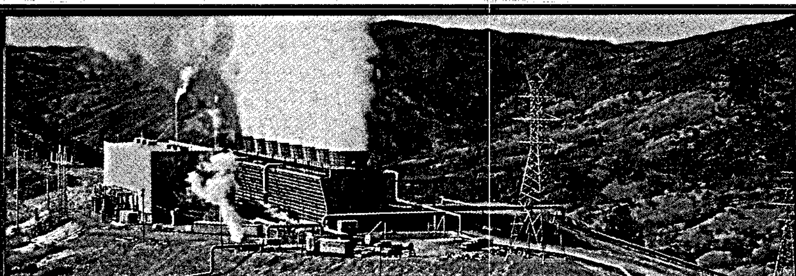
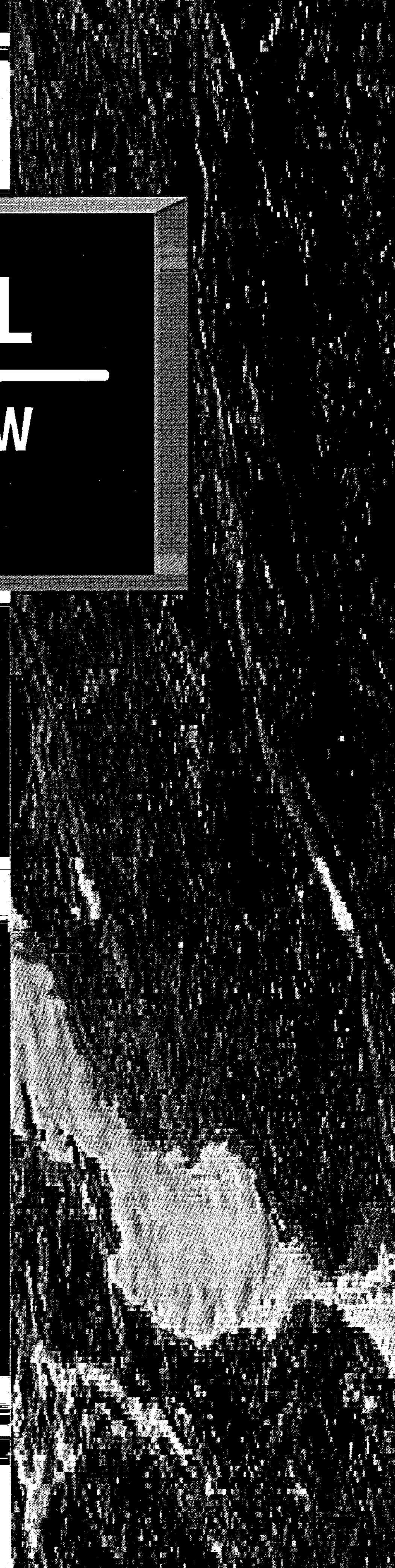
GEOTHERMAL

PROGRAM OVERVIEW
Fiscal Years 1993–1994





Geothermal Program Overview

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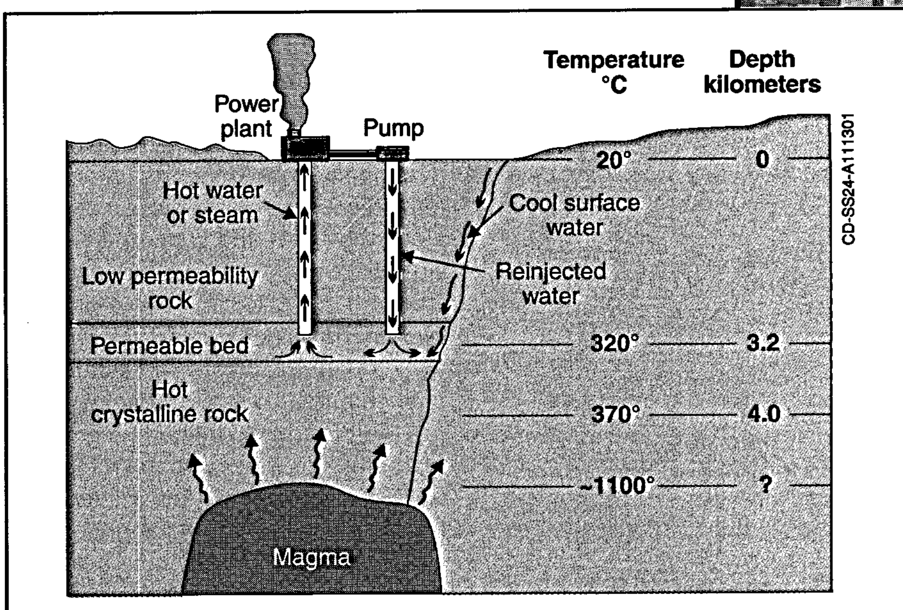
INTRODUCTION

The Geothermal Energy Resource

Geothermal energy—the heat of the earth—is one of the world's largest energy resources. In fact, geothermal energy represents the largest U.S. energy resource base and already provides an important contribution to our nation's energy needs. Geothermal energy systems offer clean, reliable, cost-effective energy for our nation's industries, utilities, businesses, and homes in the form of heat and electricity. The U.S. Department of Energy's (DOE's) Geothermal Energy Program sponsors research aimed at developing the science and technology necessary for tapping this resource more fully.

Geothermal energy originates from the earth's interior. The hottest fluids and rocks at accessible depths are associated with recent volcanic activity, particularly in the western states, Alaska, and Hawaii. In some places, heat comes to the surface as natural hot water or steam, sources that have been used since prehistoric times for cooking and bathing. Today, wells convey the heat from deep in the earth to electric generators, factories, farms, and homes.

All of these applications of geothermal energy draw on *hydrothermal* reservoirs, large pools of water trapped in the fissures and pores of underground rock and heated by the surrounding earth. These reservoirs are often fed by surface waters seeping through the ground, but they also may be fed by underground sources of water. The heat and pressure of the subterranean environment creates hot, pressurized water. Hydrothermal reservoirs are found from 100 meters (m) to several kilometers (km) below the earth's surface, and the temperature of the hydrothermal fluids can be as high as 400°C.



