevented the full power operation of this facility and left the question open as to whether this type of large scale binary plant could be economically viable. Similarly, the direct contact heat exchanger program established the technological feasibility of direct contact heat exchange. However, this technology was being developed to enable the exploitation of hypersaline brines and this need was precluded by the development of the clarifier/crystallizer technology at the GLEF.

Some programs have not contributed significantly to the advancement of power conversion technology. Others have not contributed in proportion to their cost. Included in these categories are the Baca Demonstration, the Raft River Demonstration, the Total Flow program and the Down-Hole Heat Exchanger/Gravity Head programs. I will not attempt to conduct a post mortem on these programs but there are some lessons to be learned from each of them. The Baca program is a textbook example of the risks inherent in fast track projects. Raft River represents an attempt to incorporate too many high risk technologies in the same project. This increased the project cost, delayed start-up and caused insurmountable operating problems which eventually scuttled the program. The total flow concept was based on a single thermodynamic assumption which has proved to be incorrect. If the technology is ever to compete with more conventional options, the program must be rebuilt from the ground up and founded on a firm theoretical basis. The gravity head/down-hole heat exchanger program had high technical risk but low potential payoff. An objective assessment of the program compared with competing commercial technologies should have revealed this.

The Government/Industry Relationship

One of the major ways for the government to nurture the fledgling geothermal industry is to sponsor R&D. Unlike mature industries, the geothermal industry is neither old enough, big enough or profitable enough to sustain the level of R&D required to promote increased development of this resource. With the exception of the Heber Binary and the Cove Fort plants, the public utilities have restricted themselves to single pressure steam plants at the Geysers. Innovations in power conversion technology have been made by private independent power companies. These companies with their heavy financial obligations are ill equipped to carry on long term comprehensive R&D programs. The primary alternate to the DOE for R&D has been EPRI. However, EPRI has recently de-emphasized geothermal research making the R&D shortfall even more acute. With much of the federal R&D efforts devoted to future technologies such as hot dry rock, geopressured and magma, and most of the rest devoted to drilling and reservoir technology, there is less than $2,000,000 in the current budget for hydrothermal conversion technology. Thus, R&D needs for immediate problems with these emerging technologies are not being met.

As mentioned above, geothermal power plants are capital intensive. In order to achieve long term economic viability, we need to develop cheaper plant components. This can be accomplished by standardizing designs, improving materials and reducing equipment over-design. But this requires R&D oriented toward today's problems.

Finally, in order to broaden the industry's economic base, we must translate our technological leadership into the international market. The United States has the world's largest geothermal industry and yet we are not competing with the Japanese, New Zealanders or the Italians. Technological leadership can only be maintained by a steady diet of well directed R&D effort. There is, for example, no major U.S. manufacturer of geothermal steam turbines. To serve the needs of the binary power industry, we have only two or three small hydrocarbon turbine manufacturers. If we are to sell American power plants in the world, they should be built from American components.

Given the small amount of R&D funding available for the power conversion sector, we must concentrate our efforts on those areas that will best support it. There should be greater emphasis on current problem areas and less emphasis on long term or high risk technology. There should be more emphasis on basic research and less on systems development. And we should concentrate the R&D budget on technological issues rather than economic, institutional or legal issues.

Current Programs

There are currently four programs relating to power conversion technology. The Heat Cycle Program is interesting but there is no pressing current need for advanced heat cycles. Industry has demonstrated its ability to apply the state-of-the-art in existing power plants and future developments are not being limited due to a lack of good heat cycles.

The Materials program offers us the possibility of a new type of anti-corrosive heat exchanger tubes. However, in most moderate temperature systems where these tubes would most likely be used, corrosion is not a serious problem and mild carbon steel is already being used with good success. To justify additional R&D in this area, the economic advantage of this technology should be demonstrated as well as the need for these materials.

The Brine Chemistry program warrants further support. The federal government has attempted this task without success on more than one previous occasion but the need for predictive capabilities still exists. If the computer codes developed at UCSD can be installed in a personal computer and are thus available to the industry, they could then be tested against actual experience at a number of different sites. If found to be valid, they would provide plant designers with a valuable design tool.

The Toxic Waste Handling program is also an important program for today's industry. Toxic waste is probably the only environmental issue which significantly affects the geothermal industry.

Wish List

There are three areas of basic research which would be of great assistance to the power conversion sector. The first has to do with two phase hydraulics. Geothermal gathering systems frequently involve two phase pipelines carrying steam/brine mixtures. However, little is known about the hydraulic behavior of these systems, particularly for inclined flow. We need to be able to accurately predict the flow regime, liquid holdup and friction losses for these systems. Research in New Zealand indicates that the losses in fittings (elbows, tees, valves, etc.) are greater for two phase flow than for single phase flow. Our field experience tends to confirm this. There is also need for accurate means of flow measurement in two phase systems.

