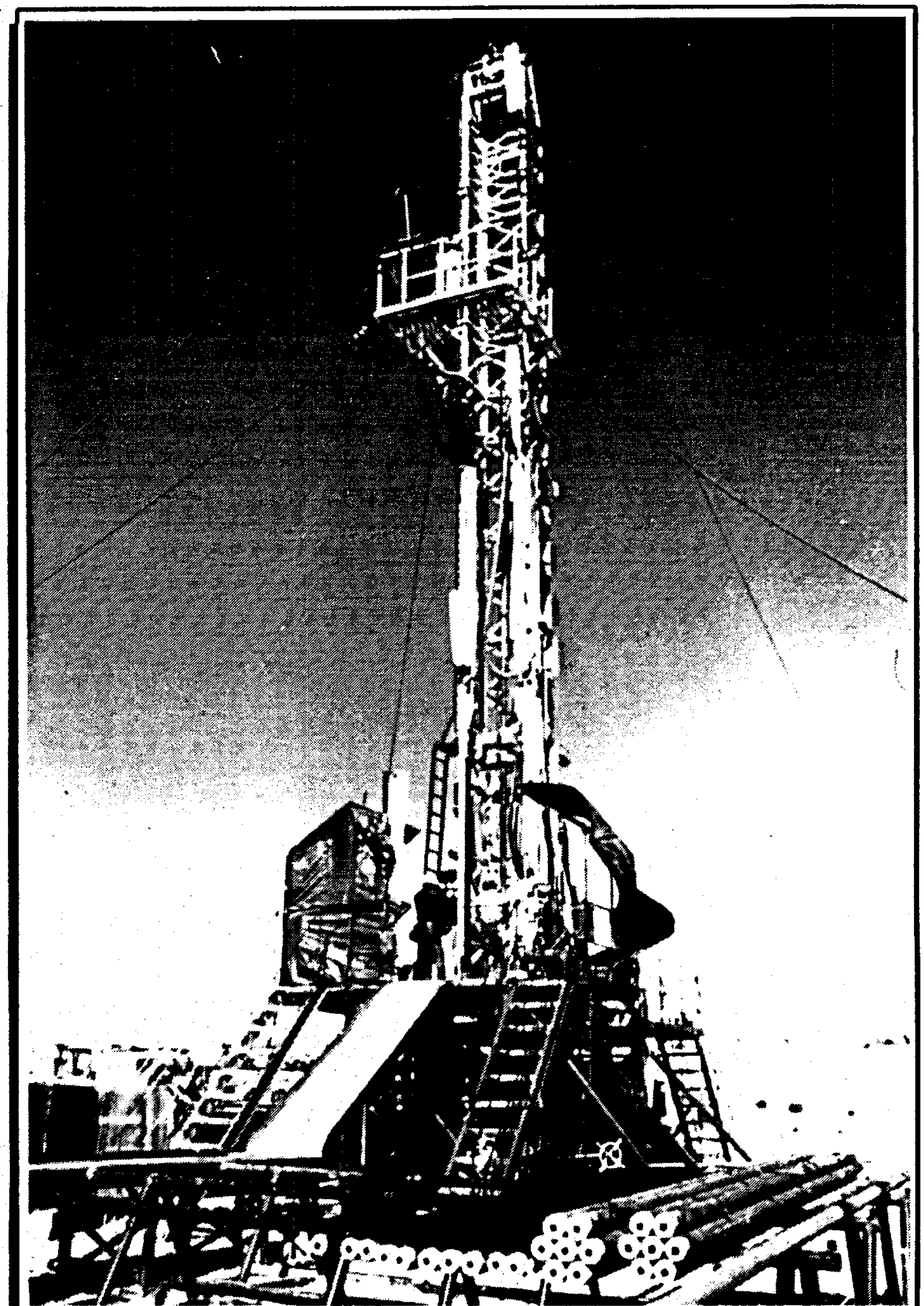
U.S. GEOTHERMAL ENERGY R&D PROGRAM
MULTIYEAR PLAN
1988-1992



ENERGY
FROM
THE EARTH

OCTOBER 1988

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Cover Photo: Geothermal drilling. Courtesy of the Longyear Company.

U.S. GEOTHERMAL ENERGY PROGRAM
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GEOTHERMAL TECHNOLOGY DIVISION

U.S. DEPARTMENT OF ENERGY

WASHINGTON, D.C.

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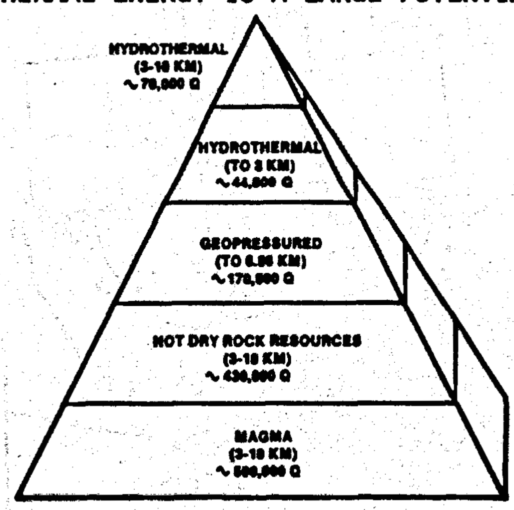
I. THE FRAMEWORK

Geothermal energy--the heat of the earth--offers distinct advantages as an energy supply option. It is the only viable base load power generation technology commercially available today as an alternative to fossil and nuclear fuels. It is available 365 days a year, 24 hours a day, unaffected by seasonal or diurnal variations. These features also make geothermal energy desirable and economical for direct heat applications. The development of this resource is representative of a continuing national trend in which a greater emphasis is placed on maintaining U.S. leadership in the application of high-technology solutions to complex, modern-day problems. Geothermal systems are suitable in a broad range of applications, and regardless of scale, require short lead times for design, installation, and start-up. Systems can be designed to minimize land use and environmental impacts and to provide for very low operation and maintenance costs. Most important, since the energy source is very large, widespread, indigenous, and secure, geothermal systems can enhance the balance and stability of our national energy supply. The size of the resource is illustrated in Exhibit 1; its location is shown in Exhibit 2.

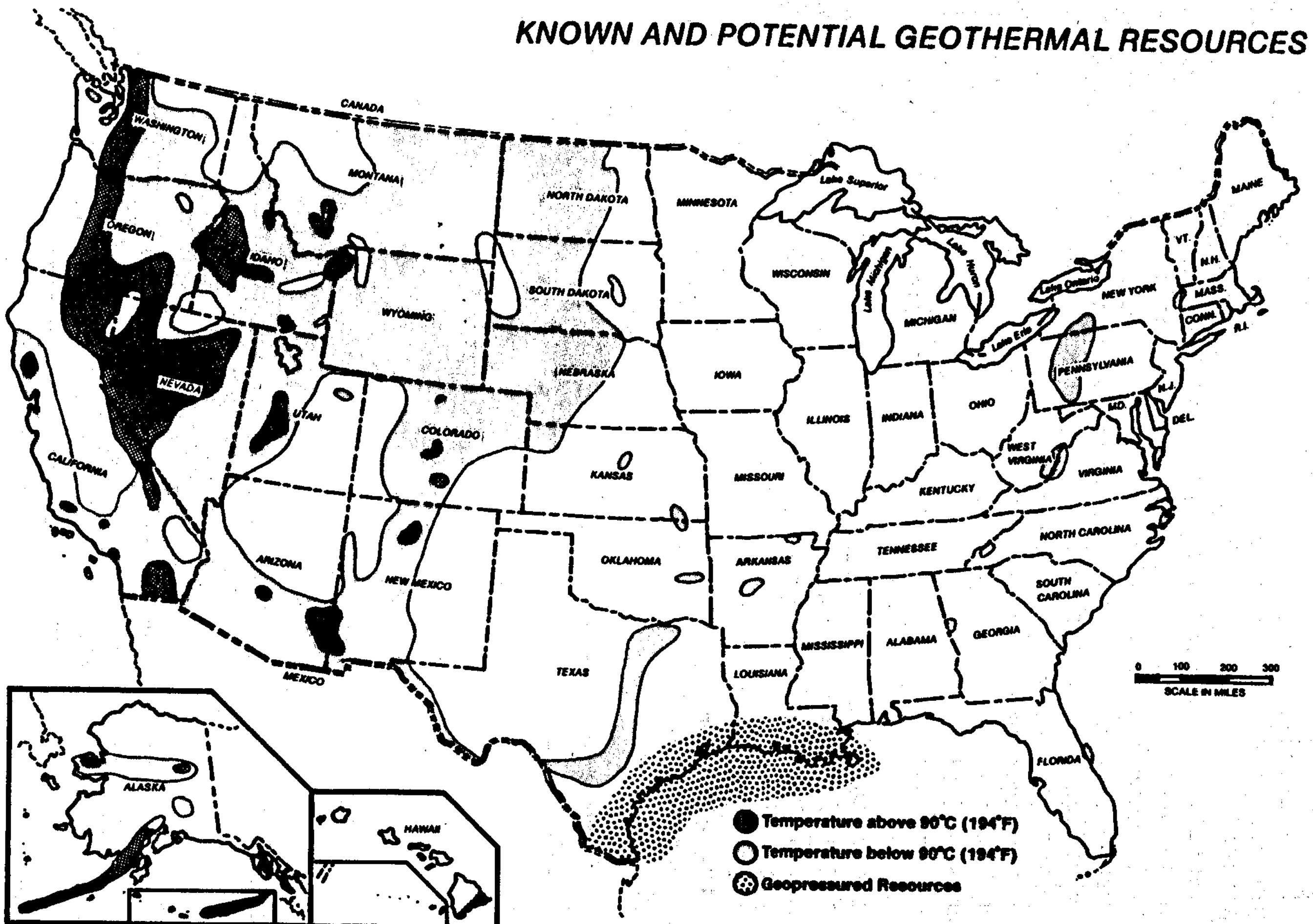
In order to expand the viability of geothermal energy as an energy supply option, the federal government sponsors research which will provide the technical solutions required to establish all forms of this resource as long-term competitive energy alternatives. Because of funding, time, and mission constraints, it is essential that a logical national research plan be developed to guide the efficient allocation of federal resources. This document presents the Multiyear Program Plan for the Geothermal Program of the U.S. Department of Energy (DOE) for fiscal years 1988 through 1992.

Exhibit 1. GEOTHERMAL ENERGY IS A LARGE POTENTIAL SOURCE OF ENERGY



Sources: U. S. Geological Survey Circular 790, Assessment of Geothermal Resources of the United States -- 1978; Circular 892, Assessment of Low-Temperature Geothermal Resources of the United States -- 1982; Muffler, L. J. P., Geothermal Systems: Principles and Case Histories, 6. Geothermal Resource Assessment; John Wiley and Sonsm, Ltd., 1981.

Exhibit 2. GEOTHERMAL ENERGY IS AVAILABLE TO A NUMBER OF STATES



Known and Potential Sources of Geothermal Energy in the U.S.

This map shows that the prime hydrothermal reservoirs in the U.S. capable of power generation with current or foreseeable technologies are located in the far western states. The 13 states with this quality of geothermal energy account for 20 percent of the U.S. population, and are projected to account for 23 percent by the year 2000. All of these states, as well as others in the west and some in the central and eastern sections of the country, have low- temperature reservoirs which are not suitable for power generation, but are very attractive for direct heat applications. Altogether, 31 states are endowed with geothermal energy.

Consistent with national energy policy guidance, the plan concentrates on research and development (R&D) and limits system experiments to only those necessary to stimulate industrial confidence in the validity of research findings. A key strategy element is the continuation of the government/industry partnership which is critical to successful development of geothermal technology. The primary near-term research emphasis is the extension of hydrothermal technology options for reservoir identification, reservoir analysis, hard rock penetration, and flash and binary electric plants. The advanced geothermal resources--geopressured, hot dry rock, and magma--are longer-term and higher-risk focal points, and research in these areas centers on establishing a technology base that will allow industry to make prudent and timely investment decisions with respect to the use of these resources.

TECHNOLOGY DESCRIPTION

The technologies for characterizing and extracting energy from geothermal reservoirs vary with the type of resource, although there are some cross-cutting similarities. The characteristics that engender these variations and the methods for energy extraction are identified in Exhibit 3.

The technologies for power generation with the different types of geothermal energy also vary considerably. Dry steam, a relatively rare occurrence, is fed to the generating system just as it comes from the earth. In plants designed to use liquid-dominated, or hot water, reservoirs, the liquid is usually allowed to flash to steam as it reaches the surface under reduced pressure; the steam and remaining liquid are separated; and the steam then enters the turbine. This is known as flash steam technology. Most flash plants in operation or under design today optimize energy extraction from the hot fluid by utilizing a dual flash design--i.e., steam is produced at two pressure levels (high/low) from the incoming brine.

In general, flash steam technology is not economic at temperatures below 200°C (400°F). The state-of-the-art technology for generating power with brines in the 150-200°C (300-400°F) range is binary cycle technology. In this type system, the heat from the geothermal fluid is used to vaporize a high-pressure fluid such as a hydrocarbon. The vaporized working fluid is expanded through a turbine, condensed, and repressurized in a closed loop.

A hybrid power system is planned that will use the heat and methane content of geopressured brines to generate electricity. The heat will operate a binary cycle turbine, and a gas-fired turbine and exhaust gases will superheat the geothermal working fluid to contribute additional energy to the power cycle. A small binary unit has operated briefly at the hot dry rock experimental site at Fenton Hill, New Mexico. Designs for power generation equipment to function on heat extracted from magma are still in theoretical stages.

Exhibit 3. TYPES OF GEOTHERMAL ENERGY

TYPE OF RESERVOIR	FORM OF ENERGY	GEOLOGIC	TYPICAL DEPTH (FEET)	TEMPERATURE (°C)	METHOD OF ENERGY EXTRACTION
			RESERVOIR CHARACTERISTICS		
HYDROTHERMAL					
Vapor-Dominated	Primarily steam	Primarily fractured and sometimes porous rocks	Between a few hundred to 14,000	150-360	Conventional oil and gas rotary equipment modified to withstand heat, hard rock, and corrosive environment
Moderate- to High-Temperature Liquid-Dominated	Primarily hot water	Same as vapor-dominated	Same as vapor-dominated for use in power generation	150-360 For power generation	Same as vapor-dominated
Low-Temperature Liquid-Dominated	Hot water	Same as vapor-dominated	Wide range	Any temperature that satisfies heat needs of direct geothermal applications	May be same as vapor-dominated; may involve only standard water well drilling
GEOPRESSURED	Brine containing dissolved methane	Deep insolated shale and sandstone formations where fluids are under far greater than normal hydrostatic pressure	10,000-16,000	120-175	High pressure oil and gas rotary drilling equipment and gas-liquid separators to extract methane from the produced brines
HOT DRY ROCK	Relatively water-free hot rocks	Rock of relatively low permeability	13,000-20,000	Highly variable	Modified conventional equipment, capable of high directional accuracy in very hard rock and creating artificial heat exchange fissures between pairs of wellbores
MAGMA	Molten or partially molten rock	Silicic volcanic system	Only the systems within 10 km of the surface are under consideration	850-1200	Theoretical concept is a downhole "open heat exchanger" where injected water would physically contact magma to extract heat.

PROGRESS TO DATE

Since the early 1970s, the federal government and the U.S. geothermal industry have worked together in pursuit of low-cost, efficient geothermal systems. The government has spent over $1 billion in geothermal R&D, a great deal of which has contributed to the growth of the hot water power industry in this country and a proliferation of direct use projects. Over 40 hot water plants with a total capacity of nearly 800 MWe are on line, under construction, or in final planning stages for completion by the early 1990s, and 213 direct use projects involving over 2000 structures were installed at the end of 1986.

Direct Use

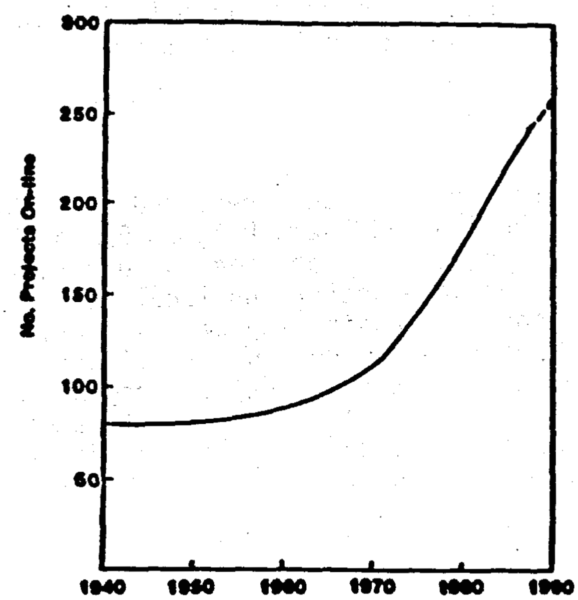
A number of direct use projects resulted from the Geothermal Program's Program Opportunity Notice (PON) and Program Research and Development Announcement (PRDA) programs. Under the PON program, field experiments were cost-shared with the private sector and local governments to test and evaluate the technical and economic feasibility of a variety of developing direct use technologies. The program produced successful district heating systems in Boise, Idaho; Elko, Nevada; Klamath Falls, Oregon; Pagosa Springs, Colorado; and Susanville, California. All of these systems have been, or will be, expanded. Several successful space heating projects also resulted from the PON program, serving a school, YWCA, prison, and hospitals, along with a large commercial greenhouse, a 50-acre aquaculture operation, and a cascade application to combine agriculture and aquaculture.

The PRDA program provided engineering and economic feasibility studies of specific direct heat applications, developing a large body of valuable information on the various technologies. This information is still transferred to potential users and to the public by the Geo-Heat Center at the Oregon Institute of Technology with DOE support.

The growth of direct use applications in the U.S. is illustrated in Exhibit 4. The upward swing beginning in the late 1970s corresponds to the period of implementation of the PON and PRDA programs.

The technologies employed in direct heat applications have matured to the extent that the Geothermal Program has discontinued direct involvement. This is in accord with policy guidance as discussed below. However, the Program supports the transfer of direct use technologies to users and potential users through the advisory activities of the Geo-Heat Center at the Oregon Institute of Technology.

Exhibit 4. DIRECT HEAT PROJECT ACTIVITY IN 11 WESTERN STATES



Power Generation

Since geothermal electric power generation began in 1960 at The Geysers in California, a large dry steam field which today serves the largest geothermal complex in the world, industry has substantially carried out its own R&D at that site. The government has provided assistance in testing methods for abating hydrogen sulfide emissions and in improving technology for all types of geothermal applications--e.g., improved materials and advances in reservoir definition and drilling technology.

However, once industry began in the 1970s to look toward hot water reservoirs as having serious investment potential--as was already occurring overseas--the industry/government R&D partnership became more intense. One of the earliest ventures was the Industry-Coupled Cost-Shared Program, initiated to accelerate geothermal development by:

- stimulating industry exploration efforts through cost (and thereby risk) sharing
- generating field data for unrestricted use

- determining optimum exploration techniques for various geothermal environments

- confirming resource potential at selected geothermal sites.

Today, 8 of 14 fields initially investigated are under development by industry.

Since 1980, when the first private sector demonstration-size hot water plant came on-line, this plant and others that have followed have achieved a high degree of reliability, most capable of service over 95 percent of the time. This level of performance is achieved by both small (<2 MWe) and larger plants (up to 49 MWe). It compares to about 68 percent availability for nuclear plants, 83 percent for coal, and 79 percent for oil.[1]

DOE's technology development program has contributed significantly to the overall reliability, as well as to the efficiency and cost-effectiveness, of geothermal power operations, both in management of the production field and in the power plant itself. These achievements include:

- High-temperature elastomer and polymer concretes

- High-temperature electronics and sensors for well logging

- Improved drill bits

- Improved water and mud-driven turbodrills for directional drilling

- Cavitating water-jet cleaning for pipes and heat exchangers

- Wellhead-size flash, total flow, and direct contact heat exchanger binary electric generation systems

- Precipitating and clarifying techniques and scale-inhibiting chemicals to handle high-salinity, corrosive brines.