A typical hydrothermal system consists of hot water or steam trapped in a layer of permeable rock. Geothermal power plants draw the hot fluid from this underground reservoir, convert the heat to electricity, and then inject the cooler water back into the reservoir.

Another form of geothermal energy is *thermal capacity,* the ability of shallow ground at ambient temperature to serve as a reservoir of heat. Unlike other forms of geothermal energy, thermal capacity is found throughout the United States and the world. This thermal reservoir can be tapped efficiently with geothermal heat pumps, also known as ground-source heat pumps. Geothermal heat pumps operate on the same principles as the familiar air-source heat pump, but take advantage of the earth's relatively constant ground temperature as a heat source in winter and a heat sink in summer. Like air-source heat pumps, geothermal heat pumps are used to heat and cool homes and commercial buildings.

Hydrothermal resources and earth energy are the only forms of geothermal energy currently being used commercially. Three other forms of geothermal energy will require advanced geothermal technologies for their development:

- *Geopressured brines* are hot pressurized waters that contain dissolved methane and lie in large sedimentary basins at depths of about 3 km to more than 6 km. The best characterized geopressured reservoirs lie along the Texas and Louisiana Gulf Coast.

- *Hot dry rock* energy consists of relatively dry, impermeable rock at high temperatures. To use this energy, a reservoir is created by pumping high-pressure water into the rock, widening existing fissures. Water is then circulated through the underground fissures to extract the heat.

- *Magma* is molten or partially molten rock that reaches temperatures of nearly 1200°C. Some magma bodies are believed to exist at accessible depths within the earth's crust, although practical means of extracting magma energy have yet to be developed.

Geothermal Technologies—Putting the Resource to Work

Finding and Tapping the Resource

The first steps in using geothermal resources (other than earth energy) are locating a reservoir, determining its size and quality, and designing a strategy for developing it. The geosciences and drilling technologies are used in each of these steps and in every subsequent stage of development.

The geosciences—geology, geophysics, geochemistry, and hydrology—help identify subsurface properties and optimize well placement. For example, in hydrothermal reservoirs, geologic models define the reservoir geometry and physical properties; geochemical models analyze changes in the composition of reservoir fluids and rocks; and numerical simulations predict long-term behavior of temperature, pressure, and fluid flow under production conditions. Other types of geothermal resources have their own special geoscience requirements.

Initial subsurface assessments are followed by exploratory drilling, production testing, and actual production of the resource. The drilling equipment is similar to that used in oil and gas fields but with unique features to accommodate the need to drill through hard, hot rock containing chemically hostile fluids. Once a resource has been tapped, it can either be converted into electric power or used directly as a source of heat.

Power Generation

Power generation is an attractive use of geothermal energy because the U.S. power grid can carry geothermal power far from the resource to where it's needed most. One of three different energy conversion technologies can be used to convert geothermal energy to electric power, depending on the state of the resource (liquid or vapor), its temperature, and its chemistry:

- *Dry Steam*—Conventional turbine-generators are used with dry steam resources. The steam is routed directly to the turbines, eliminating the need for boilers and boiler fuel that characterizes conventional power plants.

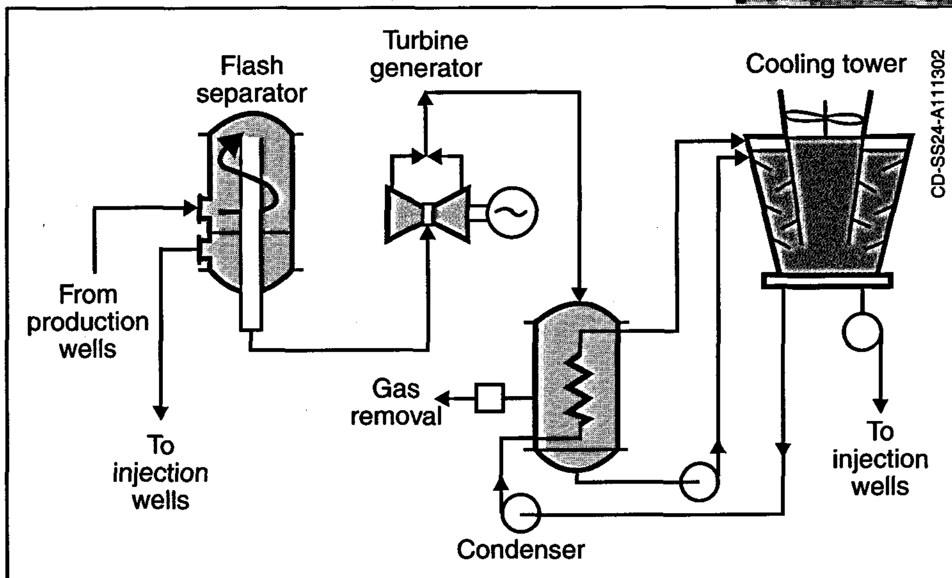
- *High-Temperature Fluid*—For hydrothermal fluids above 200°C, flash steam technology is usually employed. In these systems, the fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize or *flash* to steam, which is used to drive a turbine. Some liquid remains in the tank when the fluid is flashed to steam—*dual-flash* plants route this liquid to a second flash tank to extract more energy from the fluid.
- *Moderate-Temperature Fluids*—For fluids with temperatures less than 200°C, *binary cycle* technology is generally most cost effective. In these systems, the hot geothermal fluid vaporizes a secondary working fluid, which then drives a turbine.

In all cases, the turbine spins an electric generator that feeds power into the electric transmission system.

Dry steam resources are the easiest to develop, but they are rare. The only developed dry steam field in the United States is The Geysers in Northern California. The Geysers was the first source of geothermal power in the country and is now the largest single source of geothermal power in the world.