The second area has to do with turbine design. Since domestic steam turbine manufacturers have retreated from the geothermal industry, advances in the state-of-the-art are being made overseas and we are losing our competitive edge. A vigorous steam turbine R&D program may be what it takes to bring our manufacturers back into the game. We need inexpensive, reliable, high efficiency turbines. Our competitors are using the technology we developed against us. The only answer is to advance the state-of-the-art and regain the technological high ground.

The same applies to the hydrocarbon turbines used in binary cycles. Although we currently lead the world in the production and application of radial inflow expanders, these are expensive high tech machines. Our foreign competitors are beginning to develop axial flow impulse and reaction turbines for hydrocarbon applications. These turbines, which are less costly than RIF turbines and which can also be made in much larger sizes, represent an opportunity to make low temperature liquid dominated resources economically viable. We must build on the advances made at the Heber Binary project to retain our leadership in this area.

The third area of basic research which would immediately benefit the industry involves the air cooled heat exchangers which are used for binary cycle plants. We need a better understanding of the effects of noncondensible gases in the working fluid on the performance of working fluid condensers. This has a tremendous effect on the cost of binary cycle plants. Another problem which affects these units is the recirculation of warm air in large exchanger bays.

Conclusion

In order to make best use of limited financial resources, our efforts should be confined to those areas which we do best. With its network of national laboratories, research institutes and colleges and universities, government is best at basic R&D. Industry is best at systems development, project management, operations, economics, financing and marketing.

FINAL AGENDA

FINAL AGENDA

U.S. DEPARTMENT OF ENERGY
GEOTHERMAL PROGRAM REVIEW IX

**"The Geothermal Partnership -- Industry, Utilities, and Government
Meeting the Challenges of the 90's"**

MONDAY (March 18)

7:00 pm	**Registration and Reception**

TUESDAY (March 19)

8:00 am	**Registration and Continental Breakfast**

OVERVIEW

Chairman, John E. Mock, Director, DOE Geothermal Division

9:00 am	**DOE Welcome and Announcements**	John E. Mock, Director, DOE Geothermal Division
9:05 am	**Welcome Address**	Martha Dixon, DOE, San Francisco Operations Office
9:10 am	***Challenges for Electric Utilities -- Opportunities for Renewable Energies***	Robert L. San Martin, Deputy Assistant Secretary/Utility, Conservation and Renewable Energy, DOE
9:30 am	***Challenges Facing Utilities in the 1990's and the Role of the Geothermal Partnership***	John W. (Jack) Motter, Supervisor of Supply/RD & D, Sierra Pacific Gas and Electric
10:00 am	**Break**	
10:15 am	***Challenges Facing the Geothermal Industry in the 1990's and the Role of the Geothermal Partnership***	Darcel Hulse, President, UNOCAL Geothermal Division
10:45 am	***Constructed Cost Estimates of a Kalina Cycle Plant***	Gerald G. Johnson, Manager of Technical Services, Sandwell, Incorporated
11:00 am	***The Geothermal Education Office***	Marilyn Nemzer, Director of Educational Services, Geothermal Education Office
11:10 am	***Enhanced Geothermal Development - It's Role in Integrated Resource Planning***	John E. Mock, Director, DOE Geothermal Division
11:30 am	NGA-Sponsored Lunch ***Geothermal Energy and the Gulf Crisis***	Roy D. Alper, Independent Power Corporation

TUESDAY (March 19) continued

PROGRESS IN HYDROTHERMAL RESERVOIR TECHNOLOGY

Chairperson: **Marshall J. Reed, Program Manager, DOE Geothermal Division**

1:30 pm	*Geothermal Reservoir Technology Research*	Marshall J. Reed, DOE Geothermal Division
1:40 pm	*Optimizing Reinjection Strategy at Palinpinon, Philippines*	Roland N. Horne, Stanford University
2:00 pm	*The LBL Geothermal Reservoir Technology Program*	Marcelo J. Lippmann, Lawrence Berkeley Laboratory
2:30 pm	*Hydrothermal Opportunities and Challenges in the Basin and Range*	David D. Faulder, Idaho National Engineering Laboratory
2:50 pm	*Supporting Reservoir Technology Research*	Joel L. Renner, Idaho National Engineering Laboratory
3:00 pm	*Progress In Hydrothermal Reservoir Research at UURI*	Joseph N. Moore, University of Utah Research Institute
3:30 pm	**Break**	