In addition, the Geothermal Program has invested considerable R&D effort and funds in developing and improving technologies for characterizing the producibility and longevity of reservoirs. Accurate prediction of reservoir behavior under production conditions is essential if investment capital is to be forthcoming. Some achievements in this category are:

- Computer codes for reservoir simulation

- Reservoir engineering and geophysical tools and instrumentation

- A technique for determining fracture orientation from observation of tidal pressure fluctuations in a single wellbore

- Magnetotelluric and passive seismic exploration techniques (remote reference and in-field processor, respectively).

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1 Weighted averages released by the Atomic Industrial Forum for 1985.

The U.S. liquid-dominated geothermal power industry is an established industry in 1988 despite pressures external to technology development--e.g., low oil costs and a surfeit of electric power in geothermal states. It is competing with conventional power technologies at 20 favorable reservoirs, half of which are estimated by the U.S. Geological Survey to be collectively capable of over 10,000 MWe capacity for 30 years. However, the industry's economic expansion into more difficult hydrothermal fields--e.g., lower temperatures, greater depths, less permeability--and into geopressured zones, hot dry rock, and magma bodies--is still highly dependent on continued technology development. The possible and probable growth of the hydrothermal industry to the year 2005 is projected in Exhibit 5.

LEGAL MANDATES FOR FEDERAL R&D

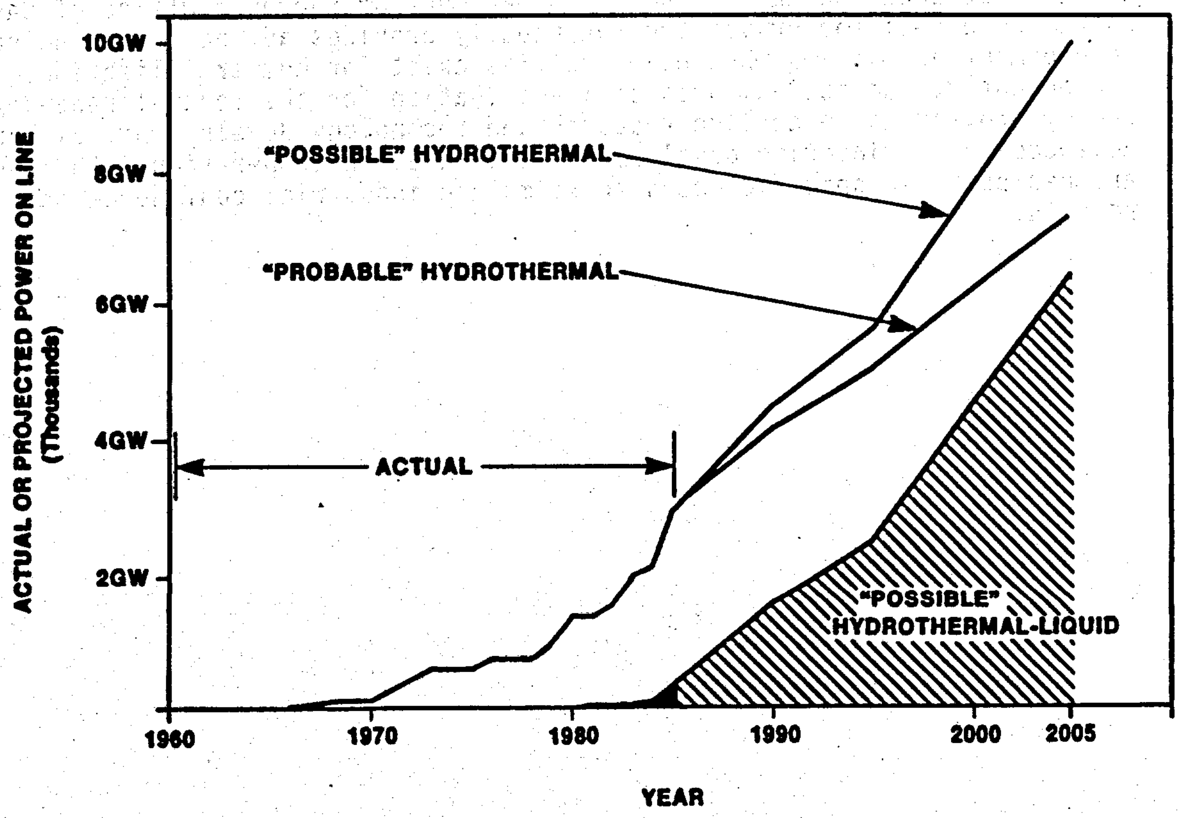
Congress first initiated federal participation in geothermal energy research and development with limited mandates to the Atomic Energy Commission and the National Science Foundation as early as 1971. However, it was not until passage of the Geothermal Energy Research, Development, and Demonstration Act of 1974 (Public Law 93-410) that a "national commitment" was made "to dedicate the necessary financial resources and enlist the cooperation of the private and public sectors in developing geothermal reservoirs...." Responsibility for coordinating and managing the federal geothermal R&D program was placed in a Geothermal Energy Coordination and Management Project, known today as the Interagency Geothermal Coordinating Council. However, when the Energy Research and Development Administration (ERDA) was created in January 1975, it was given responsibility for the federal R&D program. The responsibility was subsequently passed to DOE when it was created in 1977.

The commitment of Congress to the development of geothermal energy in this country was restated again in 1974 with passage of the Federal Nonnuclear Energy Research and Development Act (Public Law 93-577). "It is the policy of Congress," the Act stated, "to develop on an urgent basis the technological capabilities to support the broadest range of energy policy options through conservation and use of domestic resources (including geothermal) by socially and environmentally acceptable means." Through the budgetary process, Congress has continued each year since 1971 to express its support for federal participation in geothermal research and development.

FEDERAL R&D ROLE

Federal policy in energy research and development is based on the establishment of sound, stable public policies that will encourage both private and public sector organizations to develop and utilize energy resources wisely and efficiently. As defined by legislative mandates and public policy, the federal role is to undertake research activities with the potential for achieving benefits for society as a whole in areas that industry is unlikely to pursue because of the costs and risks involved. Reliance is placed upon the marketplace and private industry to develop and produce near-term renewable energy technologies at a rate consistent with market demands.

Exhibit 5. HYDROTHERMAL POWER IS POISED FOR STRONG MID-TERM GROWTH



Source: 1986 EPRI Survey; Interpreted by GTD

There are two applicable Department of Energy research and development work phases which provide a mechanism for focusing federally sponsored research. These are:

- Science and Technology Phase

  - Basic research
  - Applied research
  - Technology development

- Concept and Experimental Development Phase

  - Advanced development
  - Engineering development

Basic research is generally performed by federal agencies such as the National Science Foundation and the Department of Energy's Office of Basic Energy Sciences; the private sector usually provides advanced and engineering development activities when opportunities exist for commercialization. Consequently, the optimum area of investigation for the federal renewable energy program is in applied research and technology development, although advanced and engineering development activities in cooperation with industry are necessary in specific cases to stimulate industrial confidence in research results.

II. THE PROGRAM

Since the inception of the Geothermal Program in 1971, the federal government and private industry have developed an extensive geothermal knowledge base, and industry has succeeded in establishing an industrial infrastructure capable of applying research results in the marketplace. This accumulation of technical information has provided a basis for identifying the critical technical barriers to cost-competitive geothermal power generation and for assessing long-term research options. Private sector cooperation in planning and prioritizing geothermal program elements contributes to the process by indicating desirable improvements in technology. This guidance is critical in a balanced, logical strategy for the Program which emphasizes high-risk research directed toward a significant long-term role for geothermal energy in the U.S. electrical economy and which also addresses carefully defined, near-term research to maintain industrial momentum in geothermal technology.

For example, industry has indicated its confidence in geothermal drilling technology improvements developed by the Program--such as the downhole televiewer, aqueous foam for lost circulation control, and a pneumatic turbine for directional drilling--by cooperating in bringing these technologies to current geothermal markets. The Program, in response to industry's continuing need to reduce drilling costs, is working to resolve other drilling problems which collectively add to the costs. The primary emphasis of the Program, however, is on less developed technologies which offer the potential for major improvements in cost and performance.

PURPOSE

In accordance with legislative mandates and policy guidance, the Geothermal Program sponsors high-risk, potentially high-payoff research and development in geothermal energy technology which will result in a technology base from which private enterprise can choose options for further development and competitive application in U.S. electric markets.

FEDERAL/INDUSTRY PARTNERSHIP

Implementation of the Geothermal Program is based on the perpetuation of a mutually beneficial government/industry partnership. The federal program benefits from industrial innovation and experience in both the planning and conduct of research, and industry benefits from federal research incentives designed to stimulate aggressive industrial activity. To ensure the success of this partnership, the federal research program includes provisions for:

- Cost-shared research efforts which require long-term commitments by both industry and government
- Prompt, accurate, and complete transfer of information gained from research and development.

Federal participation in this partnership varies with the nature of the research activity. The federal government assumes a leadership position in working with industry to identify critical technical barriers to improved efficiency, lowered cost, and increased reliability and durability of materials and drilling and power plant components as well as more reliable techniques for characterizing reservoirs. The federal government sponsors industrial cost-shared team efforts which are formed to reduce these barriers and to disseminate research results throughout the industry. In-house national laboratory researchers assist this process through continued research and study of industrial research results with advanced measurement techniques to advance the understanding of the behavior of geothermal reservoirs. Further results are accomplished through working experiments which also provide a feedback mechanism for subsequent research efforts. It is left to industry to take the product of the research to the marketplace where the public will benefit from the investment.

The development of crystallizer/clarifier technology for generating power with hostile, highly saline fluids is one illustration of the success of this partnership. The technology was developed in the late 1970s at the government/industry sponsored Geothermal Loop Experimental Facility (GLEF) near the Salton Sea in California's Imperial Valley. Without this technology, the Salton Sea reservoir, one of the largest and hottest hydrothermal systems in the world, but one of the most hostile in chemical nature, would not be available for development. Neither would others of a somewhat less abrasive nature, but still harsh in character. The corrosive dissolved solids would render power generating equipment useless. The technology has since been modified and refined by the private sector through its own R&D and is installed, or soon will be, on several dual flash plants in Imperial Valley. Once industry commercialized this technology for flash steam operations, the Geothermal Program turned its power cycle R&D attention to binary technology for application with the moderate-temperature fluids which account for 70 percent of the identified reservoirs. This technology will provide industry with another option for further development and competitive application in U.S. electric markets.

PROGRAM OBJECTIVES

The major program objectives set out below were recently defined in an important companion program document entitled Programmatic Objectives of the Geothermal Technology Division (GTD), U.S. Department of Energy. As the document points out, analysis of technology performance is a critical step in determining geothermal objectives. Until recently, the performance analysis was largely qualitative, necessitating considerable subjective judgment on the part of Geothermal Program Managers. Now, however, the subjective approach has been reduced by the introduction of a quantitative, cost-of-power model (IMGEO, "Impacts of Geothermal Research," developed by Sandia National Laboratories, March 1987). The model simulates interactions among the cost components of a hydrothermal electric plant and enables a comprehensive analysis of impacts from each element of the hydrothermal research program. For example, the impact on the cost of power of a 20 percent decrease in well drilling costs can be determined. Sensitivity analyses can be done to determine which technology improvements will have the greatest overall impact.

Given its flexibility and its use of actual operating experience, the model is an important tool for developing objectives as well as for verifying their impact on power cost. Indeed, the internal structure of the model is used as the basis for organizing an objectives hierarchy of the Geothermal Program, and many of the objectives for hydrothermal research have been derived from the numerical results of the model.

The model itself has evolved through time, and future improvements are likely, especially as industrial experience accumulates. Accordingly, these improvements could necessitate changes in the objectives. Thus, none of the objectives should be considered as fixed or absolute, but rather as a target of the current state of knowledge.

While the model makes a credible simulation of hydrothermal electric projects, its current applicability to other resource types is limited, and models for geopressured, hot dry rock, and magma are under development. Once these models achieve an adequate degree of reliability, they will be used to formulate quantitative objectives. In the meantime, the hydrothermal model provides a surrogate for organizing the objectives hierarchies of these resource types.

Three levels of quantitative objectives are defined in the objectives document. The Level I objectives allow analysts and decision makers to estimate the future cost of power from geothermal energy systems. At this level, the objectives are expressed in terms of reducing the life-cycle costs of energy from a typical geothermal energy production project (e.g., a binary electric power plant including its geothermal fluid supply). The Level I objectives are identified in Exhibit 6.

The basis for the Level I hydrothermal objective is that the technology is not available for economic exploitation of the large bulk of the identified hydrothermal reservoirs in this country where, as noted above, the temperature is below the economic range of flash plants. Some very small binary units--most around 2 MWe or less in capacity--are operating successfully with low-temperature brines. However, in these cases, economics are dictated by size and very favorable site-specific conditions--e.g., sufficient heat at very shallow depths, use of existing wells--that are not generally available. While the success of these small plants is to be applauded, even a multiplicity of installations of this size will not permit geothermal energy to reach its full potential as a viable energy supply option. While industry will profitably use small capacity facilities as "ice breaker" plants at undeveloped reservoirs, and such units are very useful in filling small incremental power demand, more favorable economics for larger binary plants (e.g., 10-100 MWe) are the key to meaningful expansion in geothermal utilization. To achieve the cost goal stated above, it will be necessary to bring about economies across the board--from reservoir characterization to drilling and field development to the binary power cycle itself.

These economies are the focus of the Level II hydrothermal objectives established through the use of the IMGEO model. This level of objective gives government and industry managers an impression of how much improvement is likely to occur within major project components as a result of federally funded research. Those for hydrothermal R&D are identified in Exhibit 7.

Exhibit 6. LEVEL I OBJECTIVES FOR THE GEOTHERMAL PROGRAM

(Energy cost target range is expressed as levelized in 1986 constant dollars.)

- Reduce the life-cycle cost of producing electricity with liquid-dominated, moderate-temperature (150-200°C) hydrothermal fluids by 25-35 percent by 1992. (This will place the life-cycle cost in a range of 3-10 cents/kWh across 8 typical site cases.)
- Improve geopressured technology to the point where electricity could be produced commercially from a substantial number of sites via wells of opportunity* in a cost range of 6-10 cents/kWh by 1995.
- Improve hot dry rock technology to the point where electricity could be produced commercially from a substantial number of known hot dry rock sites in a cost range of 5-10 cents/kWh by 1995.
- Advance magma technology to the point where electricity could be produced experimentally from one or more inferred magma resource sites in a cost range of 10-20 cents/kWh in the period of 1995-2000.

* Usually abandoned oil and gas wells.

Exhibit 7. LEVEL II OBJECTIVES FOR REDUCTIONS IN THE LIFE-CYCLE COSTS OF HYDROTHERMAL ELECTRICITY BY 1992 BY COST COMPONENT

Resource Analysis	18-24 percent through improvements in exploration and reservoir confirmation technology and procedures.
Fluid Production	10-13 percent through improvements in fluid technology and procedures.
Energy Conversion	For binary plants at reservoirs in the 150-200°C temperature range, 10-22 percent through improvements in efficiency and in O&M costs.
	For flash plants, 2-6 percent through improvements in materials and auxiliary equipment related to scaling, corrosion, and other brine-handling requirements.

The Level III objectives prescribe the technical direction of individual research projects. They facilitate communication among engineers and scientists; they comprise the technical yardsticks by which progress can be measured. They are identified in the Technical Plan for all four types of geothermal energy.

As stated above, cost-of-energy models equivalent to the IMGEO hydrothermal model are not yet available for geopressured brines, hot dry rock, and magma. Thus, the quantified Level I objectives for these three types of the resource shown in Exhibit 6 were set by GTD staff through consultation with DOE field R&D managers and industry specialists. They will be reviewed and revised as indicated when the models are completed.

The Level I geopressured energy cost target range is founded on the assumption that major technological advances are not required; available petroleum industry technology is adequate to exploit the resource. Given this assumption, the research program focuses on fairly narrow technical issues unique to geopressured resources, such as the burden of handling huge volumes of brine.

However, before industry will be prepared to tap this large source of energy, improvements will be required in the understanding of the behavior of geopressured reservoirs over extended periods of time. This leads to the Level II geopressured objective which is to decrease uncertainty in reservoir performance theory to enable predictions of characteristics (i.e., reservoir size and longevity, hydrocarbon content, salinity) with 90 percent confidence over a 10-year operating period by 1992.

The economic feasibility of utilizing hot dry rock resources will depend largely upon sustaining adequate flow at low impedance, minimizing fluid losses, and maintaining controlled thermal drawdown of the man-made reservoir. Thus, the Level II hot dry rock objective is to evaluate these system characteristics of the Fenton Hill Phase II reservoir by 1993.

The economic feasibility of using magma energy will depend largely on the cost of energy extraction wells and the effectiveness of downhole heat exchange processes. Thus, the Level II magma objective is to improve the technology for locating and characterizing magma bodies by drilling into an active caldera by 1994.

Industry is actively participating in the planning and implementation of the program objectives. Industry's response to the results of objective achievement--i.e., whether or not industry's development planning and activities extend to more difficult geothermal resources in the 1990s and beyond--will be the final test of the success of this plan.

PLANNING CONCEPTS

The objectives provide guidance in selecting both mid- and long-term research activities that will collectively, over time, permit their achievement. The 25-35 percent total reduction in hydrothermal power generation costs reflects percentage reductions in each of the technologies employed in field development and power plant operation. However, some percentage reductions have more impact on total capital expenditures than others. For example, if the plant represents 60 percent of total costs and the field represents 40 percent, reductions in the plant will have the greater impact. Taking the example a step further, since injection wells account for only about 10 percent of total field costs, reductions in injection costs will have a lesser impact. However, reservoir confirmation and characterization are the areas of greatest financial risk in geothermal development, and injection is potentially the greatest environmental risk. Thus, the hydrothermal portion of this plan is balanced to address costs directly through engineering improvements--e.g., drilling, power cycle--and indirectly through reduction of risk. The IMGEO model also takes into account the monetary value of risk.

In the case of the advanced systems--geopressured, hot dry rock, and magma --such precise calculations of the impact of technology on costs are not yet possible with sufficient accuracy. Thus, the objectives guided the selection of program activities, as set forth in the Technical Plan, which will result in more reliable cost estimates for industry's use in longer-term decisions on the economics of expanding into markets for advanced systems.

In developing the Technical Plan, research tasks were carefully selected using the following criteria:

- **Technical Attainability.** The technical objective of every research task must be practically attainable although the probability of success may be highly uncertain. The potential for attainability is determined through regular interchange with the major elements of the U.S. geothermal community--industry, academia, and the national laboratories.

- **Cost Competitiveness.** Cost-effectiveness and cost-benefit considerations must influence every geothermal program research and development decision. Resources available for geothermal research must be directed toward tasks most likely to promote increased use of geothermal energy--i.e., technology developments that will support industry's mid- to long-term ability to remain cost competitive through further development of the fields already in use and by extending competitiveness to more difficult geothermal reservoirs.

III. THE TECHNICAL PLAN

While commercial geothermal development has occurred at the best understood and most favorable hydrothermal reservoirs, cost-effective technology is not yet available for industry to compete with conventional power generation using lower-temperature hydrothermal reservoirs or geopressured brines, hot dry rock, or magma. Significant cost reduction will be necessary before the nation can benefit fully from these large sources of energy.

Improvements are needed in hydrothermal reservoir technology, fluid development and management, and energy conversion; geopressured resource analysis and energy conversion; hot dry rock energy extraction, reservoir engineering, and energy conversion; and magma resource analysis and geophysical development and management. Exhibit 8 indicates the current status of state-of-the-art technology in each of these areas from which opportunities for improvement can be identified.