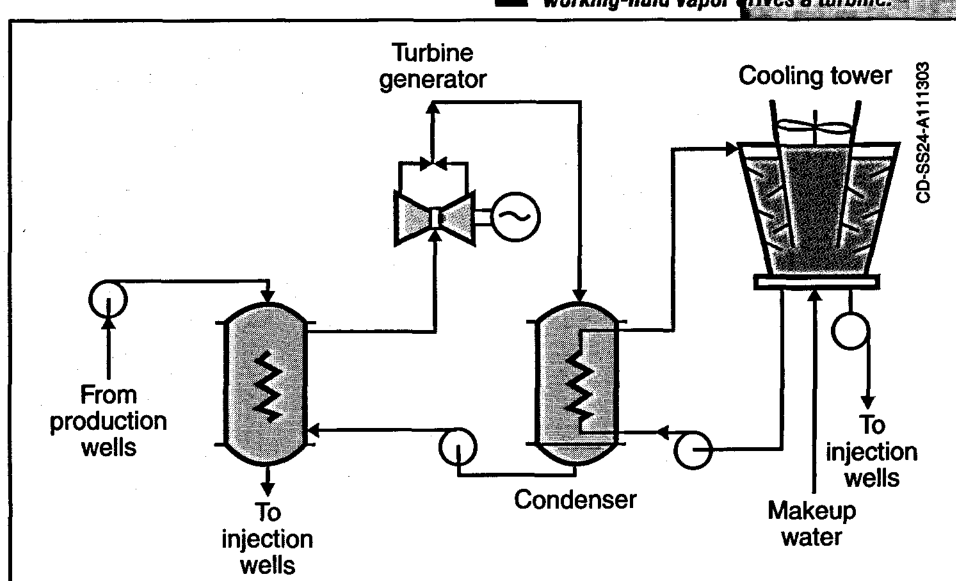
Hot water plants, using high- or moderate-temperature geothermal fluids, are a relatively recent development. However, hot water resources are much more common than dry steam. Hot water plants are now the major source of geothermal power in both the United States and the world.

Geothermal energy is a significant and growing source of power in the United States. In 1990, U.S. geothermal power plants generated 20 billion kWh of electricity, or about 7% of the electricity generated from renewable resources. DOE predicts that by 2030, geothermal electric power production could increase nearly tenfold, providing 184 billion kWh. Based on the same projections, by 2030 geothermal power will produce 25% of the electricity generated from renewable energy and 3% of the total U.S. electric power generation.



Flash-steam technology is used for high-temperature geothermal liquids. The geothermal liquid is flashed to steam, which drives a turbine.

Binary cycle technology is used for moderate-temperature geothermal liquids. The geothermal liquid vaporizes a working fluid in the heat exchanger, and the working-fluid vapor drives a turbine.



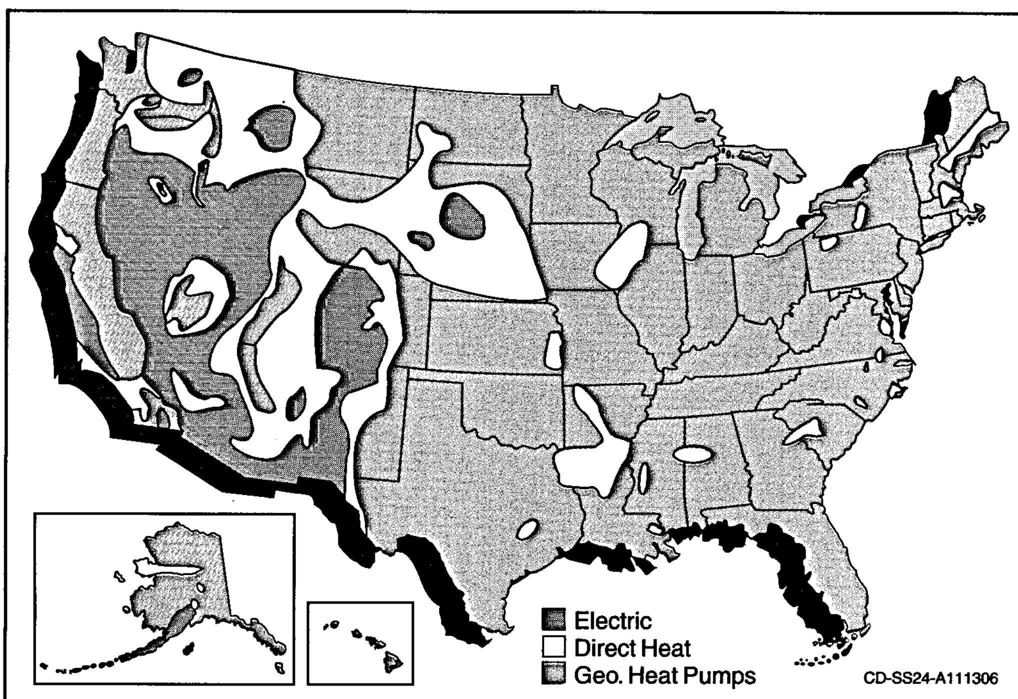
Direct Use

Geothermal resources at virtually all temperatures are suitable for direct-heating applications. The technology for direct use is drawn mainly from conventional hot-water and steam-handling equipment. For example, several communities use geothermal energy in *district heating* systems, which circulate hot water through pipes to homes or public buildings. In these systems, the geothermal production field (consisting of wells, pumps, and collection lines) replaces the boiler. Today, 21 geothermal district heating systems are operating in the United States. Geothermal energy also provides direct heat in commercial greenhouses, fish hatcheries, food-processing plants, and a variety of other applications.

These geothermal direct-use applications save energy while increasing U.S. energy independence. A 1994 survey found that these applications were using nearly 5.7 billion megajoules of geothermal energy each year—the energy equivalent of nearly 1 million barrels of oil.

Another direct-use application is geothermal heat pumps (GHPs). GHPs use 30% less energy than conventional heat pumps, which are dependent on widely fluctuating outside air temperatures. Because of their high efficiency, GHPs can cut annual heating costs by as much as 50% and cooling costs by as much as 25%. GHPs can be used at most places in the United States and have proven to be an ideal demand-side management tool for utilities.

GHPs have a great potential to enhance U.S. energy independence. In a recent report examining future U.S. energy supply options, the Energy Information Administration ranked the potential of GHPs second only to wood/biomass in dispersed applications. In 1991, U.S. energy use totaled approximately 86 x 10^{18} joules, or 86 exajoules (EJ). GHPs have the potential to supply 2.8 EJ by 2030, up from less than 0.1 EJ in 1991.