PROGRESS IN HYDROTHERMAL ENERGY CONVERSION TECHNOLOGY

Chairperson: **Kenneth J. Taylor, Project Manager,**
DOE Idaho Operations Office

4:00 pm	*Geothermal Materials Development: FY 1990 Accomplishments and Current Activities*	Lawrence E. Kukacka, Brookhaven National Laboratory
4:25 pm	*Advances in Geothermal Waste Treatment Biotechnology*	Eugene T. Premuzic, Brookhaven National Laboratory
4:50 pm	*Overview Of The Heat Cycle Research Project*	Gregory L. Mines, Idaho National Engineering Laboratory
5:10 pm	*Models of Geothermal Chemistry for Optimizing Geothermal Resource Performance*	John H. Weare, University of California, San Diego
5:30 pm	**Adjourn for the Day**	

WEDNESDAY (March 20)

7:00 am	**Continental Breakfast**	

PROGRESS IN LOW TEMPERATURE UTILIZATION AND ASSESSMENT

Chairperson: **Kenneth J. Taylor, Project Manager,**
DOE Idaho Operations Office

8:00 am	*DOE/GD State Cooperative Program -- 1988 - 1991: Results*	Howard P. Ross, University of Utah Research Institute
8:20 am	*Direct Use Industry Assistance*	Paul J. Lienau, Oregon Institute of Technology
8:40 am	*Geothermal Low-Temperature Reservoir Assessment Program -- A New DOE Geothermal Initiative*	Phillip Michael Wright, University of Utah Research Institute

PROGRESS IN HYDROTHERMAL HARD ROCK PENETRATION TECHNOLOGY

Chairperson: **George P. Tennyson, Jr., Program Manager,**
DOE Albuquerque Operations Office

9:00 am	*Overview - Hard Rock Penetration*	James C. Dunn, Sandia National Laboratories
9:25 am	*Progress in the Lost Circulation Technology Development Program*	David A. Glowka, Sandia National Laboratories
9:50 am	*Borehole Radar For Geothermal Applications*	Marion W. Scott, Sandia National Laboratories
10:15 am	**Break**	

PROGRESS IN HOT DRY ROCK TECHNOLOGY

Chairperson: **George P. Tennyson, Jr., Program Manager,**
DOE Albuquerque Operations Office

10:30 am	*Moving HDR Technology Toward Commercialization*	David V. Duchane, Los Alamos National Laboratory
11:00 am	*The Design and Construction of a Hot Dry Rock Pilot Plant*	Raymond F. Ponden, Los Alamos National Laboratory
11:30 am	*Recent Progress in HDR Reservoir Engineering*	Donald W. Brown, Los Alamos National Laboratory
12:00	**Lunch** (Not Hosted)	

WEDNESDAY (March 20) continued

PROGRESS IN GEOPRESSURED-GEOTHERMAL TECHNOLOGY

Chairperson: **Kenneth J. Taylor, Project Manager,**
DOE Idaho Operations Office

2:00 pm	*Geopressured-Geothermal Overview*	Kenneth J. Taylor, DOE Idaho Operations Office
2:15 pm	*Operation of a Geopressured Hybrid Power System*	Richard G. Campbell, The Ben Holt Company
2:40 pm	*Natural Gas Recovery & Brine Disposal for Geopressured-Geothermal Wells*	Philip L. Randolph, Institute of Gas Technology
3:05 pm	*The Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource*	Jane Negus-de Wys, Idaho National Engineering Laboratory
3:30 pm	**Break**	

PROGRESS IN LONG VALLEY EXPLORATORY WELL

Chairperson: **George P. Tennyson, Jr., Program Manager,**
DOE Albuquerque Operations Office

4:00 pm	*Advanced Energy Systems Including Magma*	James C. Dunn, Sandia National Laboratories
4:20 pm	*Phase II Drilling Operations at Long Valley*	John T. Finger, Sandia National Laboratories
4:40 pm	*Science Plans for Phase II of the Long Valley Exploratory Well*	John B. Rundle, Lawrence Livermore National Laboratory

PROGRAM REVIEW IX WRAP-UP

5:00 pm	*Observations on the DOE Geothermal Program*	Myron Tribus, Exergy Inc.
5:15 pm	*Closing Remarks*	Roland R. Kessler, Director, Office of Renewable Energy Conversion, Conservation and Renewable Energy, DOE
5:30 pm	**Adjourn for the Day**	

THURSDAY (March 21)

7:30 am **Continental Breakfast**

NGA PERSPECTIVES ON GEOTHERMAL TECHNOLOGY DEVELOPMENT

8:30 am **NGA Industry Critique Panel**

Dennis Nielson, UURI -- Moderator

Exploration/Reserve	Jim Combs, Geo Hills Associates
Drilling	Marc Steffen, Calpine Corporation
Reservoir Engineering	Gerald Niimi, ThermaSource, Inc.
Fluid Handling	Harry Veizades, Veizades & Associates
Power Conversion Technology Handling	John Brugman, Ben Holt Company

12:00 **Conference Adjourns**

1:00 pm *Geysers Research Progress Report*, Open Meeting — Marshall J. Reed, DOE Geothermal Division

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March 19-21, 1991

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