The Level III objectives of the research categories for pursuing these technical improvements as defined by the Objectives Document cited previously are identified in Exhibit 9 (located at the end of this chapter).

RESERVOIR TECHNOLOGY

The purpose of reservoir technology research is to improve the technologies used to discover and understand geothermal energy. The major technologies are the geosciences which include geology, geohydrology, geophysics, and geochemistry, among others. Although surface manifestations such as hot springs and hydrothermally altered rock outcrops led to the discovery of most of the known hydrothermal reservoirs, exploration now relies increasingly on surface surveys of subsurface properties. The geosciences are also becoming a major tool in reservoir definition which has had to rely almost entirely on costly step-out drilling to confirm a commercial resource and in siting economic and environmentally benign injection wells.

Geothermal geosciences technologies were initially adapted from petroleum and mining industry exploration methods, and the more recent technologies applied in liquid-dominated reservoirs were also based originally on methods used in historically established dry steam fields (i.e., Larderello, The Geysers). Their application to hot water reservoirs has met with only limited success. In order to ensure prudent development/investment decisions, better methods for characterizing hot water reservoirs and predicting their behavior under production/injection conditions are needed.

Reservoir definition is critical to obtaining financing for facilities that will require a 20-30 year supply of energy. Application of the geosciences in conjunction with exploratory drilling and production testing has been very successful in hydrothermal areas such as the Imperial Valley and Cerro Prieto in Mexico.

Exhibit 8. TECHNOLOGY STATUS

RESERVOIR TECHNOLOGY	
Reservoir Definition	Industry is using DOE-developed reservoir characterization techniques, but improvements are needed. Major impediment is lack of reliable techniques for locating and mapping fractures.
Brine Injection Technology	Injection is practiced by virtually all power plant operations, but industry still fears short circuiting the reservoir due to insufficient knowledge on where to site the injection wells. Removal of solids prior to injection creates large amounts of sludges for which disposal as hazardous waste is required.
Exploration Technology	Methods for locating and defining masked hydrothermal systems in young volcanic provinces are presently unavailable. Although many geophysical techniques are promising, none has proven to be effective for locating hydrothermal systems in regions with abundant precipitation.
HARD ROCK PENETRATION	The capital costs for drilling production and injection wells are still a significant fraction of the costs of a geothermal project. This is due primarily to the heat, hard rock, and harsh fluid chemistry encountered during geothermal drilling.
CONVERSION TECHNOLOGY	
Heat Cycle Research	Binary technology has been tested at the government/industry 45-MWe plant in Heber California. However, the costs of this research project are subeconomic for commercial application.

Exhibit 8, continued

CONVERSION TECHNOLOGY, Continued

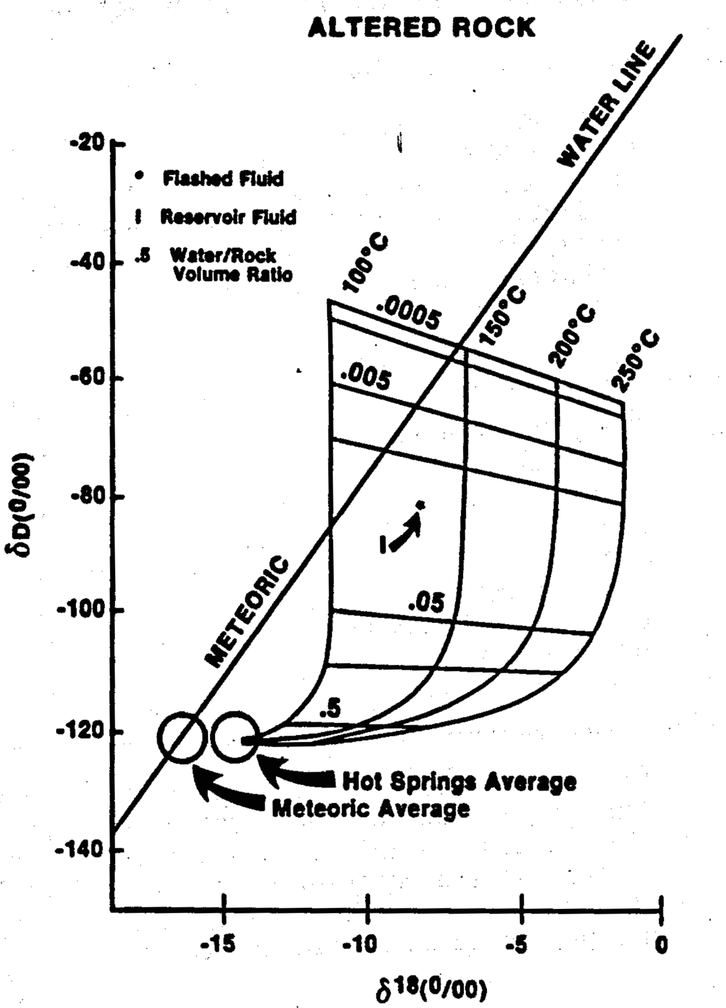
Advanced Brine Chemistry	Enough has been learned about the complex chemistry of brines that it should be possible to identify cost-effective power cycles, equipment, and materials when a brine falls within well-defined chemical bounds, experience, and technical approaches used at other sites. However, brine-related problems remain the most costly cause of undue maintenance requirements and downtime.
Materials Research	While considerable progress has been made in materials developed to withstand the hot, hostile geothermal environment, the expected lifetimes of certain surface and downhole components are not yet cost-effective.
GEOPRESSURED RESEARCH	Long-term production tests have shown that the geopressured reservoir will produce more brine than conventional oil reservoir models would predict. While this result is desirable in one sense, it is due to unknown causes, and some potential causes may result in eventual reservoir failure.
HOT DRY ROCK (HDR) RESERVOIR RESEARCH	The HDR resource is known to be very large, but the characteristics and limits of a resource reservoir need to be more clearly understood; more cost-effective technology for creating heat exchange fractures and completing and logging HDR wells under the high temperature conditions is needed to develop more economical HDR systems.
MAGMA ENERGY RESEARCH	The scientific feasibility of extracting energy from molten rock has been proven by experiments at a shallow lava lake in Hawaii. However, the scientific and engineering technology to locate such chambers and to extract energy from them has yet to be developed and tested.

Reservoir Definition

The development and exploitation of a geothermal reservoir depend to the greatest extent on understanding the reservoir's nature and establishing its properties. The overall hydrogeological characteristics of the system (e.g., lithology, structure, boundaries, fractured versus porous media, recharge) largely control the circulation of the geothermal fluids under natural conditions and during exploitation. The thermodynamic and geochemical properties of the formation fluids and mineral characteristics will govern, in large part, the processes occurring in the reservoir; however, the management of the energy resource (e.g., well locations and completions, rates of mass production, and injection) is also an important factor controlling these processes, ultimately affecting the economic life of a geothermal field.

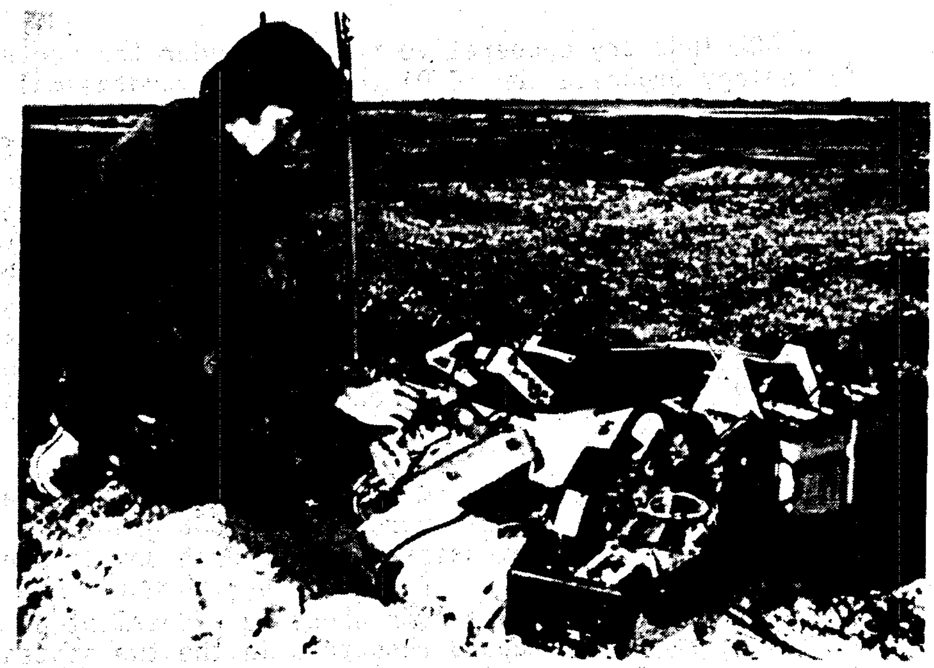
The primary focus of the Geothermal Program's R&D on reservoir definition through FY 1987 has been: (1) characterization and mapping of reservoir parameters, processes, and spatial dimensions; (2) monitoring and prediction of reservoir changes during production lifetime; (3) fracture detection and mapping; and (4) field case studies.

RESERVOIR DEFINITION



This illustration shows the relationship between the oxygen and deuterium isotopic composition of fluids at Meager Mountain in the Cascade Range, British Columbia, as a function of temperature and water rock ratio. The location of Point I indicates that calculated water-rock ratios are low, less than 0.05, a feature consistent with the poor productivity of the system. Calculations of this type are being compared by the University of Utah Research Institute with other geologic and geothermal data, such as fracture, mineral, and trace element distributions, to develop means of characterizing and evaluating fracture-dominated geothermal systems.

FRACTURE DETECTION AND MAPPING



Seismic Monitoring -- Setting Up Instruments in the Field

Because many geothermal systems occur in highly heterogeneous and fractured rocks, a key element in the targeting of production wells is to determine and understand how and where the reservoir rocks are fractured. To this end, geophysicists at Lawrence Berkeley Laboratory (LBL) have been analyzing and testing several techniques by numerical analysis and field experience.

LBL has collected and analyzed 25 difficult vertical seismic profiling (VSP) offsets for geothermal wells at The Geysers, the Salton Sea, and Japan. Another 15 offsets of VSP data were taken in nongeothermal volcanic and crystalline rock environments. Using both compressional (P) and shear (S) wave sources, LBL is attempting to understand how VSP data are related to fundamental properties of the rocks and fluids, e.g., fracture density and the orientation of dominant fractures, liquid saturation, and hydrothermal alteration.

In FY 1988 and beyond, R&D activities will be devoted to reservoir technology research areas that have a direct impact on the characterization and assessment of geothermal reservoirs, topics of fundamental importance to industry. Some of these activities are:

- Conduct on-going reservoir studies in various states
- Complete reservoir investigations of Salton Sea Scientific Well and present findings to industry
- Test geophysical methods for fracture mapping; expand activities to include vertical seismic profiling
- Provide interpretative techniques for fracture detection and mapping of geothermal reservoirs; develop models for fractured geothermal reservoirs and verify with field data
- Fund DOE-industry cooperative research under the Geothermal Technology Organization (GTO) to advance hydrothermal technology.

The GTO is a new joint DOE/industry group that will identify and support technology development projects that have a high probability of yielding short-term benefits to the geothermal industry in the areas of reservoir performance and energy conversion. The emphasis will be on products or services that can be commercialized after project completion. Each project will be jointly funded by DOE and participating industry partners, with industry providing at least 50 percent of the total cost. The GTO has started operation with four members and one project -- a microseismic study of The Geysers geothermal field, is underway. GEO Operator Corp. and the Unocal Geothermal Division are the industry participants.

Other reservoir studies are being conducted through DOE/state cost-shared research projects. Research areas covered by the DOE grants to state agencies or universities include resource assessment, resource development, technical assistance, and related activities. For example, the North and South Dakota Geological Surveys are conducting a comprehensive assessment of the significant, but relatively untapped resources in the two states. Twelve grants have been awarded.

Brine Injection Technology

The ability to control thermal and chemical effects of fluids injected into producing hydrothermal reservoirs is an established priority of the geothermal industry. Injection of spent geothermal fluid is most often an environmental necessity, and injection may allow more efficient utilization of a resource if it does not cause reduced permeability or premature breakthrough of cool fluids to producing wells. The Program places major emphasis on research which the geothermal industry has stated that it cannot perform.

Thus, brine injection technology R&D addresses the industry's needs by developing techniques to predict the chemical, thermal, and hydrologic effects of injection. These research activities will lead to more effective numerical simulators for the prediction of the effect of injection on a producing reservoir and developing efficient methods of heat extraction from reservoirs.

The research activities directed to the preparation of these simulators and development of techniques to monitor and collect the data needed to operate the simulators include:

- Development of computer codes to simulate the thermal, chemical, and hydrologic effects of injection
- Laboratory and field studies of tracer species needed to delineate fluid in reservoirs
- Development of surface geophysical techniques to monitor subsurface fluid movement
- Cooperative field testing to evaluate research results.

Exploration Technology

Existing geothermal exploration technologies leave a great many questions to be answered in their application to young volcanic caldera environments. Such environments where high-silica volcanic rocks are found are believed to contain a large subsurface magma chamber which would provide a heat source for geothermal systems. Thus, while they are fruitful places to look for geothermal energy, it is difficult with available technologies to locate and evaluate such systems and to site wells to intersect production zones. Therefore, the objective of the exploration technology task is to develop analytical and interpretive tools for industry to use in locating and evaluating geothermal reservoirs within young volcanic regions.

During the past two years, this task has concentrated on the Cascades region of the northwestern U.S. where exploration is made even more difficult by abundant rainfall which causes hot reservoirs to be overlain and masked by shallow, cooler ground water. DOE has supported cost-shared drilling with industry in specifically selected areas. Downhole geophysical well logs have been obtained from the wells, and the physical and chemical properties of the core retrieved have been analyzed. These data are being compared to surface geological, geochemical, and geophysical data for the purpose of developing and verifying new analytical tools and testing existing tools. Results to date indicate that better tools are needed for use in conjunction with surface electrical geophysical surveys because some of the low-resistivity zones found from surface surveys correlate with low-temperature hydrothermal alteration rather than selectively pinpointing high-temperature positions of geothermal systems. A second important result is the measurement at three sites of the depth to which cold surface water circulates, which is the minimum depth that industry must drill to obtain reliable heat-flow measurements.

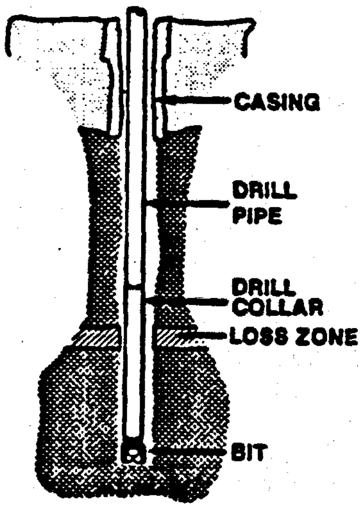
HARD ROCK PENETRATION

The hydrothermal geothermal environment is more hostile than the oil and gas drilling environment because of three factors--temperatures, the associated rock formations, and the corrosive production fluids. Bottomhole temperatures, typically of 225-275°C (436-527°F) and higher, adversely affect the drilling mud as well as the drilling equipment, elastomers, metals, and lubricants. The rock formations are hard, abrasive, sometimes fractured, and underpressured, causing bit wear, lost circulation, and drill pipe wear. Corrosion is a problem when the production fluid contains extensive total dissolved solids, which also results in contaminated drilling mud. Yet drilling is critical to every phase of geothermal reservoir development. It is needed for exploration, reservoir analysis, production, and injection of spent fluids.

Well costs account for 30-50 percent of total costs for power plant development, and exceed the costs for oil and gas drilling by up to four times. Thus, the hard rock penetration R&D is directed toward reducing drilling costs for geothermal wells, and its agenda embraces three major areas of study.

In borehole mechanics, the major effort is directed at developing lost circulation control materials and practices. Lost circulation in the drilling fluid system is, by industry consensus, the single most expensive consideration in geothermal drilling because of the time and expense incurred in recovering circulation. The R&D effort includes developing, through analyses and experiments, a basic understanding of the two-phase flow phenomena that control fracture plugging and evaluating the high-temperature plugging characteristics of specific lost circulation materials.

HARD ROCK PENETRATION



WELLBORE
Drilling Into a Typical Lost Circulation Zone

The Lost Circulation Project at Sandia National Laboratories has three major elements: 1) detection and characterization of loss zones; 2) development of new techniques and materials for control of loss zones, and 3) integration of the first two items for wellsite application. Progress has been made in the last two years in the development of new pumpable cementitious muds, in situ mixing and placement of polyurethane foams, and fundamental analysis of and materials development for particulate lost circulation materials. Work is now planned in the area of zone detection and characterization, including development of a transient, lost circulation hydraulics simulator and field zone characterization using an advanced wellbore televiewer.

Rock penetration mechanics includes the development of insulated drill pipe for high-temperature deep drilling and coring technology development for deep wells where scientific interests require extensive core recovery.

Industry cost-shared research includes several projects which are being developed to the point where joint industry and government support can be sought for final development and technology transfer. The most recent development projects in this area are drill string dynamics computer codes, a radar fracture mapping tool, and borehole diagnostics.

An example of the innovations involved in these technologies is the use of directional antennas for both the transmitter and the receiver in a single fracture mapping tool which provides both the distance and the direction of a fracture in a downhole application. Unique downhole sampling and uphole data reconstruction techniques are used to obtain high frequency data using standard logging cable. In a recent test conducted in a lake, radar returns from a target were clearly observed. Problems in the impulse return signals remaining in the performance of this tool will be addressed by the addition of a high-power programmable attenuator before the receiver circuit.

Other cooperative drilling projects with industry are carried out through the Geothermal Drilling Organization (GDO), a joint DOE/industry group that identifies and funds technology development projects that will have near-term impact on costs of geothermal wells. The emphasis is on products or services that can be commercialized after project completion. Each project is jointly funded by DOE and participating industry partners with industry providing at least 50 percent of the total cost. Currently, the GDO has 23 members with both geothermal operators and service companies represented. Four separate projects with different participating groups are underway. These include a high-temperature borehole acoustic televiewer; a downhole pneumatic turbine; urethane foam for use in lost circulation zones; and drill pipe protectors using new high-temperature elastomers.

CONVERSION TECHNOLOGY

Because of the variable nature of geothermal energy, a variety of technologies is used to convert its heat to electricity, as discussed in the Framework above. Dry steam conversion technology is mature and has been in commercial use for many years. The basic technology for flash steam plants is also well advanced, and at today's state of the art is usually used when the resource temperature is over 200°C (400°F). Binary cycles are more thermodynamically efficient than flash cycles in the 150-200°C (300-400°F) range. However, the larger size and higher costs of equipment required for lower temperature fluids, and the tendency of some brines to foul binary cycle heat exchangers and scale downhole pumps, have inhibited the use of binary systems in all but very small units. Heat cycle R&D is underway which is expected to lead to advancements in binary technology that will permit it to operate from 30 to 40 percent more efficiently than flash steam technology on the more abundant moderate-temperature reservoirs.

Areas of major remaining concern to geothermal power producers are the problems associated with handling highly saline brines within production wellbores, wellfield pipelines and steam separators, power plant plumbing and valves, and injection wells. Many costly problems are caused by precipitation of hard mineral scales from supersaturated brine as temperature falls and acidity changes with loss of dissolved carbon dioxide. In fact, mineral scaling due to brine chemistry is the dominant cause of increased costs associated with the operation of geothermal power plants that use highly saline hot brine reservoirs.