Geothermal resources include high-temperature hydrothermal resources for electricity production, low-temperature hydrothermal resources for direct use, and earth energy resources for geothermal heat pumps. Although hydrothermal resources exist primarily in the West, earth energy resources are found throughout the country.

The DOE Geothermal Energy Program

The Geothermal Energy Program is managed by the director of the Geothermal Division in DOE's Office of Energy Efficiency and Renewable Energy in Washington, D.C. The division provides central leadership to ensure that Geothermal Energy Program activities are consistent with national energy policy and priorities. The management of technical activities is decentralized among DOE field offices and national laboratories to ensure that technical expertise is available to supervise the research.

The Geothermal Energy Program has a tradition of working with industry to develop advanced technologies and commercialize research discoveries. Program managers interact regularly with the geothermal industry to set program priorities and establish cooperative research and technology transfer projects. Much of the cooperative work with industry is coordinated and funded by technology type in one of three cost-share organizations: the Geothermal Technology Organization, the Geothermal Drilling Organization, and the Geothermal Power Organization. These three cooperative organizations give priority to funding near-term development projects that address the most daunting barriers to future commercial development of geothermal energy, especially cost barriers and environmental concerns.

Barriers that currently elevate resource development costs and limit geothermal operations include the lack of truly effective exploration methods and technologies; the difficulty of drilling in hard, hot rock formations that are characteristic of geothermal reservoirs; and the high capital cost of energy conversion systems. Environmental concerns include groundwater consumption, hydrogen sulfide emissions, waste sludge disposal, and land subsidence. DOE/industry partnerships have developed methods for effectively addressing all of these issues.

The Mission of the Geothermal Division

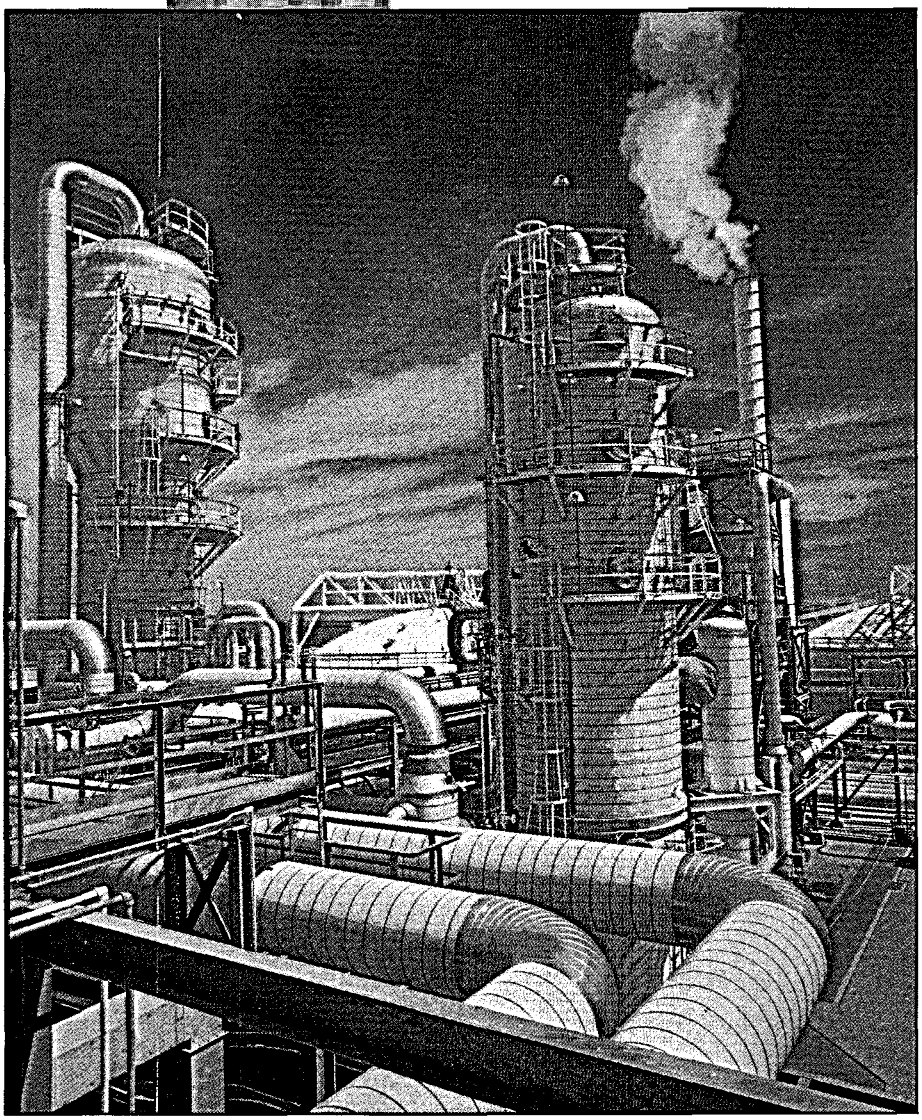
The Geothermal Division sponsors research and development in advanced technology, in partnership with U.S. industry and electric utilities, and transfers the results to industry. This reduces costs, enabling these firms to develop geothermal energy on competitive terms in energy markets worldwide.

Stakeholders with whom the program maintains close ties include electric utility companies, geothermal developers, a wide range of service and supply companies, researchers and others in the R&D community, public utility commissions and regulators, environmental advocates, and end-users. To ensure a vigorous and continuing exchange of information and opinion about the program, the Geothermal Division sponsors an annual program review during which the field offices, national laboratories, universities, and private contractors discuss the results of their work. This review is open; industry stakeholders and the general public are encouraged to attend. In addition, the participants in each program area (for instance, the drilling technology program) meet twice a year for program reviews to discuss their status and review plans.

The Vision of the Geothermal Energy Program

U.S. industry leads the world in making geothermal energy available at competitive prices worldwide.

Although it is focused primarily on hydrothermal electric power, the Geothermal Energy Program also includes geothermal energy direct use (including



PIX412

DOE research helped develop the technology to produce power from the concentrated brines in California's Imperial Valley. Now 15 commercial power plants are in operation there, providing more than 400 MW of electric generating capacity for southern California.

GHPs) and geothermal advanced technologies. Each of these programs has made impressive contributions toward the increased use of geothermal energy. However, despite substantial progress made since the early 1970s, geothermal energy remains handicapped by competition from inexpensive natural gas in the United States.

Hydrothermal Power Programs

When the federal Geothermal Energy Program was established in 1971, the United States had less than 200 megawatts electric (MW_e) of geothermal power in operation—all at The Geysers dry steam field in California—and the nation's first hot-water demonstration plant was 9 years in the future. Geothermal drilling costs were as much as four or five times those of oil and gas drilling, yet drilling was necessary to identify and characterize reservoirs in the absence of reliable geoscientific techniques. The chemically aggressive brines of some major reservoirs would corrode and erode turbine blades, plug injection wells, and deposit scale in wells, piping, and valves, impairing their operation.

Twenty-two years later, the successful teamwork of the Geothermal Energy Program and the geothermal industry has overcome many of these problems. Drilling, operating, and maintenance costs for hydrothermal fields decreased, while reliability greatly improved. These advances have resulted in a significant growth in the industry. In 1994, U.S. geothermal plants had a combined installed capacity of 2733 MW_e.

One example of this success is the cooperative research between government and industry performed at the Geothermal Loop Experimental Facility in the Imperial Valley of California. That research pioneered the practical use of a unique reservoir where fluids are eight times saltier than seawater. Six power plants in the Imperial Valley now depend on the crystallizer/clarifier technology developed at the experimental facility. The reservoir is estimated to have an ultimate capacity of 2000 MW_e.

Direct Use Programs

The direct use of geothermal fluids has a long history in this country. For instance, geothermal district heating, now a mature technology, was first used in Boise, Idaho, in 1892. Today, 21 geothermal district heating systems are operating in the United States. Other direct-use applications have also matured—small projects for greenhouse heating, fish farming, and industrial process heat are common throughout the West.

Although new applications for geothermal hot water are still being explored, this field is relatively low-technology by today's standards. The DOE Geothermal Energy Program is focused on identifying the location of geothermal resources for direct use and encouraging their development.

The Geothermal Energy Program supports the transfer of direct-use technologies to private and public sectors. In 1994, for example, the Oregon Institute of Technology, under contract to the Geothermal Energy Program, responded to several hundred requests for information and technical assistance related to direct-use geothermal systems. The Oregon Institute of Technology also worked with the State of New Mexico on the cost-shared construction of an aquaculture facility that uses spent geothermal fluid from a nearby geothermally heated greenhouse. Such cascaded direct-use applications have favorable economics while making greater use of the resource.

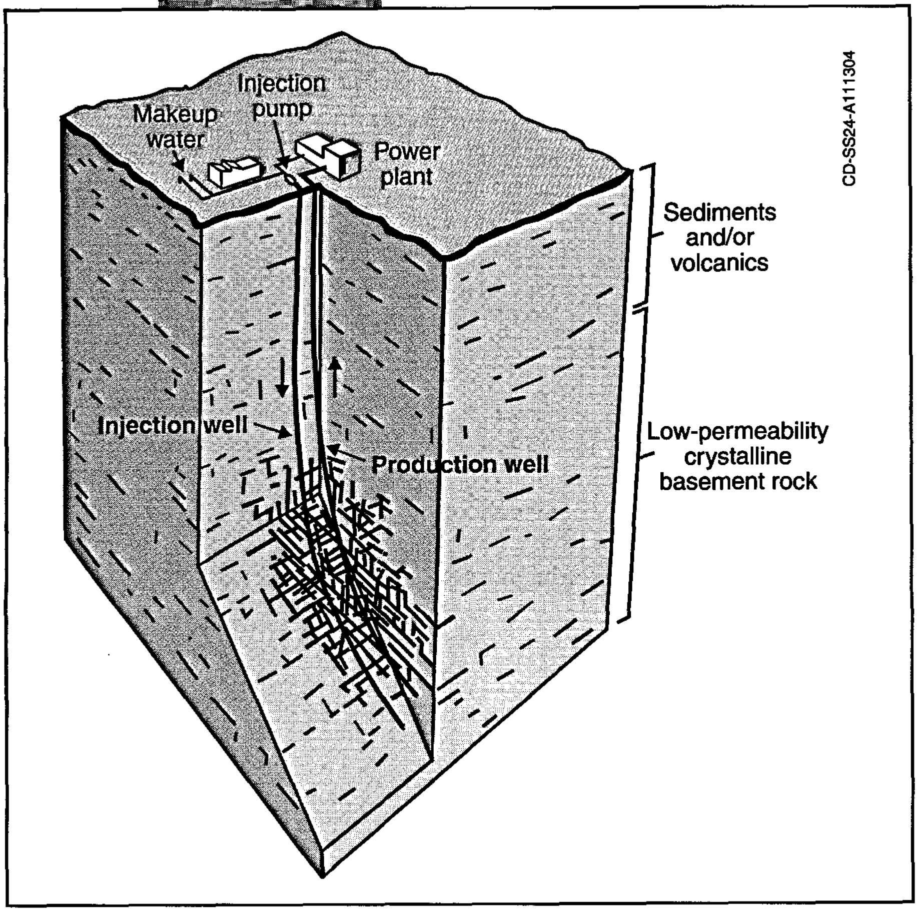
One relatively new direct-use technology is GHPs. Although GHPs are commercially available, efforts are still under way to enhance installation economics while improving performance. To document thermal performance of GHPs, Sandia National Laboratories installed an instrumented vertical ground loop.

In a parallel effort to encourage the growth of GHPs, DOE sponsored four teleconferences on geothermal heating and cooling. The first teleconference, in 1992, was designed for utility executives and state regulators. The second teleconference, in 1993, focused on sales and equipment design, selection, and installation for drilling and service contractors. The third teleconference, also held in 1993, was directed to architects and engineers, to inform them about how GHPs can reduce heating and cooling costs for their commercial clients. The fourth teleconference, in 1994, was targeted at school administrators to encourage them to specify the installation of GHPs in new schools or in older schools during retrofits. Each conference was viewed nationwide by an audience of more than 3000 professionals.