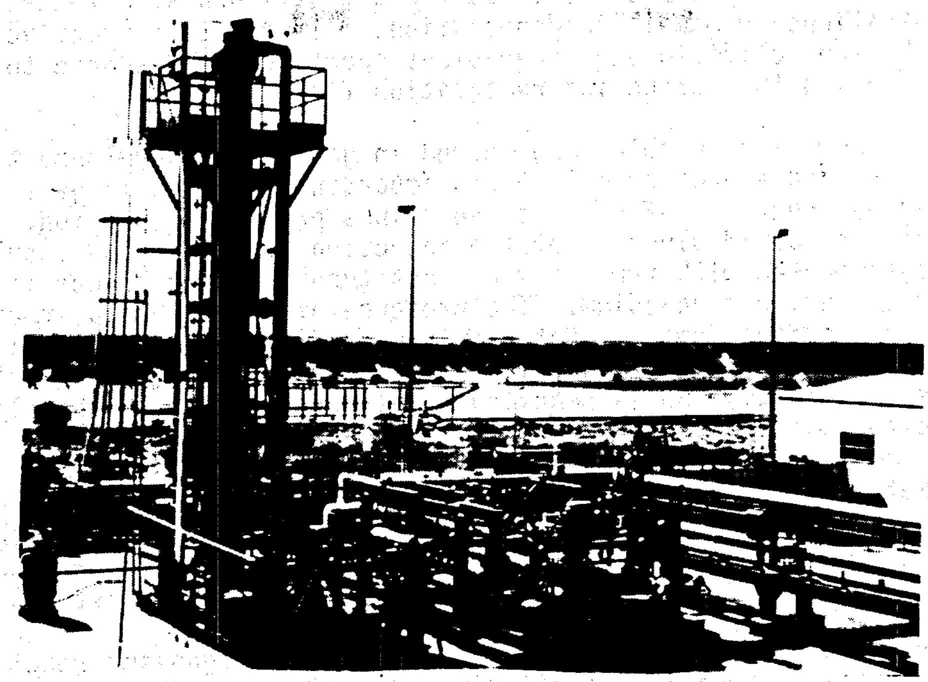
Another major problem related to brine chemistry, as well as to high temperatures, is the extraordinary demand these factors make on materials commonly used in other industries. The combined effects of thermal stress and corrosion and scaling on equipment and components limit their durability to such a degree that plant availability, lifetime, power output, and heat exchange capability may be seriously affected. Any of these problems decrease the cost-effectiveness of the operation through downtime and costly replacement.

Heat Cycle Research

The Program's heat cycle R&D is focused on the development of technology for effecting the improved utilization of moderate-temperature geothermal fluids for power generation. Thus, a major emphasis of the research, as suggested above, is improvement of the performance of geothermal binary cycles to levels approaching the practicable thermodynamic maximum. In pursuit of this goal, tests are being conducted at the Heat Cycle Research Facility (HCRF) located at East Mesa, California. In the near future, the HCRF will be moved to another site for tests with hotter and more saline fluids. The current testing involves the investigation of binary power cycle performance utilizing mixtures of non-adjacent hydrocarbons as the working fluids, with supercritical vaporization and in-tube condensation of the working fluid. In addition to the present test program, preparations are being made to investigate the binary cycle performance improvements which can be achieved by allowing supersaturated vapor expansions in the turbine. These efforts are anticipated to verify that through the utilization of these advanced power cycle concepts and allowing the supersaturated turbine expansions, improvements of up to 28 percent in the net fluid effectiveness (net watt hours plant output per pound of fluid) over conventional binary power plants can be achieved. Results of recent testing, including those tests examining the performance of the countercurrent condenser at different tube inclinations, support the assumptions used in projected performance improvements.

Future efforts will include examination of those concepts which will allow the base of resources that can be economically developed to be expanded through the use of innovative technology. Specific areas for investigation include the utilization of direct contact heat exchangers in binary power cycles with resources "too dirty" for conventional heat exchangers, as well as heat rejection systems which will minimize the cooling water make-up requirements while retaining performance approaching that of conventional wet cooling systems.

HEAT CYCLE RESEARCH



Heat Cycle Research Facility

The Heat Cycle Research Facility (HCRF) is an experimental binary cycle facility used to investigate different concepts and/or components for generating electrical power from geothermal energy. The HCRF components have the same functions as those in a typical geothermal binary power plant, with major differences being in size (the HCRF has a nominal power output of 40 kWe) and in component design; the components are designed to take advantage of the advanced plant concepts. This facility is currently located at the DOE Geothermal Test Facility at East Mesa, California. Heat cycle research is carried out by the Idaho National Engineering Laboratory.

Advanced Brine Chemistry

Two approaches are being pursued to define the expensive operating problems associated with brine chemistry. First, numerical modeling of complex brines will allow improved prediction of the thermodynamic conditions under which problems will occur in geothermal power plants from scale deposition, corrosion, and suspended solids. These predictions will in turn allow engineering design, materials selection, and power plant operations to be modified to optimize the economic utilization of the resource.

Second, research is focused on detection and monitoring of constituents in the brine stream which can damage piping, valves, and wells as brine flows through the power plant and is injected back into the wellfield. Chemistry monitoring instrumentation is inserted in the brine flow lines to detect serious corrosion, scaling, and particulate matter before these problems result in plant failure. Tests of a prototype corrosion in-line meter in the Magma Power Co. binary power plant at East Mesa, California, detected unexpected acid concentrations from wellfield operations. Immediate corrective action was taken by the wellfield and power plant operators in response to the information gained during this brine instrumentation field test.

Another major problem engendered in geothermal development due to brine chemistry, and a problem growing in importance, is the large volume of sludges created by treatment of hypersaline brines prior to injection. This step is necessary to avoid plugging of the injection well, but the resulting sludges are contaminated with trace toxic constituents of the brines itself, such as mercury, lead, and vanadium. The presence of these metals, though small in quantity, invokes federal/state environmental regulations requiring that the waste be disposed of in sites licensed to receive hazardous wastes. Thus, disposal is costly and is becoming highly uncertain with the closure of many such sites due to tightening restrictions.

Before large-scale development of hypersaline brines can occur, environmentally and economically acceptable methods for disposing of the wastes must be found. Experiments are thus underway on the use of biochemical techniques to concentrate and remove toxic metals from wastes.

There are several mechanisms by which microorganisms react with metals. Two of these mechanisms are being addressed because they provide a basis for development of process technology suitable for removal of toxic metals from wastes. One is the solubilization of metals by microorganisms which leach out the metals, and the other is concentration and removal of the metals by their sorption on cellular materials. Both processes are applicable in situations where metals are present in large volumes of waste at concentrations unsuitable for conventional technology.

Materials Research

Geothermal materials research was initiated early in the Program to ensure that the private sector development of geothermal energy is not constrained by the availability of technologically and economically viable materials of construction. Major successes have been attained in the development of elastomers for high-temperature applications and in the use of polymer concrete liners for corrosion protection.

The development of the high-temperature Y-267 EPDM (ethylene, propylene, diene, methylene) elastomer can be classified as a technology breakthrough. Used in seals for well logging tools, packers, valves, and other equipment exposed to hostile high-temperature environments, the Y-267 EPDM elastomer has proven to be at the leading edge of technology. Tests performed for applications in the oil, gas, nuclear, and coal industries have given equally impressive results.

Cements represent another area where considerable progress has been made. The cementing of a well is considered to be one of the most critical items in geothermal development. As part of a comprehensive examination of the geothermal problem, DOE participated in a cooperative test at Cerro Prieto, Mexico, in which nine cements were determined to satisfy American Petroleum Institute test criteria. These results serve as the basis for the selection of cements used for geothermal well completions throughout the world.

Research and development efforts aimed at further cost reductions and extension of service life are currently in progress. Projects include:

- Nonmetallic heat exchanger tubing
- Chemical systems for lost-circulation control
- Very high-temperature well completion materials
- Metallic liners for well casing.

GEOPRESSURED RESEARCH

The geopressured R&D has successfully completed estimating the size and magnitude of geopressured reservoirs and is in the process of developing technology for producing and utilizing them. Tests are planned on two wells, the Gladys McCall and the Pleasant Bayou.

The Gladys McCall in Louisiana is under test at the present time and has successfully produced over 25 million barrels of brine. The reservoir has proven more productive than initial test data predicted, and research is concentrated on identifying reservoir drive mechanisms. A comprehensive test program of variable flow rates, pressure recovery, logging, and coring is planned in the effort to understand the reservoir performance.

Testing will start in FY 1988 on the Pleasant Bayou well near Houston, Texas. The Electric Power Research Institute hybrid electrical power generation system will be tested on this well, and work will continue to understand reservoir performance.

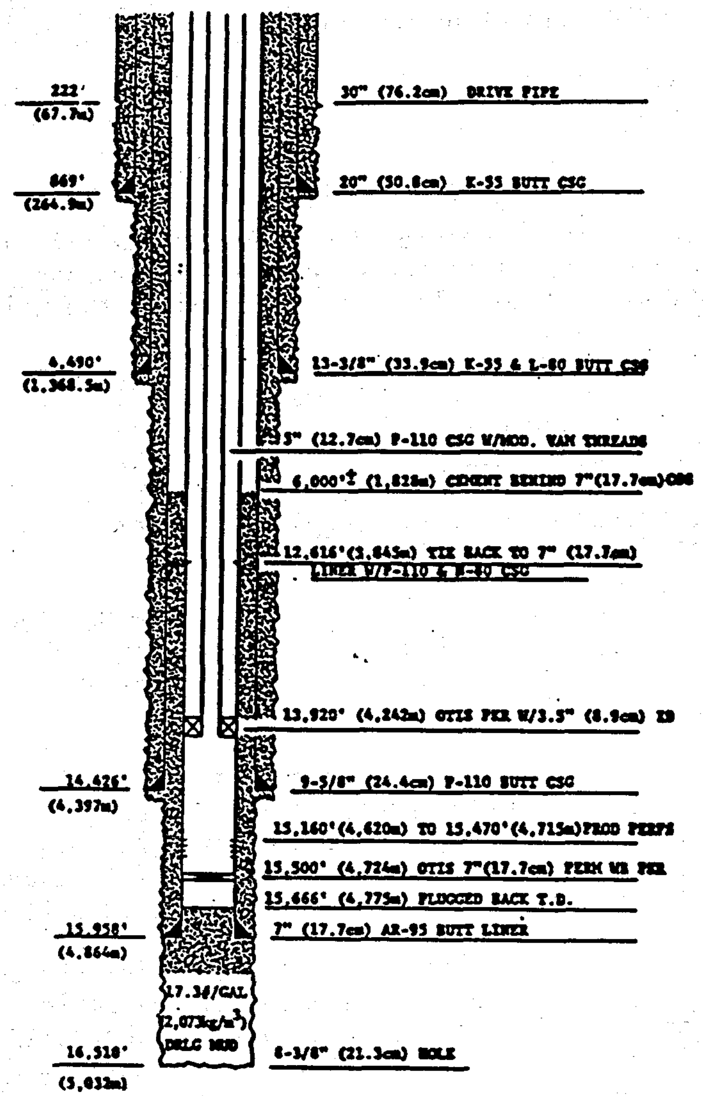
One other deep well is available to the Program for possible testing. This is the Hulin well located in south-central Louisiana, a former gas well contributed by industry, and, at 21,000 feet, it is much deeper than any other wells tested. It has the potential to be economical in the near future and could serve as a verification of the geopressured technology developed to date.

A major accomplishment has been the development of a successful procedure for scale control at the Gladys McCall. Prior to injection of the scale inhibitor into the reservoir, the well flow was limited to 15,000 barrels/day. With the new procedure, the well has flowed for over a year at a maximum rate. A similar treatment will be prepared for the Pleasant Bayou well, in which scale deposition previously necessitated replacement of the production tubing.

Operators have been required at the Gladys McCall around the clock. Trouble-free performance of the well indicates full-time operators are not required, and the Pleasant Bayou well is being instrumented for semiautomatic operation, with an operator in attendance or on call. If the Hulin well is

GEOPRESSURED-GEOTHERMAL PRODUCTION TESTS

GLADYS McCALL NO. 1 AS COMPLETED BY T-F&S 8/15/83



Based on the geology and initial flow testing of the Gladys McCall geopressured well in Cameron Parish, Louisiana, a reservoir size of 430 million barrels of brine was predicted. The subsequent long-term flow testing indicates a reservoir of 2.5 billion barrels. Potential explanations for this discrepancy are gas drive, incorrect interpretation of the geology, rock compaction, shale-dewatering, and/or leakage from adjacent zones. Research is in progress on rock compaction, analysis of hydrocarbons, updating the geological model, chemical analysis of the produced brine, and improving the simulation model.

The Gladys McCall well was flowed at a maximum rate from October to April of FY 1987. During this period, the flow rate gradually declined from about 26,000 B/D to 24,000 B/D. The well was on-line over 98 percent of the time with no indications of scaling in the wellbore and a minimum of surface facility problems. An analysis of the pressure decline indicated it would be many years before anything additional might be learned about the reservoir drive mechanisms driving the reservoir fluid. Thus, the well will be shut in, and the downhole pressure and the environment around the well will be monitored as the pressure recovers. This information is required as part of the plan to assess the various theories which might explain the reservoir performance.

Significant geopressured research is carried out at the University of Texas at Austin which also coordinates research results with other entities.

tested, it will be fully automated with operator requirements similar to oil and gas wells.

All geopressured production well sites have been monitored for subsidence, seismicity, and water quality. No adverse environmental effects have been detected, and environmental monitoring will continue for two to three years after well testing is completed.

The equipment to be used in the power generation experiments will incorporate both gas combustion and geothermal heat in a hybrid binary cycle. This type system can produce in excess of 15 percent more electricity than the same amount of fuel and geothermal fluid used in separate power plants. The first three months of operation will be a start-up, shakedown, and testing period. Following the intensive test, the facility is scheduled to be operated for nine months on a continuous basis. The intent of this long-term test is to evaluate system reliability and to obtain data over an extended period.

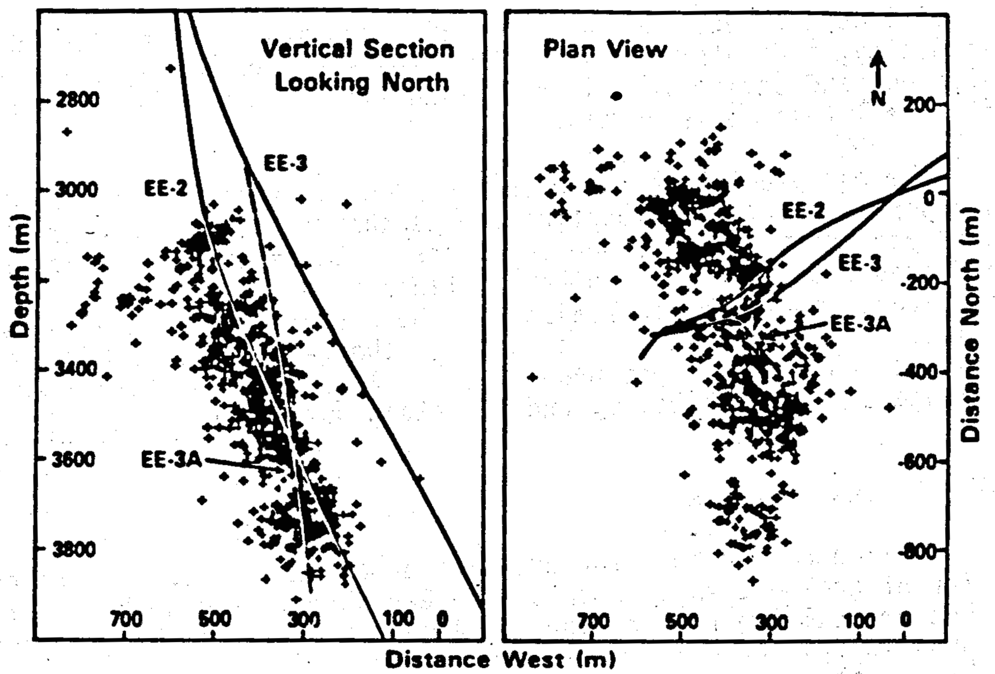
HOT DRY ROCK RESEARCH

While other methods for creating a man-made reservoir are possible in different geologic environments, the Geothermal Program has so far concentrated on hot crystalline rock of low initial permeability; the use of fluid pressure (hydraulic fracturing) to create flow passages and heat-transfer surface in the rock; and operation of a closed, recirculating, pressurized-water loop to extract heat from the rock and transport it to the earth's surface. Large-scale field experiments are conducted at Fenton Hill in the Jemez Mountains of northern New Mexico. Concomitant supporting activities include development of new or improved downhole equipment and instruments, field and laboratory experimental techniques, and analytical and numerical data analyses and modeling procedures. Many of these developments have been found useful in other experimental programs and in a variety of industrial applications.

The technical issues faced in hot dry rock (HDR) development are demanding. To be suitable for power generation, wells must be drilled to depths where temperatures of 200 to 300°C (392-572°F) can be found. Even in regions with favorable geothermal gradients, such temperatures are found only at great depths, usually 10,000-16,000 feet. The rock formation must then be fractured at great stress, and the fractures held open so that the permeability remains high and flow resistance low. Furthermore, large areas of hot rock must be adequately bathed by the injected water to result in high heat production. At the same time, since all water must be provided from an external source, excessive water losses to the rock surrounding the fractured reservoir must be avoided. Potential geochemical problems, such as scaling of surface equipment with precipitated products of aqueous rock dissolution and corrosion of surface and downhole piping, must also be avoided. The incentive for meeting these challenges is the enormous resource base that HDR energy provides as shown in Exhibit 1.

The small Phase I reservoir created at Fenton Hill in 1977 was the world's first hot dry rock geothermal energy system. Water was produced from the man-made reservoir at temperatures and thermal power rates as high as 175°C (347°F) and 5 MW_t. A much larger Phase II reservoir was created at the site in 1983, and has been flow tested briefly. A long-term flow test is planned in order to

HOT DRY ROCK



Locations of Microearthquakes Induced by
Massive Hydraulic Fracturing

In December 1983, a massive hydraulic fracturing operation was conducted at the Fenton Hill experimental site in which nearly 6 million gallons of water were injected at 2.2 miles depth. The locations of the microearthquakes induced are shown here as monitored by microseismic instruments. The downhole seismic sensors are extraordinarily sensitive, which enable detection of events with extrapolated Richter body wave magnitudes as low as -5; however, this representation shows only the 850 high-quality events with magnitudes from -3 to 0. Note that seismicity is induced over a rock volume that is about 2,640 feet high, 2,640 feet wide in the north-south direction, and about 500 feet thick, or about 158 cubic feet of stimulated rock volume. This rock volume is 3,000 times greater than the water volume injected. The hot dry rock experiments are carried out by the Los Alamos National Laboratory.

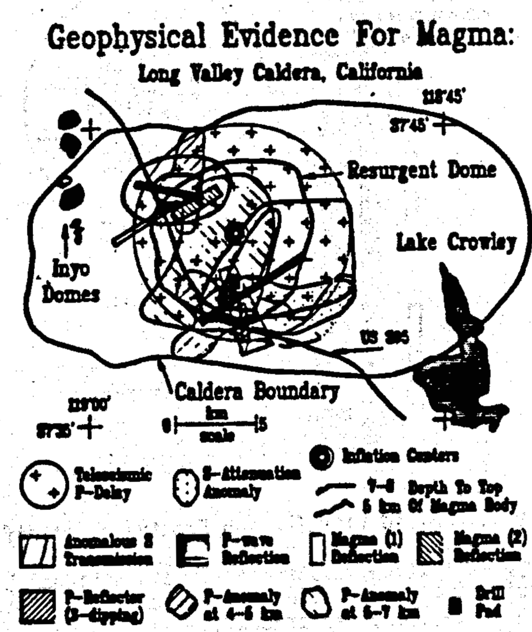
evaluate the longevity of a hydraulically fractured HDR reservoir. The target design for the system is a lifetime of at least 10 years with less than 20 percent thermal drawdown.

MAGMA ENERGY RESEARCH

The thermal energy contained in magmatic systems also represents a huge potential resource. The thrust of the magma energy extraction R&D is to determine the engineering feasibility of locating, accessing, and utilizing magma as a viable resource. This effort is a follow-on to the DOE/OBES-funded Magma Energy Research Project that determined the scientific feasibility of the magma energy concept.

The rate of energy extraction from magma has a direct influence on the economic viability of the concept. Therefore, ongoing research is directed at developing a fundamental understanding of the establishment and long-term operation of both closed- and open-loop, direct-contact heat exchangers in a crustal magma body. An open heat exchanger, in which fluid is circulated through the interconnecting fissures and fractures in the solidified region around drilling tubing, offers the promise of very high rates of heat transfer. Studies show that an open heat exchanger can be formed by solidifying magma around a cooled borehole and that the resulting mass will be extensively fractured by thermally-induced stresses. Numerical models indicate that high-quality thermal energy can be delivered at the wellhead at nominal rates from equivalent thermal rates 25 to 30 MW electric. It is shown that optimum well circulation rates can be found that depend on the heat transfer characteristics of the magma heat exchanger and the thermodynamic power conversion efficiencies of the surface plant.

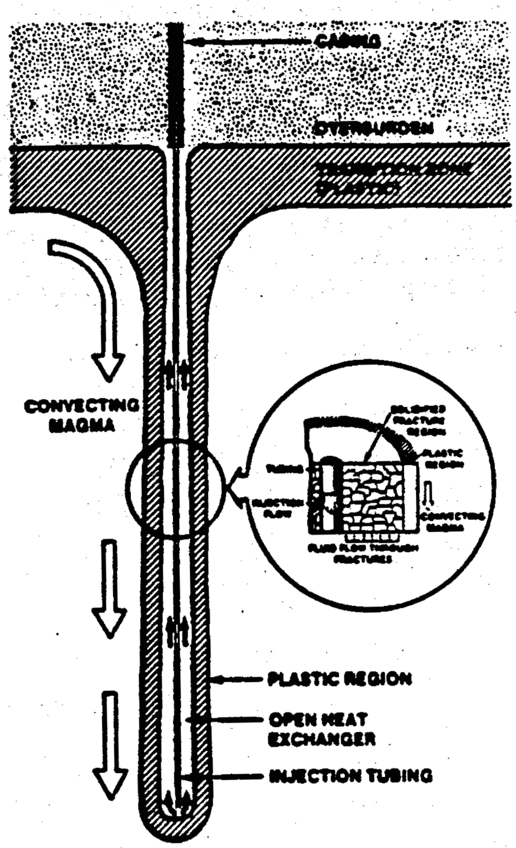
Previous heat extraction research indicated that most magma configurations are practical for utilization at energy extraction rates that are comparable to or better than those in conventional geothermal fields. The high temperatures of the magma resource and the corresponding high temperatures of the working fluid lead directly to efficient, conventional techniques for generating electricity. Processes have also been considered for using this high-quality energy to generate transportable fuels in addition to electricity.



This map of the Long Valley Caldera, based on the results of numerous geophysical surveys, shows overlapping anomalous areas, and the anomalies are consistent with the impression that there is a magma body there. This type of map is called "overlapping bull's-eyes."

A primary long-range target of this effort is to conduct an energy extraction experiment directly in a molten, crustal magma body. Critical to determining engineering feasibility are several key technology tasks: (1) to obtain detailed geophysical definition of potential magma targets; (2) to characterize the magma environment and select compatible engineering materials; (3) to develop drilling and completion techniques for entry into a magma body; and (4) to develop heat extraction technology. Industry will make the final assessment of commercial feasibility.

MAGMA ENERGY EXTRACTION



Open Heat Exchanger with Fluid Flow Through Fractured Solidified Magma

Ongoing magma energy extraction research at Sandia National Laboratories is directed at developing a fundamental understanding of the establishment and long-term operation of an open, direct-contact heat exchanger in a crustal magma body. The energy extraction rate has a direct influence on the economic viability of the concept. An open heat exchanger, in which fluid is circulated through the interconnecting fissures and fractures in the solidified region around drilling tubing, offers the promise of very high rates of heat transfer. The formation and operation of an open heat exchanger, as presently envisioned, involves numerous complex processes. Current research is following two paths: 1) research into the formation of a fractured, solidified region suitable for heat exchange, and 2) analysis of the local heat exchange processes within the fractured mass and in the external convecting magma.

Exhibit 9. LEVEL III RESEARCH AND DEVELOPMENT OBJECTIVES

Category/Task	Objectives
RESERVOIR TECHNOLOGY	
o Reservoir Definition	• Increase the success rate of siting exploration wells by 15 percent by 1992.
	• Improve production well siting by 20 percent for both reservoir identification and confirmation wells by 1992.
	• Decrease the uncertainties for long-term wellhead temperature estimates by 25 to 35 percent by 1992.
	• Decrease the uncertainties for estimates of long-term brine flow rate per production well by 40 to 50 percent by 1992.
o Brine Injection	• Decrease the uncertainties associated with long-term reservoir temperature decline predictions by 25 percent by 1992.
	• Reduce injection well maintenance costs by 30 percent by 1992.
o Exploration Technology	• Improve methods for detecting and confirming geothermal reservoirs in the Cascades and other young volcanic regions by 1990.
	• Formulate a model for fracture permeability in the Cascades region by 1990.
HARD ROCK PENETRATION	
- Lost Circulation Control	• Reduce costs associated with low circulation episodes by 30 percent by 1992.
- Coring Technology	• Reduce deep coring costs by 50 percent by 1992.
- Drill String Dynamics	• Decrease cost of drilling production-related geothermal wells by about 5 percent by 1992, through more accurate completion zone siting.
	• Reduce costs of deep wells and directionally drilled wells by 10 percent by 1992.
- Radar Fracture Mapping Tool	• Improve well siting accuracy through better identification of fractures by 1992.

Exhibit 9. LEVEL III RESEARCH AND DEVELOPMENT OBJECTIVES

Category/Task	Objectives
HARD ROCK PENETRATION, Continued	
- Wellbore Diagnostics Tools	• Decrease the cost per well by about 1 percent through decreasing the uncertainties for short-term downhole and well-heat temperature, pressure, and flow measurements for moderate-temperature hydrothermal reservoirs by 25 percent by 1989.
	• Decrease the undercertainties for similar measurements at reservoir temperatures greater than $250^{\circ}C$ -- by 50 percent by 1992.
- Geothermal Drilling Organization	• Develop and transfer other related technology to effect additional 5 percent reductions in well costs by 1990 and 10 percent by 1992.
CONVERSION TECHNOLOGY	
o Heat Cycle Research	• Increase net fluid effectiveness with conventional (surface) heat exchangers by 20 percent by 1990.
	• Increase net fluid effectiveness of conventional binary plants an additional 8 percent by 1990 through utilization of supersaturated vapor turbine expansions.
	• Reduce heat rejection system cooling water make-up requirements for geothermal power plants by 20 percent by 1991, while retaining performance comparable with conventional wet cooling.
o Advanced Brine Chemistry	• Reduce certain power plant equipment maintenance and replacement costs due to scale deposition by 20 percent by 1992.
	• Reduce geothermal surface equipment costs related to scale deposition by 20 percent by 1992.
	• Reduce costs of surface disposal of sludge from geothermal brines by 25 percent or more by 1995.
o Materials Research	• Develop a corrosion-resistant and low-fouling heat exchanger tube material costing no more than three times carbon steel by 1991.

Exhibit 9. LEVEL III RESEARCH AND DEVELOPMENT OBJECTIVES

Category/Task	Objectives
GEOPRESSURED RESEARCH	• Develop techniques to increase confidence in the ability to locate and evaluate geopressured resources by 1992. (These techniques should be of sufficient quality that at least 90 percent of wells recompleted for geopressured development are subsequently shown to be economic.)
	• Study of the effect of rock stress, temperature, and wetability on rock resistivity, and determine the effect of trace elements on neutron logs.
	• Determine the drive mechanism(s) for the design well reservoirs.
	• Develop a test procedure which has sufficient accuracy to predict the capability of any geopressured reservoir to be produced for a period five times as long as the test period by 1992.
	• Prove the long-term injectability of large volumes of spent geofluid into shallow injection wells.
	• Develop a modified scale inhibition procedure by 1988.
	• Evaluate the methane/geothermal hybrid concept as an efficient energy conversion design.
	• Determine source and flow mechanisms for the oil and methane being obtained from producing geopressured reservoirs by 1991.
	• Determine if fluids can be disposed of in an environmentally acceptable manner.
	• Develop material specifications, equipment specifications, and maintenance procedures which will guarantee over 95 percent operating efficiency with only a two-week annual shutdown for routine maintenance.
HOT DRY ROCK RESEARCH	
- Energy Extraction System	• Improve instrumentation and hardware to control, locate, and measure fracture propagation in hot dry rock reservoirs by 1995.
	• Establish reservoir mapping techniques to locate drilling targets for production wells by 1995.

Exhibit 9. LEVEL III RESEARCH AND DEVELOPMENT OBJECTIVES

Category/Task	Objectives
HOT DRY ROCK RESEARCH, Continued	
- Reservoir Engineering	• Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics by 1993.
	• Complete studies on water-rock interactions and their effects on flow through a hot dry rock reservoir by 1993.
	• Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers by 1994.
	• Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system by 1995.
	• Determine means to locate accurately the intersection of fractures with the wellbore by 1997.
	• Develop cement formulations that result in low-density, moderate-strength, zero free-water cements for casings by 1995.
	• Verify that the environmental and social consequences of HDR development are acceptable by 1997.
MAGMA ENERGY RESEARCH	• Determine the nature of identified geophysical anomalies at Long Valley using actual well observation data and verify the depth and lateral extent of a magma body by 1992.
	• Evaluate performance of materials in the corrosive and volatile-rich magma environment for use in drilling tools by 1992.
	• Predict rates for dissolution of silicate minerals and the composition of fluid in a rock-to-water heat exchanger system and evaluate the potential for loss of permeability due to precipitation of secondary minerals by 1995.
	• Design and develop technology capable of drilling into magma at temperatures of at least 900°C and total depths of 6 km by 1992.
	• Evaluate magma degassing hazards associated with drilling and energy extraction at Long Valley.

IV. THE MANAGEMENT PLAN

The management, operation, and direction of the Geothermal Program are necessarily affected and influenced by national policy. Federal energy policy, which incorporates recommendations from the Executive Office and national energy advisory boards, is developed by the Secretary of the Department of Energy. It provides general guidance and directives to ensure that federal programs reflect the appropriate role of the government in energy technology research and development. Actions of Congress also affect program activities and direction through legislation and budget appropriations. Moreover, geothermal groups, such as the Lawrence Berkeley Laboratory Industry Advisory Panel, as well as technology participants in the private and public sectors, submit recommendations for consideration by geothermal program managers. Within this dynamic, multiple input environment, program managers develop operating plans that are responsive to the changing requirements of federal policy, Congress, and program constituents, while maintaining overall progress in the technology. Organization and management mechanisms for the program as a whole and for each program area ensure that the direction, operation, and technical and budgetary allocations reflect the directives of pertinent authorities and experts.

DOE HEADQUARTERS

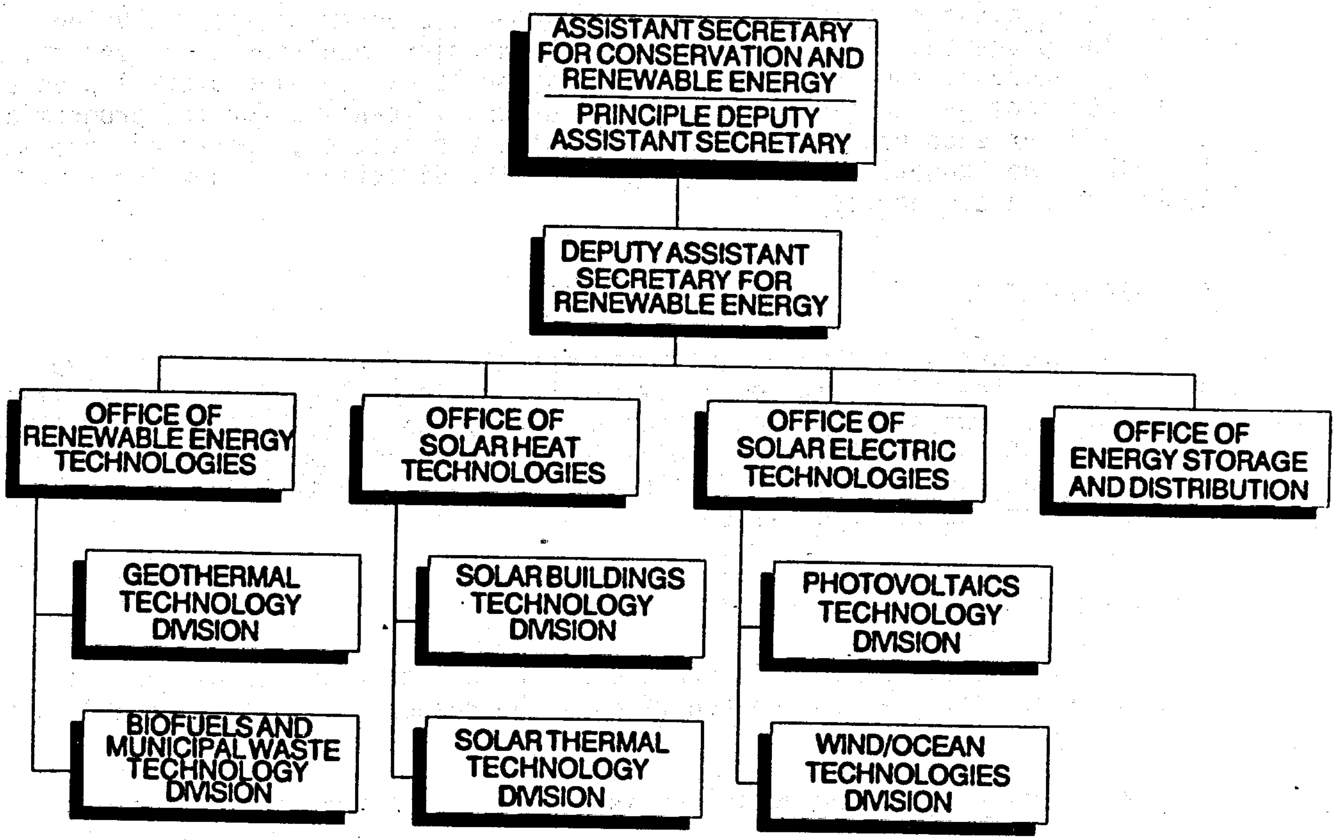
The Geothermal Technology Division operates under the administrative oversight of the DOE Office of Renewable Energy Technologies under the Office of the Deputy Assistant Secretary for Renewable Energy (Exhibit 10). With the assistance of these offices, the Division Director implements energy research policy at the program level and allocates the necessary technical and budgetary resources for program activities.

PROGRAM ORGANIZATION

The Geothermal Program is managed by the Director of the Geothermal Technology Division at DOE Headquarters. The responsibilities of the Director include:

- Identifying and acting on issues, alternatives, and programmatic positions
- Developing and implementing program concepts, strategies, and plans
- Providing program guidance and priorities for planning and operation
- Regularly performing program reviews and evaluations
- Determining the direction of program operations and redistribution of resources as necessary
- Responding to requests from DOE authorities, other federal agencies, and Congress for information on the Program and project activities.

Exhibit 10. OFFICE OF CONSERVATION AND RENEWABLE ENERGY



The Division Director also establishes operating policy for the operations offices and national laboratories and approves annual plans for performing their assigned activities, providing the centralized leadership necessary to ensure that implementation of the Program conforms to national energy policy, priorities, and directives.

For headquarters management purposes, program categories sharing closely related technology interests are grouped into two R&D teams: Geosciences Research and Conversion Research. The categories comprising each team, their managers, and team leaders are identified in Exhibit 11. Management of technical activities is decentralized so that specialized technical expertise can be utilized to implement research projects. These management and technical activities are provided by DOE operations offices and national laboratories.

OPERATIONS OFFICES

Field organizations implement program plans, execute prime contracts for R&D, direct contractors and review their performance, and provide the Geothermal Technology Division with recommendations on program needs and direction. The operations offices involved in geothermal R&D are identified in Exhibit 12.

CONTRACTORS

Actual implementation of the geothermal program objectives is performed by contractors, including the national laboratories identified in Exhibit 12. These laboratories are responsible for the conduct and day-to-day management of geothermal research activities. They assist in the management of program activities, perform some projects in-house, and subcontract other work in areas assigned to them. Consequently, the contractors are directly responsible not only for conducting and managing federal geothermal research, but also for ultimately meeting the technical goals of the program.

Specific functional responsibilities of the contractors include:

- Conducting research projects
- Monitoring and managing technical research subcontracts
- Responding appropriately to policy, guidance, and directives from the Operations Office
- Preparing annual research plans
- Preparing periodic reports on research results as required
- Transferring the technologies developed in the research to other DOE laboratories and centers, private industry, and universities.