Advanced Technology Programs

The technologies for using the energy found in geopressured brines, hot dry rock, and magma, although less developed than those for hydrothermal energy, advanced significantly in the past 22 years. The near-term potential for economic power generation from these resources, however, appears to be limited. Consequently, the Geothermal Energy Program has scaled back its involvement in these areas to focus its industry-driven efforts on hydrothermal technologies. However, all three of these resources have the potential to yield vast amounts of energy for this country. Production from even a small fraction of any of these resources would greatly enhance the nation's domestic energy supply.

Technically, the most fully developed of these technologies is power generation from geopressured brines. Data obtained from geopressured test wells in Louisiana and Texas indicate that the energy source is large, usually saturated with methane, and can be developed with minimal



The hot dry rock process circulates water down an injection well and through man-made fissures in the rock, returning hot water for power production through the production well.

operational or environmental problems. Research has eliminated the problems of scaling and brine disposal, bringing the technology nearer to commercial application. A 1-MW_e demonstration hybrid power system at the Pleasant Bayou site in Texas proved the technical feasibility of power generation from both the heat and the methane of geopressured brines. The demonstration was concluded in FY 1992, ending DOE research in geopressured brines. Although DOE has developed a proven technology for recovering this resource, it is not competitive in today's energy markets. Geopressured reports are available from the National Technical Information Service.

The potential power production from domestic geopressured energy sources is estimated by the U.S. Geological Survey to be 23,000 MW_e–240,000 MW_e for 30 years. The current U.S. electric generating capacity totals about 700,000 MW_e. The methane content of the brines is estimated at 161 trillion m^3 (5700 trillion ft^3), by far the largest known natural gas resource.

Hot dry rock technology is somewhat less well developed. The basic technology for extracting heat has been proven on a small scale at a site in New Mexico called Fenton Hill. An economic analysis of hot dry rock technology, performed by the Massachusetts Institute of Technology during FY 1990, suggests that with lower drilling and well completion costs, hot dry rock technology might be economical. If so, hot dry rock could provide more than 2,300,000 MW_e for 200 years at a cost as low as $0.057 per kWh. DOE has solicited industrial partners to cost-share the development of a larger scale demonstration power plant to confirm the technology and establish economic parameters.

The geothermal resource farthest from commercial use is magma energy. The scientific feasibility of extracting energy from magma was proven by DOE experiments at a shallow, encrusted lava lake in Hawaii. However, the technology to locate subsurface magma chambers and economically extract energy from them has yet to be developed. The economic feasibility of magma energy will depend on the resource's accessibility, the costs and lifetimes of wells, and the effectiveness of various energy extraction techniques. DOE research on magma energy was deferred indefinitely in FY 1991.

Crustal magma bodies in the United States may contain as much as 530,000 EJ of thermal energy at temperatures in excess of 600°C and at depths less than 10 km. This is more than 6000 times greater than the total U.S. energy use in 1993.

Research Accomplishments for FY 1993 and FY 1994

Exploration Technology

Exploration is the starting point for all geothermal developments. Exploration may include geologic and geophysical surveying and mapping, geochemical studies of water and soil, and remote sensing using airplanes or satellites. Geophysical techniques typically include measurements of heat flow and thermal gradients; measurements of electrical resistivities, using sophisticated *magnetotelluric* techniques (low resistivities often indicate the presence of high-temperature liquids); measurements of natural voltage differences, or *self-potentials* (voltage anomalies may indicate geothermal flows); measurements of gravity (areas where the earth is more dense may indicate hot, intrusive rocks or underlying magma); magnetics (anomalies may indicate intrusive rocks or geothermal fluids); and seismics (to determine subsurface structures). Geochemical techniques yield a variety of data, including the temperature of the underground reservoir based on studies of geothermal spring water. These studies culminate in the drilling of exploratory wells at promising locations. Drilling is usually the most expensive part of the exploratory process.

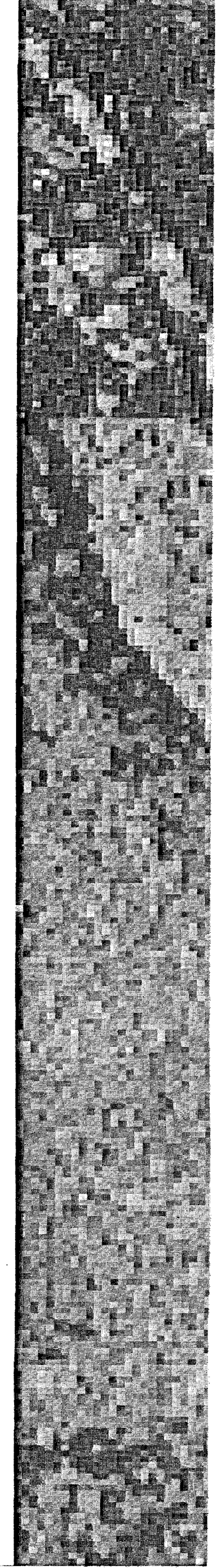
DOE exploration technology research provides better methods and techniques for the geothermal industry to discover and evaluate new geothermal resources. These new techniques are often tested and verified by performing a wide range of interrelated tests at known geothermal reservoirs. The battery of tests may include geological, geophysical, geochemical, hydrological, and reservoir engineering techniques. Comparing the results of the various tests helps create a complete understanding of the geothermal reservoir, and thus helps clarify the meaning of the results from new test techniques.

One goal of this research is to develop reliable techniques for locating geothermal reservoirs with no surface manifestations such as hot springs. This is particularly important in the Pacific Northwest, where surface and groundwaters may mask underlying geothermal reservoirs. Future geothermal development depends on locating such "hidden" resources, because most of the obvious resources have been developed.

The exploration technology programs also include resource assessments, which provide the basic groundwork for industry to draw on in developing exploration strategies. For instance, an assessment may find new geothermal hot springs in a certain region. Because hot springs indicate the presence of a geothermal reservoir, such a find may lead private industry to carry out detailed studies in that region.

Geophysical and Geochemical Technologies

Geophysical and geochemical tests are the bread and butter of geothermal exploration. Because the industry relies heavily on these techniques for evaluating geothermal reservoirs, reducing the costs and improving the accuracy of the techniques could have a dramatic effect on industry growth. Reduced costs encourage exploration in new regions, and improved accuracy encourages the development of resources that might otherwise have been considered too risky. Those benefits can



synergistically result in a greater development of the nation's geothermal resources.