Exhibit 11. MANAGEMENT STRUCTURE OF THE GEOTHERMAL PROGRAM

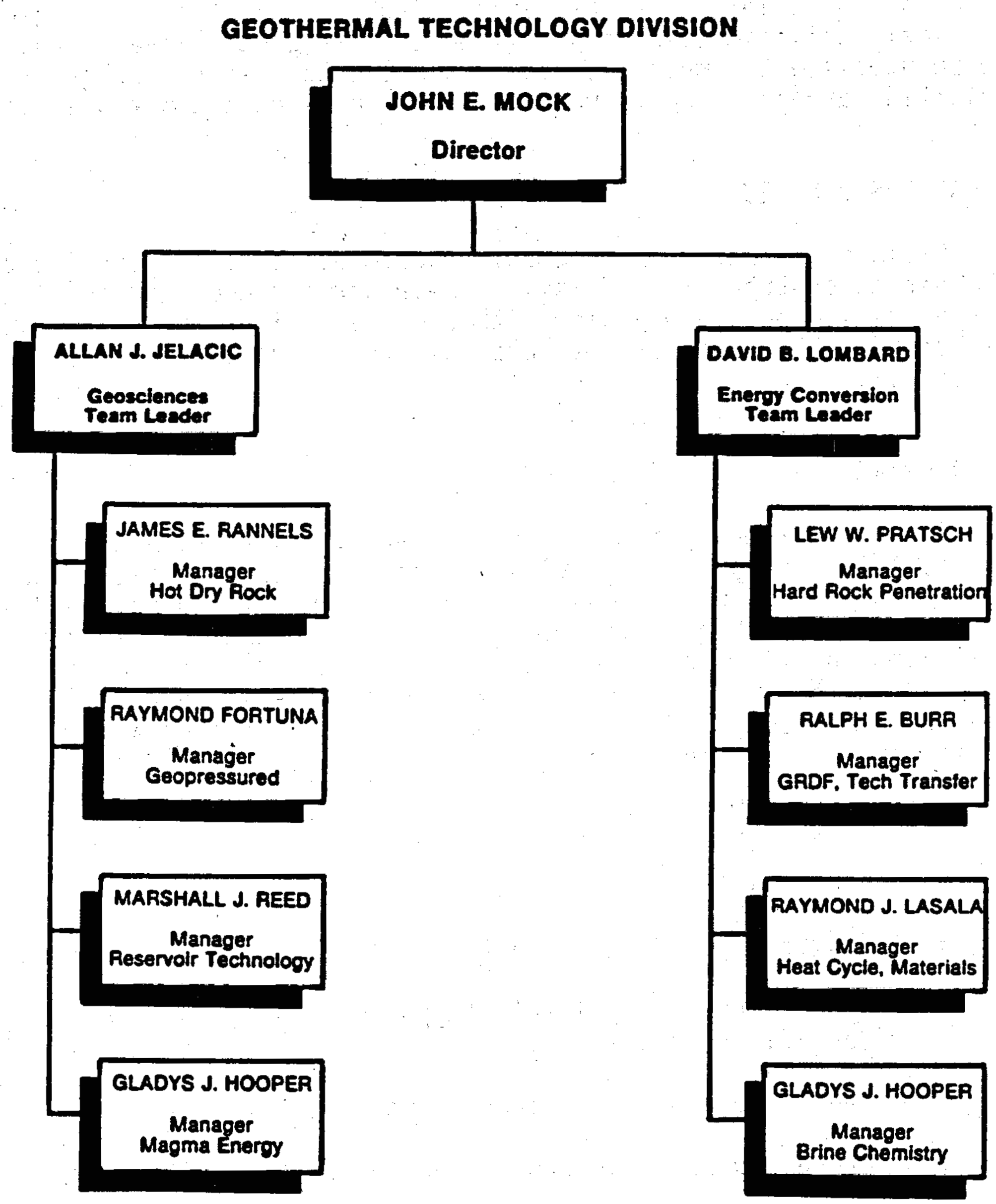


Exhibit 12. DOE FIELD OFFICE AND NATIONAL LABORATORY PARTICIPATION IN THE GEOTHERMAL PROGRAM

	OPERATIONS OFFICES			NATIONAL LABORATORIES						
	ALO	IDO	SAN	BNL	INEL	LBL	LLNL	LANL	PNL	SANDIA
• RESERVOIR TECHNOLOGY										
- Reservoir Definition		○				□				
- Brine Injection		○			●	●				
- Exploration Technology		○			●					
• HARD ROCK PENETRATION	○			●						□
• CONVERSION TECHNOLOGY										
- Heat Cycle Research		○			□			●		
- Advanced Brine Chemistry		○		●						●
- Materials Research		○		□						
• GEOPRESSURED RESEARCH		○			●	●				
• HOT DRY ROCK RESEARCH	○							□		
• MAGMA ENERGY	○				●	●				□

KEY

○ Responsible Field Office
□ Responsible National Laboratory
● Participant

OPERATIONS OFFICES

ALO - Albuquerque*
IDO - Idaho
SAN - San Francisco**

NATIONAL LABORATORIES

BNL - Brookhaven
INEL - Idaho
LBL - Lawrence Berkeley
LLNL - Lawrence Livermore
LANL - Los Alamos
PNL - Pacific Northwest
Sandia - Sandia

*Field management only.

**Loan Guaranty monitoring only and project closeouts, including Heber binary plant.

MANAGEMENT CONTROL

Due to the decentralized nature of the Geothermal Program, processes for management control are required at three levels: at Headquarters to provide mechanisms to ensure program success and adherence to program policy; at Operations Offices to ensure that contractual requirements are met and quality assurance plans implemented; and at the prime contractor level, to ensure that operations in each respective area of responsibility are consistent with guidance and technical goals.

Toward this end, planning documents and technical progress reports are prepared, and program reviews are conducted periodically. This Multiyear Program Plan outlines the general technical direction of the Program. Specific technical emphases and proposed modifications in direction, however, are examined each year as the Division Director reviews planned research activities, contractor participation, project milestones and deliverables, and resource requirements.

Laboratories provide written reports of progress and activities on a regularly scheduled basis. On a prescribed schedule, each contractor prepares a report that describes resource expenditures, technical activities, and progress by task area.

To ensure the continuing exchange of technical and programmatic concerns, the division sponsors an annual program review during which the operations offices, national laboratories, contractors, and other industry representatives provide updates on their activities. Twice a year the participants in each research category gather for a program review to report on category-specific activities. At Headquarters, the Director holds monthly informal conferences where Program Managers report on current technical and programmatic issues and problems in their respective areas.

SCHEDULE

To provide management with guidance for evaluating the progress and direction of research tasks, technical milestones, shown in Exhibit 13, have been established. The milestones are used as targets for technical achievement over time. They are subject to annual reevaluation in terms of progress made to date and budget considerations.

Program assessments are conducted routinely during regularly scheduled management review meetings. However, industry advice and guidance sought during technical geothermal conferences and when other opportunities for interchange arise, also contribute to the program assessment process.

generation. These sites are estimated to contain a potential electric energy capacity of over 5400 MWe for 30 years. In addition, other such sites are expected to be identified with the exploration technologies under development as part of this R&D plan.

The near-term outcome of research on the more advanced geothermal systems--geopressured, hot dry rock, and magma--cannot be predicted at this early point of plan execution. In geopressured R&D, the process of verification of all the technical knowledge that has so far been gained is part of the five-year effort, and industry's response to the economics of this form of the resource is not expected until this process is completed and methods for developing hard data on reservoir producibility and longevity are shown to be valid. For hot dry rock, industry's response is expected to await improved understanding of man-made reservoirs and more cost-effective methods for creating them. Thus, if the geopressured and HDR objectives of this plan are achieved, industry should be positioned to make knowledgeable decisions on these forms of geothermal energy on completion of the plan.

The research on magma energy will continue beyond the time frame of this plan. However, the research performed during this five-year period will narrow the magma research paths and further define magma's ultimate potential as a viable source of economic energy.

Though geothermal technology has developed significantly in recent years, the continuation and strengthening of the federal/industry partnership addressed in this plan establish the necessary framework for stimulating even greater technical progress. It is, however, the mutual commitment to, and continuing confidence in, geothermal technology as a viable, long-term energy supply option, as well as the formulation of a logical approach to achieving technical goals, which are critical to overall success.

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

CATEGORY/ TASK	FY 1988	FY 1989	FY 1990	FY 1991	FY 1992
CONVERSION TECHNOLOGY					
• Heat Cycle Research	C1	C2-C5	K6-K7	C8	K9
• Advanced Brine Chemistry	C1-C4	C5-C8	C9	C10	
• Materials Research	C1-C3				
GEOPRESSURED RESEARCH	C1-C3	C4-C5	C6	C7	C8
HOT DRY ROCK RESEARCH	K1	K2		K3	C4
MAGMA ENERGY	C1, K2, C3	C4-C5, K6, C7	C8-C9	C10-C11	C12

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

CATEGORY/ TASK	FY 1988	FY 1989	FY 1990	FY 1991	FY 1992
RESERVOIR TECHNOLOGY					
• Reservoir Definition	K1-K3		K4-K5		
• Brine Injection	K1-K3			K4	
• Exploration Technology	K1-K2	K3			
• Geothermal Technology Organization	K1				K2
HARD ROCK PENETRATION	C1-C3	C4-C6	C7-C9	C10-C12	
• Industry Cost-Shared Research	C1-C3	C4-C6	C7-C8	C9	
• Geothermal Drilling Organization	C1-C5	C6-C8	C9	C10	

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

RESERVOIR TECHNOLOGY

- Reservoir Definition

K1 Complete survey and issue report evaluating state-of-the-art pressure transient production and injection test instrumentation.

K2 Sponsor 13th Annual Workshop on Geothermal Reservoir Engineering.

K3 Issue report on detailed logging and fluid inclusion studies at Coso, coupled with detailed mapping of productive fluid channels.

K4 Demonstrate the application of geophysical techniques for fracture control of permeability.

K4 Formulate and test conceptual methods of fracture control of permeability.

- Brine Injection

K1 Issue report on laboratory rock tracer studies.

K2 Publish dual-permeability reservoir code.

K3 Issue report on heat extraction and thermal breakthrough in fractured reservoirs.

K4 Complete development of kinetics and transport approach to fluid flow coupled with thermal and chemical reactions.

- Exploration Technology

K1 Complete field data gathering from the cost-shared core holes.

K2 Issue report on characterization of fracture systems in young volcanic environments.

K3 Publish data sets and the results of investigations of deep thermal gradient tests in young volcanic environments.

- Geothermal Technology Organization

K1 Select and complete contracting for initial research tasks.

K2 Complete initial series of cost-shared research tasks and transfer technology to industry.

HARD ROCK PENETRATION

C1 Develop analysis of wellbore transient hydraulics during loss of circulation.

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

C2 Document design changes of API slot tester and publish conclusions on particulate testing.

C3 Publish SAND report on Sandia's PDC development.

C4 Complete plugging model analyses and experiments.

C5 Design and test geothermal lost circulation materials.

C6 Design and begin procurement of high-temperature drilling system.

C7 Provide analytical support to field evaluation of lost circulation materials.

C8 Field test geothermal lost circulation material.

C9 Field test high-temperature drilling system.

C10 Correlate lost circulation analyses experimental data and field data.

C11 Complete final report on lost circulation materials testing.

C12 Develop and test improved high-temperature drilling systems.

- Industry Cost-Shared Research

C1 Complete field testing of prototype radar fracture mapping tool in a rock quarry.

C2 Report test results and evaluate performance of prototype tool.

C3 Complete analysis and issue technical publication on acoustical data telemetry.

C4 Collect field drilling data and update drill string dynamics computer model.

C5 Develop radar fracture mapping tool for geothermal wells.

C6 Test data telemetry system in full-scale experiment.

C7 Field test radar fracture mapping tool in geothermal wells.

C8 Field test telemetry system during drilling.

C9 Complete final report on borehole radar fracture mapping.

- Geothermal Drilling Organization

C1 Place contract for logging phase of borehole televiewer development.

C2 Complete field testing of foam lost circulation tool.

C3 Complete final field test of downhole air turbine at The Geysers.

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

C4 Test high-temperature elastomer drill pipe protectors in geothermal wells.

C5 Identify and develop new projects.

C6 Televiewer commercially available.

C7 Develop and test high-temperature elastomer rotating head seals and BOP rubbers.

C8 Identify and develop new projects.

C9 Identify and develop new projects.

C10 Identify and develop new projects.

<u>CONVERSION TECHNOLOGY</u>

- <u>Heat Cycle Research</u>

C1 Specify and receive a reaction turbine for testing at Heat Cycle Research Facility.

C2 Complete preliminary estimate of binary geothermal cycle performance using mixed fluorocarbon or halocarbon working fluids and of applicability of modified Kalina Cycles; prepare report.

C3 Complete supercritical cycle testing with impulse turbine and report results on effects of mixtures and supersaturated turbine expansions on turbine efficiency.

C4 Complete system study for the Advanced Heat Rejection System.

C5 Complete supercritical testing with condenser oriented at final attitude with the isobutane, hexane family.

K6 Complete supercritical cycle testing at final condenser attitude; prepare report.

K7 Complete testing of metastable supersaturated vapor expansions; report results.

C8 Complete system study for the Advanced Heat Rejection System.

K9 Complete termination of Heat Cycle Research Task.

- <u>Advanced Brine Chemistry</u>

C1 Begin laboratory tests of particle counter at PNL.

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

C2 Initiate optimization experiment using thermophilic bacteria (e.g., Sulfalobus).

C3 Prepare peer-reviewed publication on progress to date in geothermal waste detoxification experiments.

C4 Issue annual report on experiments.

C5 Scale-up experiments using best candidate organisms.

C6 Conduct a short field test of particle counter.

C7 Analyze data and prepare final report on particle counter.

C8 Dismantle lab trailer at Heber Binary Plant.

C9 Assess kinetics of scale-up waste detoxification experiments.

C10 Evaluate the effectiveness of overall process.

- Materials Research

C1 Complete 1-year downhole exposure testing of advanced high-temperature cements at 300°C (572°F).

C2 Commence field testing of nonmetallic heat exchanger tubing.

C3 Complete large-scale flow test of chemical systems for lost circulation control at Sandia Lost Circulation Test Facility.

GEOPRESSURED RESEARCH

C1 Begin long-term pressure build-up test of Gladys McCall well.

C2 Decision to start flow testing at Pleasant Bayou well.

C3 Decision to assemble EPRI hybrid binary power system.

C4 Decision to shut down EPRI system.

C5 Decision to plug and abandon Gladys McCall well.

C6 Decision to start rework of Hulin well.

C7 Decision to plug and abandon Pleasant Bayou well.

C8 Decision to test electrical generation system at Hulin well.

HOT DRY ROCK RESEARCH

K1 Start Long-Term Flow Test (LTFT) surface system installation.

K2 Complete instrumentation development.

Exhibit 13. GEOTHERMAL PROGRAM KEY (K) AND CONTROL (C) MILESTONES -- FY 1988 - FY 1992

K3 Start LTFT.

C4 Complete LTFT.

MAGMA ENERGY

C1 Select drilling engineer and drilling contractor for Long Valley well.

K2 Spud the Long Valley exploratory well.

C3 Complete basic magma chamber convection experiment.

C4 Experimentally determine importance of magma/water interactions.

C5 Complete initial scientific plan for Long Valley well.

K6 Deepen Long Valley well.

C7 Instrument Long Valley well.

C8 Complete final scientific plan for well.

C9 Develop models of magma heat transfer patterns.

C10 Determine safety factors associated with drilling into magma chamber.

C11 Instrument second phase of magma well.

C12 Finalize material and equipment requirements for drilling into a magma chamber.

V. THE OUTCOME

This Multiyear Program Plan presents a realistic, comprehensive approach to establishing all forms of geothermal energy as significant contributors to the nation's energy supply. It is designed to maintain momentum in the growth of the existing hydrothermal industry while continuing to develop long-term options which show the greatest promise for practical applications.

The plan is realistic. It is consistent with national energy policy, thus ensuring continued support for planned research activities.

The plan also acknowledges the importance of private sector participation, yet accepts the fact that industry's ability to assume risks is limited. This recognition ensures that research will be complementary to private sector activities and that industry will be prepared to adopt successful research results.

Moreover, the plan is based on sound technical objectives that have evolved from over 15 years of research experience. Although the ultimate success of research activities is uncertain, the insight gained from previous research has been used to substantiate selected research paths, enhancing the likelihood that successful results will yield practical applications.

Finally, the plan is realistic because it is flexible. It not only provides mechanisms for reevaluation through continued technical assessments and program reviews, but also incorporates a set of technical objectives based on the projected performance and costs of systems and subsystems. This planning consideration offers flexibility by providing a range within which cost and performance tradeoffs can be optimized.

The plan is also comprehensive. It represents a balanced approach to geothermal research and development by addressing all major areas of geothermal research including the most promising known technology options as well as mechanisms for developing innovative ideas.

The selection of research options is based on years of research and experience. Although the success of some options remains uncertain, the carefully designed multiple approach makes the risk of total program failure very low. In essence, the plan consolidates individual risks that industry is unable to assume into a program with a high probability of overall success.

It is difficult to predict the specific future of a technology whose outcome will be affected by both the risks inherent in research and the uncertain future status of competing alternatives. Furthermore, this plan addresses geothermal technology development for the ensuing five years, a relatively short time frame in the development of major new technologies.

Nevertheless, general observations can be made. For example, the plan calls for a 25-35 percent reduction in the cost of producing electricity from most U.S. liquid-dominated moderate-temperature (150-200^{o}C) hydrothermal reservoirs by 1992. Depending on the cost of power in the 1990s, achievement of this objective could open 30 or more hydrothermal sites identified by the U.S. Geological Survey as having temperatures in this range to economic power generation. These sites are estimated to contain a potential electric energy capacity of over 5,400 MWe for 30 years. In addition, other such sites are expected to be identified with the exploration technologies under development as part of this R&D plan.

The near-term outcome of research on the more advanced geothermal systems--geopressured, hot dry rock, and magma--cannot be predicted at this early point of plan execution. In geopressured R&D, the process of verification of all the technical knowledge that has so far been gained is part of the five-year effort, and industry's response to the economics of this form of the resource is not expected until this process is completed and methods for developing hard data on reservoir producibility and longevity are shown to be valid. For hot dry rock, industry's response is expected to await improved understanding of man-made reservoirs and more cost-effective methods for creating them. Thus, if the geopressured and HDR objectives of this plan are achieved, industry should be positioned to make knowledgeable decisions on these forms of geothermal energy on completion of the plan.

The research on magma energy will continue beyond the time frame of this plan. However, the research performed during this five-year period will narrow the magma research paths and further define magma's ultimate potential as a viable source of economic energy.

Though geothermal technology has developed significantly in recent years, the continuation and strengthening of the federal/industry partnership addressed in this plan establish the necessary framework for stimulating even greater technical progress. It is, however, the mutual commitment to, and continuing confidence in, geothermal technology as a viable, long-term energy supply option, as well as the formulation of a logical approach to achieving technical goals, which are critical to overall success.

APPENDIX A

GEOTHERMAL RESOURCES AND EXPECTED IMPACTS OF TECHNOLOGY IMPROVEMENTS ON COSTS

INTRODUCTION

The purpose of this appendix is to describe expectations of the Geothermal Program for improvements in the performance and economics of geothermal energy systems during the next few years.

The objectives of the Geothermal Program have recently undergone extensive review, updating, and quantitative analysis (1). The objectives comprise expectations for improvement of technology components, and thus are key inputs to estimates of future geothermal energy costs. Other key inputs are the physical characteristics of geothermal resources and the current performance and cost of geothermal technology.

The performance and costs of hydrothermal electric power systems are the main focus of this appendix because they are relatively well understood and are expected to provide the largest additions to the nation's energy supplies from geothermal resources during the next ten years. Much of the research being performed to improve hydrothermal technology will be applicable to geopressured, hot dry rock, and magma energy systems.

The performance and cost data for hydrothermal energy systems reflect U.S. industry practice as of early 1986. They have been incorporated into a computer model, IM-GEO, that analyzes impacts of technology improvements upon the cost of electricity from hydrothermal projects (2). The economic estimates for geopressured, hot dry rock, and magma energy systems come from other recent studies. Models similar in level of detail to the hydrothermal model are being developed for these types of energy systems.

GEOTHERMAL RESOURCES

Current knowledge of the relative size and economics of the resource bases is a primary consideration in setting the Program's goals. The geothermal resource statistics come from studies performed by the U.S. Geological Survey (USGS), in cooperation with DOE and its predecessors, and are expressed in terms of 10^{18} joules in USGS Circulars 726 (1975), 790 (1979), and 892 (1982). This value is approximately equal to one "quad", a quadrillion British Thermal Units (10^{15} BTU).

Geothermal resource estimates include the important distinction made by the USGS between the "accessible resource base" and "resources." The "accessible resource base" is that part of the geothermal energy in the earth that is shallow enough to be reached by production drilling in the foreseeable future, with reasonable technical and near-future economic considerations. The "resource" is the energy that could be extracted from the accessible resource base at costs competitive with other forms of energy, at a foreseeable time, under reasonable assumptions about technological improvements and economic feasibility. Thus, the "resource" is always less than the "accessible resource base."

For hydrothermal systems (steam and hot water other than in geopressured systems) the accessible resource base with fluid temperatures above 90°C (194°F) is estimated to be about 9,600 quads. This includes between 3,800 and 5,900 quads of fluids with temperature above 150°C (300°F). The size of the resource is about 25 percent of the accessible resource base, thus about 2,400 quads.

Previous estimates indicated that U.S. hydrothermal resources (including reservoirs not yet discovered) could power electric plants totalling about 120,000 MWe capacity for 30 years, the equivalent of 120 large coal or nuclear plants. In addition, the lower-temperature portions of the hydrothermal resources could provide about 8 quads of useful heat per year for 30 years. A large portion of this resource is economic or nearly economic, based on substantial U.S. and world experience with producing electricity and heat from the resource.

However, the above estimates of hydrothermal resources may be on the low side by a factor of two or more, due to an underestimate of the potential of the Cascades range in Washington and Oregon. Cool ground waters may have masked the detection of hydrothermal resources associated with relatively young magma bodies.