Current geophysical research is focused on advanced electrical self-potential measurements, using finer grid spacing and better tools for data collection and interpretation; cross-borehole electrical measurements; and improved magnetotelluric measurements through better instruments and noise-reduction algorithms. In FY 1993, researchers performed several electrical self-potential field measurements using advanced techniques. Also, a first-generation cross-borehole field system was built and used to survey two boreholes in central Utah.

Geochemical tests have focused on the use of fluid inclusions in core drillings to determine the conditions of a geothermal reservoir at the time of its formation, when the fluid inclusions were first trapped in the rock. The original temperature, salinity, and carbon dioxide content of the included fluid can be determined and compared with today's conditions. This method has been used to determine a detailed evolutionary model for the Coso geothermal field in California,

The practical application of slimhole drilling for geothermal exploration was demonstrated in FY 1993 at the Steamboat geothermal field in Nevada. Six-inch diameter core samples such as these are now being compared to the known characteristics of the field to validate the slimhole techniques.


PIX1756

improving the predictions of the reservoir's long-term productive capacity. Researchers also verified that the fluid chemistry correlated favorably with the chemistry results from earlier well samplings.

Slimhole Drilling for Exploration

When used for oil and gas exploration, slimhole drilling—typically using bores only 8–10 centimeters in diameter—has reduced costs by 25%–75%. Similar cost savings may be realized for geothermal exploration, but the practical use of slimhole data for this purpose must first be demonstrated. In support of this goal, in FY 1993 a slimhole well was drilled at the Steamboat geothermal field in Nevada. The well was drilled to 1220 m and tested during and after drilling.

The Steamboat slimhole well lies in a developed geothermal field near a production well, allowing a direct comparison of the slimhole data to the known geothermal field characteristics. Thus far, the results are promising—in fact, the slimhole discovered a new fracture with commercial production potential. Researchers estimated that with moderate deepening of a nearby production well, the developer could double production from that well.

Data from the slimhole well include downhole pressure, temperature, and flow rate; surface wellhead temperature, pressure, and flow rate; injection flow rate; continuous core and lithology logs; temperature logs; and televiewer borehole images of the top 150 m.

Resource Assessment

The earth's heat flows to the surface at different rates in different locations, depending on the underlying geology. Knowledge of these heat flow rates can help explorers pinpoint possible geothermal resources. To encourage exploration in new areas, researchers compiled a data base for the contiguous 48 states that includes rock type, temperature gradients, and thermal conductivity. The data base is available in the form of maps.

A similar project for identifying low- and medium-temperature resources in 10 western states is now complete. Under DOE funding, the Oregon Institute of Technology's Geo-Heat Center and the University of Utah's Earth Sciences and Resources Institute worked with resource teams in each of the 10 states to review and update their geothermal resource inventories. This effort more than doubled the number of identified low-temperature resources in the states; some previously unknown high-temperature reservoirs were also discovered. A full analysis of the results is being published, and the resource data will be available in map form.

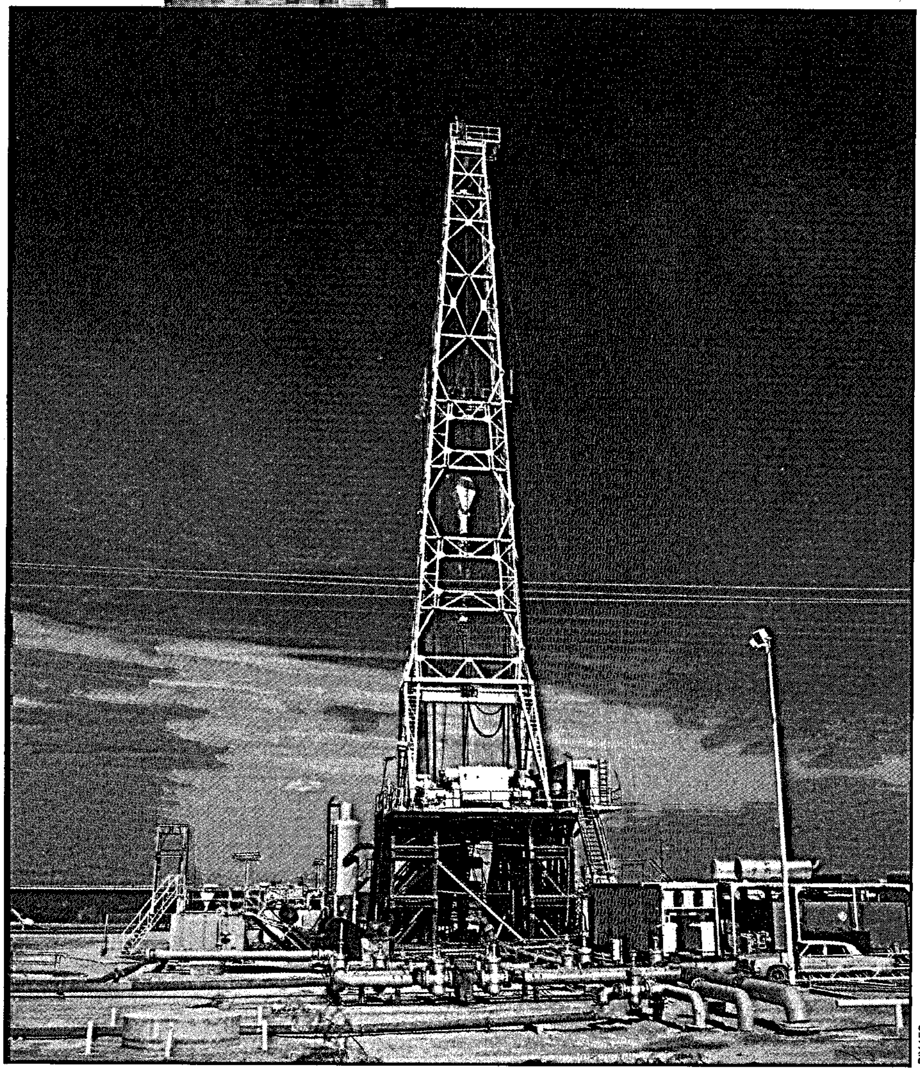
An assessment of high-temperature resources is being carried out in the Basin and Range Province, which spans California, Nevada, and Utah. This geologic province is believed to have many more geothermal resources than have been discovered thus far, and success in locating geothermal reservoirs will encourage future development in this area. To spur this development, DOE is participating in joint studies with industry at several productive geothermal fields in this province. The studies involve a variety of field tests to characterize these reservoirs. The test results will be used to develop advanced techniques for discovering new reservoirs in the Basin and Range. The intent is to eventually use these techniques throughout the region to generate a map that would indicate likely geothermal resources.