For geopressured energy (methane and hot water from U.S. Gulf Coast locations) the accessible resource base in the fluids is estimated to be 63,000 quads of methane plus 107,000 quads of thermal energy, for a total of 170,000 quads of energy. Systems that capture mechanical energy in addition to methane and heat could add about three percent to this total.

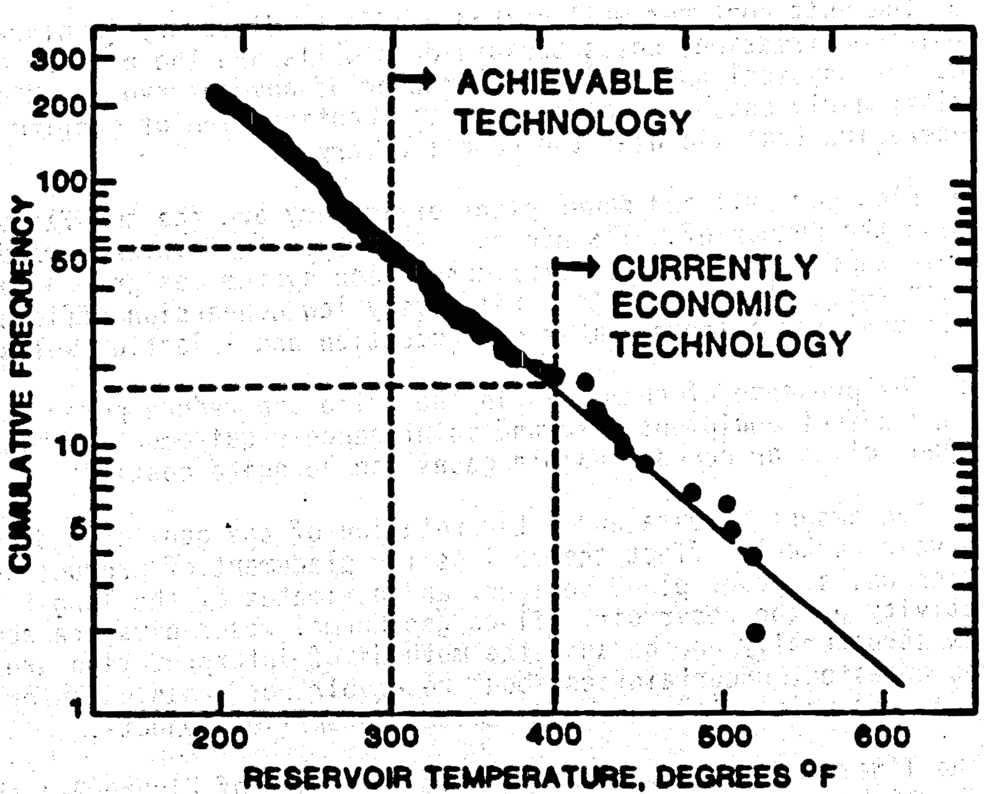
The USGS estimate of the size of the geopressured resource (the economic or nearly economic portion), is 270 to 2,800 quads of methane plus 160 to 1,600 quads of heat, for a total of 430 to 4,400 quads of these two forms of energy. Thus the geopressured resource has been estimated to be between 0.5 and 3.3 percent of the accessible resource base. One important physical factor that contributes to this seemingly low producibility is that the pressure drive in the reservoirs will be depleted as fluid is extracted. The time limits of this depletion are one of the current R&D questions being addressed by the Program. Current estimates of the costs to produce geopressured energy are quite variable, due to limited practical experience with these systems.

For hot dry rock systems, the USGS estimated the accessible resource base to be about 450,000 quads. For magma systems, the accessible resource base has been estimated to be about 500,000 quads. DOE experiments and analyses to date indicate that at least a portion of the hot dry rock accessible resource base might be economically recoverable, but the relative amount is still highly uncertain. Estimates of how much magma energy might be economically recoverable will have to await the results of attempts to drill into such systems to characterize their configurations and properties.

All of these energy types contain enough potentially recoverable energy to warrant continued interest in technology development and eventual exploitation. The resource estimates will continue to become more accurate as more is learned about the energy types and the economics of extraction and conversion.

It is especially important to conduct R&D on technology that could extend hydrothermal electric generation capability into the moderate-temperature range of 150°C to 200°C (300°F to 400°F). Resources with temperatures of greater than 150°C (300°F) have been identified at 53 sites in the U.S., and have a potential for generating over 20,000 MWe of electric power for 30 years, employing present electric generation technology, as shown in Figure A-1. Substantial improvements in hydrothermal production and conversion technologies would enable most of these reservoirs, and many more yet to be discovered, to be used for electric power generation production. A drop in economically exploitable resource temperature of 100°F (from 400°F to 300°F) would triple the number of exploitable resources.

FIGURE A-1. TEMPERATURES OF KNOWN HYDROTHERMAL RESOURCES



Cumulative frequency of U.S. hydrothermal reservoirs as a function of reservoir temperature, for reservoirs identified as of 1978. The straight line is the least squares best fit to the data. Note semilog plot. Source: USGS Circular 790.

HYDROTHERMAL RESOURCE, TECHNOLOGY, AND COST RELATIONSHIPS

The economics of energy extraction differ among the energy types (3). To be competitive with conventional sources of electric power generation the cost of power must be less than approximately six cents/kWh (4,5).

The cost of power from geothermal energy systems depends markedly on the physical characteristics of the specific geothermal reservoir. Some of the major relationships are shown in Figure A-2. In general, the performance and economics of a hydrothermal electric power system are dominated by reservoir temperature (the higher the better), cost per well (increases with both well depth and rock hardness), and flow per well (increases with formation permeability and reservoir temperature).

When estimating technology performance and the cost of power from a specific hydrothermal reservoir and power plant system, four technical interactions dominate:

- The unit cost per well markedly affects discovery (exploration and reservoir confirmation) costs because deep wells are the primary tools for proving the physical and economic character of any reservoir. High costs in this risky early phase can discourage the continuation of confirmation efforts for reservoirs that lie near the economic margin.

- Flow per well and power plant efficiency are the two factors that determine the number of wells needed. Power plant efficiency is dominated by reservoir temperature and by power conversion system design. A relatively low reservoir temperature leads to a relatively low conversion efficiency and thus a requirement for a large number of production and injection wells.

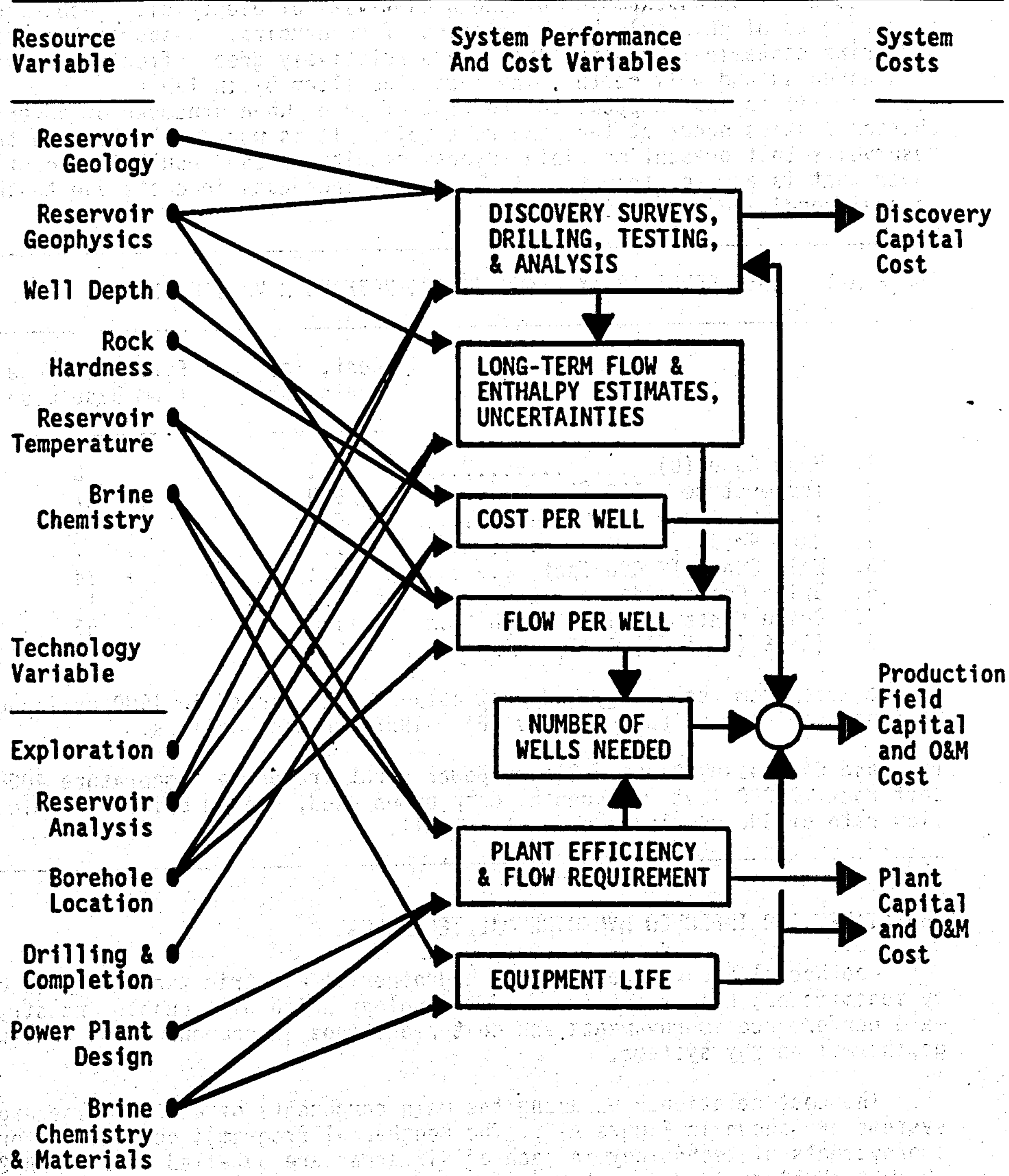
- The presence of chemicals in the brine can reduce power output from the plant and affect equipment life and maintenance requirements. High levels of dissolved solids or noncondensible gases can be quite costly.

- The amount of data and interpretation of the geology and geophysics of a reservoir markedly affect the designs for placement of production and injection wells, power plant designs, and estimates of the long-term productivity of the reservoir. Since geothermal reservoirs are sometimes complex structurally and because the methods of interpretation are relatively new and untested, uncertainties about reservoir performance confer a certain degree of financial risk in these capital-intensive projects.

The lines leading up from the lower left part of Figure 2-A show the paths through which technology performance and potential improvements in technology affect hydrothermal system costs.

Because the interactions among reservoir characteristics, technology performance, and the cost of power are complex, the geothermal industry and the Geothermal Program rely on computer models to quantify the interactions, to estimate the cost of power, and to estimate the degree to which possible

FIGURE A-2. IMPACTS OF RESOURCE AND TECHNOLOGY VARIABLES ON COSTS



improvements in technology might reduce the cost of power from various reservoirs. Most of the estimates presented here come from the new IM-GEO model (2).

Table A-1 shows examples of the sensitivity of electricity busbar cost to some aspects of physical characteristics of reservoirs. Resource temperature and brine contamination differences have relatively great effects compared to rock hardness and well depth. The last line (Item 8) in Table A-1 exemplifies what happens to the cost of power when a number of adverse characteristics occur at the same reservoir. It is worthwhile to note that reservoirs that present multiple adverse conditions can result in a cost of power that is greater than the simple sum of increases in costs due to the several conditions operating alone.

TABLE A-1. COST SENSITIVITY EXAMPLES FOR RESERVOIR VARIABLES

	Cost, (a) cents/kWh	Percent Change from Base Case
1. Base Case (b)	7.1	0
2. Temperature = 350 °F...........	9.0	+ 27
3. Temperature = 450 °F...........	6.1	- 14
4. Hard Rock	7.6	+ 7
5. Well Depth 12,000 feet	8.1	+ 14
6. Brine Contamination = Low	5.9	- 17
7. Brine Contamination = High	11.0	+ 55
8. (2) & (4) & (5) & (7)	24.8	+ 249

(a) Derived from technology and cost estimates developed in 1980 by Idaho National Engineering Laboratories (6). 1986 constant dollars.

(b) Base Case assumptions: Binary power plant, resource temperature 400°F., soft rock, 7,000-foot well depth, deep pumps used, medium brine contamination, flow rate of 600,000 lb/hr/production well.

OBJECTIVES FOR IMPROVED HYDROTHERMAL TECHNOLOGY

Geothermal Program research on hydrothermal electric technology is guided by specific objectives for improved technology which will enable industry to make performance improvements and cost reductions in components of real-world geothermal energy systems.

The cost relationships among the main components of geothermal energy systems are shown in Figure A-2. The Geothermal Program's objectives for improvements of technology in each of six areas are detailed in Table A-2. These technology improvements are drawn from and documented in Reference 1.

They are expressed here in terms of the degree to which current technology ("1986 Technology", from the technology baselines in the IM-GEO model (2)) is expected to be improved through Geothermal Program research by the start of calendar year 1992. The resulting technology is referred to here as "1992 Technology".

Some additional time for technology transfer will be required before industry adopts all of the anticipated innovations. It is reasonable to suppose that all of the improvements, and their related cost savings, will be fully incorporated by industry by 1995.

The technology categories used in Figure A-2 and Table A-2 are major impact entry points to the IM-GEO hydrothermal cost of power model, and are defined here in terms of the types of technology that the Geothermal Program is seeking to improve.

Exploration technology advances are being pursued through technical improvement of geological and geophysical survey instruments, methods, and interpretive techniques. These are anticipated to improve the likelihood that the first deep well drilled at a new prospect will strike substantial quantities of hot fluid.

Reservoir analysis instruments, strategies, procedures, and analytical models are being developed to provide a technology base which industry can use to reduce the cost of evaluating the performance of geothermal reservoirs and various long-term uncertainties associated with their use. The cost impacts of improvements in reservoir analysis technology will occur through improved abilities to predict the long-term behavior of reservoirs, and thus use energy extraction and conversion designs that are optimized more accurately.

The technology advances anticipated in this area are expected to substantially reduce both the cost of electricity and the financial risks involved in the development of many hydrothermal reservoirs.

Borehole location refers to improving the ability to aim for and to hit highly productive deep reservoir zones during production-oriented drilling. An example is the use of slant (directional) drilling to increase the probability of intersecting large fractures in reservoirs where the permeability is fracture-dominated. While GTD has no specific research task area by this name, a number of anticipated instrumentation and interpretation improvements from the Geoscience and Hard Rock Penetration task areas converge in this area.

Drilling tools and instruments are being developed to withstand the high temperatures and chemically complex conditions of geothermal reservoirs. Advanced technology is also being developed to increase drilling penetration rates in hard rock and for maintaining the circulation of drilling fluids in fractured rock. Completion equipment, materials, and methods being developed include well casings and casing cements that can withstand high temperatures and harsh chemical conditions. Artificial fracturing methods to increase flow rates remain of technical interest but are not now being studied actively by GTD.

TABLE A-2. TECHNOLOGY IMPROVEMENTS EXPECTED FROM HYDROTHERMAL RESEARCH OBJECTIVES FOR 1992 (Percent of 1986 Value)

1. EXPLORATION:		
- Wildcat Success Ratio	:	127
- Testing Costs, Exploration	:	110 (a)
2. RESERVOIR ANALYSIS:		
- Reservoir Confirmation Success Ratio	:	135
- UNCERT: Reservoir Temperature	:	62 (b,c)
- UNCERT: Non-Condensible Gases	:	70
- UNCERT: Hydrogen Sulfide Content	:	70
- UNCERT: Total Dissolved Solids	:	70
- UNCERT: Production Well Flow	:	66
- UNCERT: Flow Decline Coefficient	:	70
- UNCERT: Injection Well Flow	:	66
3. BOREHOLE LOCATION:		
- Dry Holes per Production Well	:	60
- Flow Rate, Production Well	:	108
- Producer Redrill Fraction	:	40 (d)
- UNCERT: Well Cost, Extension	:	40 (d)
- UNCERT: Producer Redrill Fraction	:	60
- UNCERT: Dry Holes per Producer	:	60
4. DRILLING AND COMPLETION:		
- Well Problems, Lost Circulation	:	70
- Well Problems, Cementing	:	60
- Total Cost, Average Well	:	86
5. POWER PLANT DESIGN:		
- Binary Plant - Efficiency	:	128
- Binary Plant - Capital Cost	:	102 (a)
- Heat Exchanger - Capital Cost	:	200 (a)
- Heat Exchanger - O&M Cost	:	50
- Cooling Water - Use Cost	:	80
6. BRINE CHEMISTRY AND MATERIALS:		
- O&M Cost, Gathering System	:	50
- Cost per Workover, Production Well	:	90
- Binary Plant Availability	:	102
- TDS-Sludge Disposal Cost	:	75
- TDS-Scaling, O&M Cost	:	80

(a) Increased cost required to achieve improved performance
(b) "UNCERT" = Predictive uncertainty
(c) With some contribution from Bore-Hole Location improvements
(d) With some contribution from Reservoir Analysis improvements

Power plant design requires engineering solutions matched to the thermodynamic and kinetic properties of geothermal fluids. Significant system life-cycle cost savings are being pursued by analyzing the geothermal reservoirs and energy conversion equipment as integrated systems. Fluid withdrawal and injection rates, pumping strategies, and turbine and heat exchanger designs are all being studied and refined.

Brine chemistry and materials research seeks to ameliorate the effects of corrosive or scale-forming chemicals that are often present in geothermal fluids. Methods to minimize the fouling of heat exchanger surfaces and blocking of wellbores by scale are especially important in geothermal energy systems. Effluent control technology is being developed where needed.

COST IMPACTS EXPECTED FROM IMPROVED HYDROTHERMAL TECHNOLOGY

The overall reduction in the cost of power expected from reaching the hydrothermal research objectives stated in Table A-2 is about 32 percent for the resource-weighted average across the eight cases in the hydrothermal cost-of-power model scenario. When various uncertainties in the technical analysis of the cost impacts of the objectives are considered, it is reasonable to predict that the overall cost impact will be on the order of a 25 to 35 percent reduction in the average cost of power from U.S. hydrothermal reservoirs that will be developed in the 1992 to 1997 period.

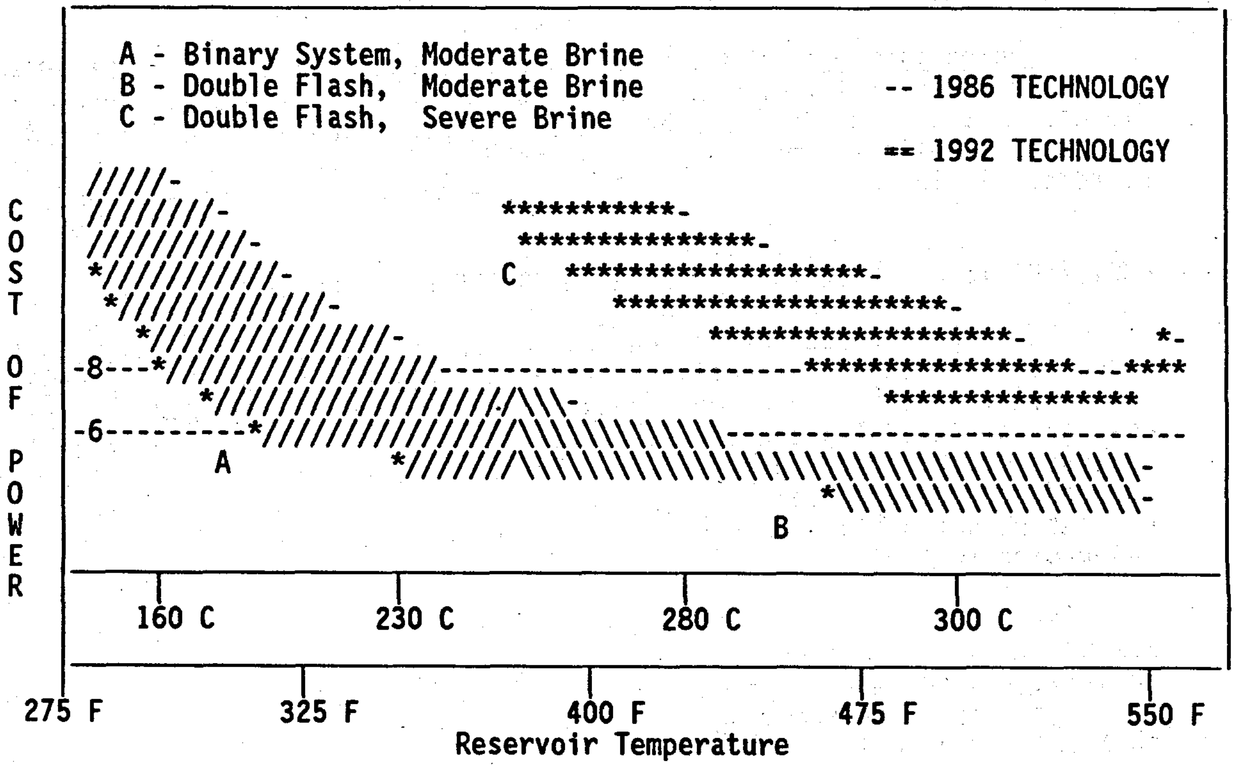
The largest cost reductions are anticipated to result from improvements in Resource Analysis technology and Drilling and Completion technology. The relatively high impacts projected from these two areas of research underscore the degree to which knowledge about the interactions of technology and the physical characteristics of a reservoir is a relatively new area of science and engineering. Power plant technology is comparatively mature, but significant economic gains are expected from the adaptation of supercritical cycle designs to binary power plants.

The expected busbar cost impacts of these improvements are shown in Figure A-3 for a range of temperatures. Cases A and B are premised on moderate brine-chemistry conditions, similar to those encountered in the Heber, California field (reservoir conditions as in Site-Case IV-BI in Table A-5, below). Case C is premised on severe brine conditions similar to those encountered at the Salton Sea, California field (Site-Case IV-FL in Table A-5). All costs of electricity discussed here are presented as busbar costs levelized in 1986 constant dollars.

Only those projects whose levelized busbar cost of power falls below 5.5 cents/kWh, the lower horizontal line in Figure A-3, would have been cost-competitive with a new coal-fired plant in the West in 1986. In 1997, costs of competitive electricity could be as high as 8.2 cents/kWh, the upper horizontal line in Figure A-3. (See the section on "Cost of Power from Competing Resources," below for background information.)

The least expensive liquid-dominated hydrothermal systems promise to deliver electricity at about 3 to 4 cents/kWh, which falls well within the

FIGURE A-3. COST IMPACTS OF HYDROTHERMAL OBJECTIVES, BY RESERVOIR TEMPERATURE



competitive range. Moreover, substantial fractions of the identified hydrothermal resources lie near the economic threshold (see Figure A-1). In this situation, every improvement in technology helps industry reduce costs, which brings more of the resource into the region of economic feasibility. This indicates the value of continuing to improve hydrothermal technologies.

With 1986 technology, the economic threshold requires a reservoir temperature of about 400°F. With 1992 technology that meets the goals in Table A-2, the economic threshold can be met at about 325°F.

Most of the hydrothermal reservoirs that will be brought into competitiveness by these improvements are lower-temperature reservoirs, which will employ improved binary technology. But, as shown for Case C in Figure A-3, significant cost reductions are also expected for flash plants at higher-temperature reservoirs with problematic brine conditions.

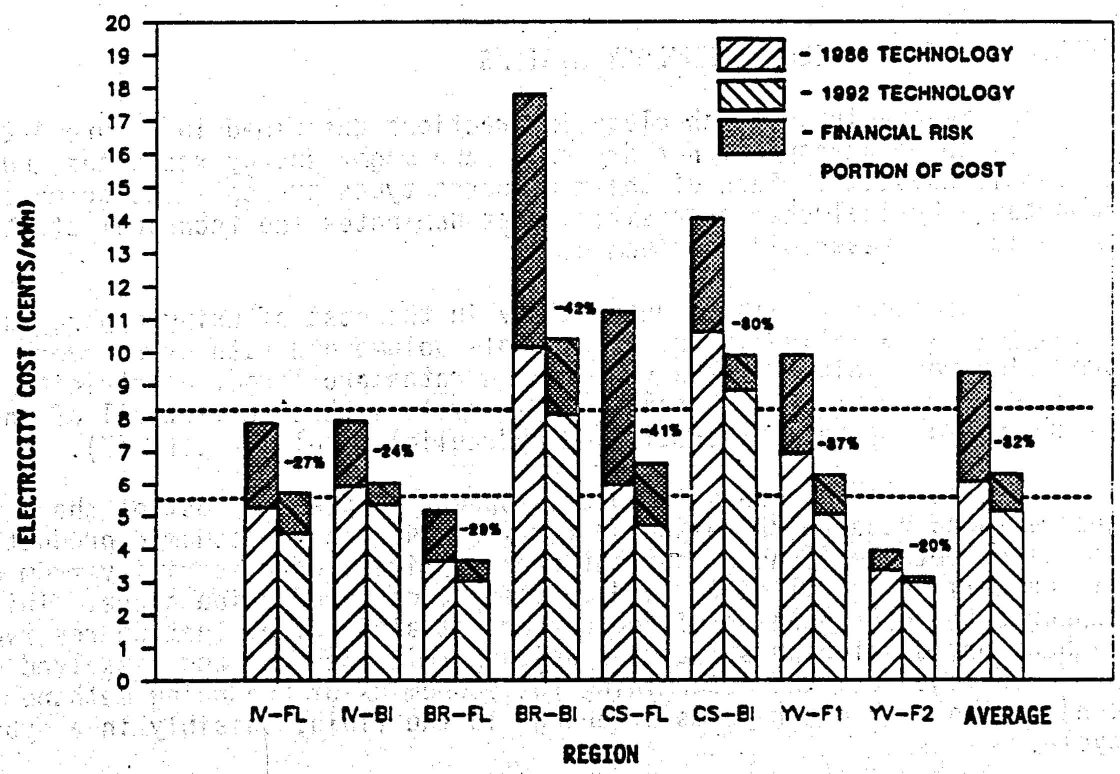
Region-specific estimates of the impacts of the research objectives are of interest because they portend the degree to which problematic conditions currently encountered in some regions will be ameliorated by the economic impacts of improved technology. The regions analyzed by the cost-of-power model are identified in Table A-3; the estimated region-specific cost impacts of the research objectives are shown in Figure A-4.

TABLE A-3. IDENTIFICATION OF ANALYZED REGIONS

IV-FL. Imperial Valley - Flash
IV-BI. Imperial Valley - Binary
BR-FL. Basin & Range - Flash
BR-BI. Basin & Range - Binary
CS-FL. Cascades - Flash
CS-BI. Cascades - Binary
YV-F1. Young Volcanics - Flash 1
YV-F2. Young Volcanics - Flash 2

"BI" denotes a binary plant design.
"FL", "F1", and "F2" all denote double-flash designs.

FIGURE A-4. COST IMPACTS OF HYDROTHERMAL OBJECTIVES, BY REGION



(The numbers show the estimated percentage cost reduction for each region due to 1992 technology compared to the 1986 technology baseline.)

It is noteworthy that six of the eight modeled regions will be brought within or below the band of cost competitiveness. Moreover, it is noticeable from Figure A-4 that the financial risk associated with such projects is expected to be substantially lowered, especially through reduced uncertainty about long-term reservoir performance. This is expected to reduce the cost of financing such projects.

The Basin and Range binary case and the Cascades binary case shown in Figure A-4, do not reach the price threshold even for 1992 technology. In those regions, scattered development is nonetheless expected at prospects where reservoir depths, and thus the cost per well, are less than those postulated for use in the cost-of-power model.

Most of the already discovered U.S. hydrothermal reservoirs that are technically feasible to develop for electricity production have fluid temperatures between 300 and 400^{o}F (see Figure A-1). Improved technology will open up most of these resources to economic use. Such improvements will produce economic benefits synergistic with those induced by discoveries of more moderate-temperature resources, which are anticipated from mid-term private-industry exploration efforts.

ECONOMICS OF ADVANCED TECHNOLOGY SYSTEMS

The reservoir and technology interactions described in Figure A-2 apply directly to geopressured, hot dry rock, and magma energy resources and production systems. Each of these resource types presents one or more important physical characterisitics that dominates the technical strategy and economics for reservoir development.

The greatest remaining uncertainty in the cost of using <u>geopressured resources</u> is variation in the recoverable volume and rate of recovery from the producing reservoir. If the volumes and rates are large, electricity could be produced for about 6 to 10 cents/kWh in systems that convert all of the energy in the fluid (methane, thermal, and hydraulic) to electricity (7).

Limitations in reservoir volumes appear to prevent most of the geopressured reservoirs tested so far from sustaining economic production of dissolved methane alone at current energy prices, or electricity from heat even if the well were drilled for and charged to gas production alone. This supports the continuation of the current strategy of evaluating reservoir drive mechanisms, developing strategies which permit free gas and dissolved gas to be produced together, and determining the economics of producing methane in conjunction with other forms of energy in the fluid, possibly in a hybrid power cycle.

The <u>hot dry rock</u> reservoir being developed at Fenton Hill, New Mexico, provides the technical foundations for power systems with a busbar cost that could be as low as about 6 cents/kWh (8,9), near the lower end of the competitive range. The costs at other sites will depend markedly on the well depth required to access rock of sufficient temperature. The economic attractiveness could fall off quickly after the reservoir depth exceeds 16,000 feet (5 km). Nevertheless, a substantial fraction of the technically recoverable resource base is expected to be economic. There is therefore continued justification for assessing the engineering economics of this resource type.

The technology for producing energy from <u>magma</u> bodies and its potential economic feasibility are not yet known, but are being explored in a preliminary manner through conceptual design and costing studies. The high-temperature reservoirs, 850-1,200°C (1,600-2,250°F), will produce high-quality energy which should result in high efficiencies. Preliminary cost analyses indicate electricity costs in initial magma energy projects in the year 2000 time frame might fall in the range of 10 to 20 cents per kWh (10).

COST OF POWER FROM COMPETING SOURCES

Estimates of the cost of power from technologies that compete with hydrothermal electric projects are shown in Table A-4. The estimates were supplied by the California Energy Commission in March 1988 for prices that would compete with geothermal when new supplies are needed in the 1990's.

Using data from the Electric Power Research Institute (3), the price of electricity from a new coal-fired plant in the West would have been about 5.5 cents/kWh if brought into service in 1986. This is used as the low estimate of competitive price in Figures A-3 and A-4.

TABLE A-4. COST-OF-POWER FROM COMPETING SOURCES

Technology	Price, Cents/kWH (a)
Coal	4.7 - 8.2
Nuclear	4.8 - 15.9
Oil (Steam Plant)	3.7 - 8.2

(a) Competitive price range for new electricity supplies in California. Prices are in 1986 constant dollars.

The data in Table A-4 suggest that the mid-1990's competitive costs of electricity could be as high as 8.2 cents/kWh. This is used as the high estimate of competitive price in Figures A-3 and A-4. The upper limit of competitive price in 1985 was about 6.7 cents/kWh (in 1986 dollars), e.g., for California PURPA Standard Offer Number 4 contracts.

HYDROTHERMAL ELECTRIC COST DETAILS

This section presents detailed information about the eight regional hydrothermal electric project site cases that form the basis for estimates presented above.

The data that define the major technical parameters for each of the eight sites in the model are shown in Table A-5 and Table A-6. Table A-5 lists reservoir properties and plant type. Table A-6 lists well drilling and completion costs. Other properties that are essentially the same for all sites include:

- Wildcat Drilling Success Rate = 0.20
- Reservoir Confirmation Success Rate = 0.60
- Dry Bulb Temperature, ^{o}F = 77
- Well Workover Cost, $1,000s = 25 to 55

Table A-7 shows estimates of the capital cost, O&M cost, and cost of electricity for the eight regional site-cases, assuming 1986 technology. Flash technology is usually most appropriate for high-temperature reservoirs and binary technology for moderate-temperature reservoirs. The estimates in Table A-7 show the large effects that varying levels of brine chemical constituents have upon both capital and O&M costs.

Table A-8 lists the financial and economics factors used in this analysis. The assumptions are for a "utility financing" case being used by the Office of Research and Technology Integration, Office of Renewable Technology, DOE to compare electricity costs among different types of renewable energy technology.

TABLE A-5. SITE-CASE DATA: PLANT TYPE AND RESERVOIR PROPERTIES

SITE CASE:	IV-FL	IV-BI	BR-FL	BR-BI	CS-FL	CS-BI	YV-F1	YV-F2
1. Plant Type: 1=Binary 2=Flash								
BASE:	2	1	2	1	2	1	2	2
2. Reservoir Saturated Temperature, Deg. F.								
BASE:	525	360	450	300	425	280	600(a)	550
UNCERT:	-25	-20	-50	-20	-50	-10	-25	-75
3. Non-Condensible Gases, Percent								
BASE:	0.5	0.1	0.1	0.2	0.1	0.1	0.2	0.1
UNCERT:	1.5	0.5	0.5	0.8	0.1	0.1	0.07	0.02
4. Hydrogen Sulfide, Parts per million								
BASE:	50	0	10	0	0	0	1500	50
UNCERT:	50	50	50	200	25	25	500	75
5. Total Dissolved Solids, Parts per thousand								
BASE:	250	5	1.5	1.2	1.0	0.5	15	10
UNCERT:	125	1	1.0	1.3	1.5	0.5	20	5
6. Well Depth, 1000 Feet								
BASE:	6	9	8	3	10	3	6	5
7. Producer Well Redrill (Side-Track) Fraction								
BASE:	.15	.10	.33	.20	.35	.20	.35	.20
UNCERT:	.05	.05	.07	.05	.10	.05	.10	.05
8. Dry Holes per Producer								
BASE:	.17	.17	.25	.17	.17	.17	.20	.14
UNCERT:	.03	.03	.08	.03	.33	.08	.13	.06
9. Yrs Between Workover, Producer								
BASE:	2.0	10.	15.	3.	10.	10.	7.	10.
UNCERT:	-1.5	-2.	-5.	-2.	-2.	-1.	-2.	-3.
10. Yrs Between Workover, Injector								
BASE:	2.0	10.	15.	3.	10.	10.	7.	10.
UNCERT:	-1.5	-2.	-5.	-2.	-2.	-1.	-2.	-3.
11. Producer Well Flow, Klb/hr								
BASE:	450	580	750	400	350	500	70	550
UNCERT:	-100	-130	-250	-50	-100	-50	-5	-100
12. Producer Flow Decline Coefficient, 1/Years								
BASE:	.002	.024	.020	.027	.020	.010	.036	.020
UNCERT:	.008	.006	.015	.011	.025	.010	.064	.010
13. Injector Well Flow, Klb/hr								
BASE:	1350	1160	2250	1200	700	1500	210	2200
UNCERT:	-450	-580	-750	-800	-175	-500	-70	-550

(a) Modeled as wellhead enthalpy of 900 BTU/lb.

TABLE A-6. SITE-CASE DATA: WELL DRILLING AND COMPLETION COSTS

SITE-CASE:	IV-FL	IV-BI	BR-FL	BR-BI	CS-FL	CS-BI	YV-F1	YV-F2
1. Base Cost of Well, $Million								
BASE:	1.123	0.956	1.217	0.556	2.032	0.576	2.038	0.906
2. Cost, Lost Circulation Problems, $Million								
BASE:	0.149	0.053	0.097	0.048	0.253	0.088	0.219	0.120
3. Cost, Cementing Problems, $Million								
BASE:	0.067	0.001	0.040	0.001	0.107	0.027	0.191	0.086
4. Cost, Other Problems, $Million								
BASE:	0.034	0.029	0.036	0.017	0.061	0.017	0.061	0.027
5. Cost to Extend 500 feet Downward, $Million								
BASE:	0.112	0.110	0.171	0.062	0.144	0.032	0.179	0.102
6. Cost to Sidetrack and Redrill Lower Third, $Million								
BASE:	0.247	0.210	0.268	0.122	0.447	0.127	0.448	0.199

TABLE A-7. ELECTRICITY COST ESTIMATES, 1986 TECHNOLOGY, BY REGION

SITE-CASE:	IV-FL	IV-BI	BR-FL	BR-BI	CS-FL	CS-BI	YV-F1	YV-F2
Capital, $ Million:								
Discovery	24.	24.	27.	15.	39.	16.	44.	21.
Field, Initial	73.	88.	52.	226.	224.	168.	143.	27.
Plant, Core	45.	105.	60.	207.	68.	204.	40.	51.
Plant, Auxil.(a)	24.	1.	4.	1.	4.	0.	10.	3.
Total, Capital	166.	218.	143.	449.	335.	388.	237.	102.
O&M, $ Million/Year:								
Field, Initial	3.8	1.3	0.6	6.6	0.9	2.6	0.8	0.6
Field, Makeup	0.0	0.5	0.5	3.1	3.9	0.2	8.2	0.2
Plant, Core	2.2	4.0	2.7	7.0	2.9	6.9	2.0	2.2
Plant, Auxil.(a)	4.8	0.0	0.2	0.0	0.2	0.0	1.0	0.6
Total, O&M	10.8	5.8	4.0	16.7	7.9	9.7	12.0	3.6
Cost of Power, Cent/kWH:								
Cost	7.8	7.9	5.2	17.9	11.2	14.0	9.9	3.9
Risk Portion	2.7	2.0	1.6	8.1	5.5	3.6	3.0	0.6

(a) Major equipment or O&M related to brine total dissolved solids handling, scaling, corrosion, hydrogen sulfide, other noncondensible gases.

TABLE A-8. FINANCIAL FACTORS USED IN ANALYSIS

FACTOR	VALUE
- Cost basis date and reporting year	1986.0
- Years to construct power plant	2.5
- Levelized annual Capacity Factor	0.80
- Adjust as-built costs	1
- Cost Basis: Overnight Construction	
- Cost Basis: AFDC not included in model costs	
- AFDC Ratio	1.081
- Financial Assumptions:	
- General inflation rate	0.06
- Discount rate; Weighted cost of capital	0.1249
- Book life of project, years	30
- Tax Life, years	15
- Investment Tax Credit Rate	0.00
- Property Tax & Insurance Rate	0.02
- Federal + State Income Tax Rate	0.38
- Accounting Method: Normalization	
- Depreciation Schedule: Double Declining Balance	
- Levelized Annual Capital Charge Rate (Includes Amortization, Income Taxes, Tax Incentives, Property Tax, General Property Insurance)	0.1683
- General Cost Levelization Factor	1.748
- Other Factors:	
- Royalty Rate	0.10
- Severance Tax	0.04
- Percent Depletion Allowance	0.15
- Intangible Fract. of Well Cost	0.75

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ABBREVIATIONS USED

BTU	-	British Thermal Unit (a measure of thermal energy)
°C	-	Temperature, Degrees Celsius
DOE	-	U.S. Department of Energy
°F	-	Temperature, Degrees Fahrenheit
GTD	-	Geothermal Technology Division, Department of Energy
KM	-	Kilometers
KW	-	Kilowatts
kWh	-	Kilowatt hours
MW	-	Megawatts, electric
MWe	-	Megawatts, electric
MWt	-	Megawatts, thermal
PPM	-	Parts per million by weight
Quad	-	Quadrillion British Thermal Units, about one seventy-fifth of U.S. annual consumption of all forms of primary energy.