In other research, the hydrothermal resources associated with young silicic calderas—the craters left behind by the collapse or explosion of volcanos—are being explored in a DOE-funded exploration well in Long Valley, California. The well is providing significant information about the structure and history of the hydrothermal system there. The well reached 2300 m in FY 1992; in FY 1993 and FY 1994, researchers performed a number of experiments in the well to evaluate the effectiveness of new analytical tools and methods. Among these was a downhole seismometer that operated at a depth of 2010 m for more than 10 months.

Drilling Technology

Geothermal drilling technology is adapted from the oil and gas industries. To drill a well, a drill bit is mounted on the end of a long metal tube called a drill string. The entire drill string is turned to rotate the drill bit. New lengths of metal tubing are added to the top of the drill string as the drill goes deeper into the ground. To cool and lubricate the drill bit and carry away the bits of rock cut by it, a viscous fluid called drilling mud is pumped down the tube. The mud comes out through holes in the drill bit and flows back up the well in the space between the well wall and the drill string. A successful well is completed by lining the well (except in the area where the geothermal fluid is produced) with metal casings that are cemented in place.

DOE drilling technology research pursues the development of drilling and well completion technologies that considerably reduce the cost of geothermal wells. Geothermal drilling costs are high because of the hard rock, high temperatures, highly corrosive fluids, and problems with lost circulation—the loss



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The drilling of production wells, such as this one in southern California, results in one-third to one-half of the cost of a geothermal project. The DOE Geothermal Energy Program pursues the development of technologies that will considerably reduce the cost of drilling these wells.

of drilling muds into rock fractures that the well passes through. Because the cost of well field development can represent more than one-third the cost of a geothermal project, reductions in drilling costs are important for the expansion of the industry.

Lost Circulation Control

The most costly aspect of geothermal drilling is the loss of circulation in the drilling fluid system. Loss of circulation occurs when the drilling fluids flow into fractures or voids in the rock, rather than returning up through the borehole. Lost circulation episodes result in downtime and expensive corrective measures and can constitute 20%–30% of the cost of a well. They also can result in more severe problems, such as borehole instability or stuck drill strings, that can lead to the loss of the well. To reduce the costs of these problems, scientists are developing new techniques for identifying the locations and magnitudes of loss zones as soon as they are encountered. They are also developing new materials and techniques for controlling the loss of drilling mud.

One effort involves developing new, high-temperature, cementitious muds or cements that can be introduced through the drill pipe into the loss zones to plug them without removing the drill string. Eliminating the need to remove the drill string will greatly reduce downtime and aid in locating the fractured zones, resulting in considerable cost savings.

DOE has entered into an agreement with Halliburton Services and the California Energy Company to field test a cementitious mud formulation at a well in the Coso geothermal field in California. DOE will pay half the cost of the drilling test, and the two companies will split the remaining cost.

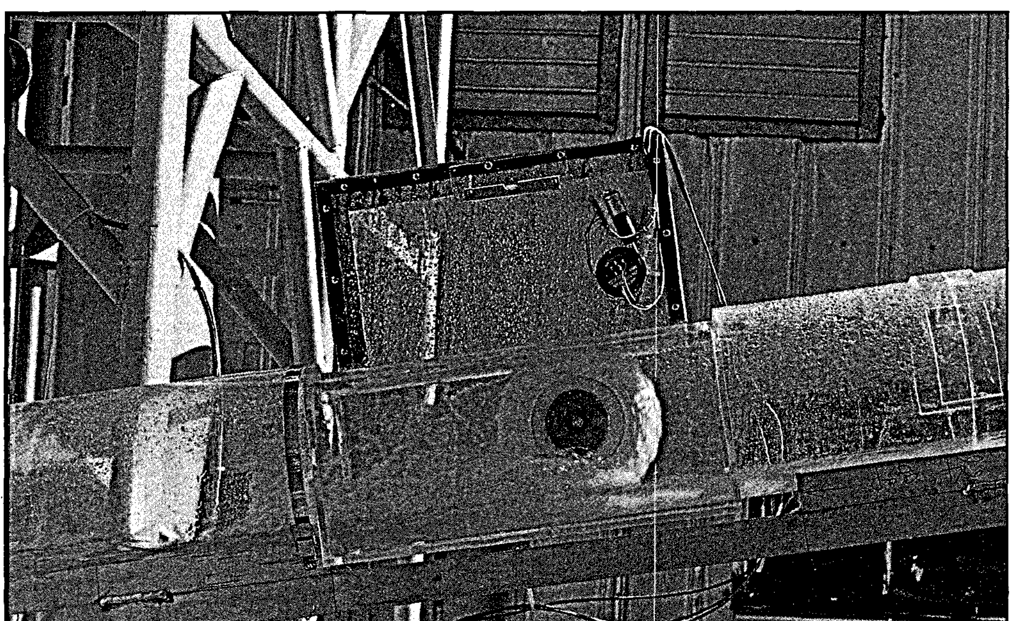
Early detection of lost circulation will help minimize the cost of responding to it. The key to early detection is accurate measurement of the rate of mud flow into and out of the well during drilling. A crucial step towards such accurate mud flow measurement was achieved in FY 1992, when a field test was successfully completed on a prototype flow meter that allowed real-time measurement of the rate of drilling fluid outflow from a well.

Since the field test, seven drilling service companies have tested the flow meter, and in FY 1993, one company expressed interest in marketing it to the drilling industry. But although the meter worked well in a number of tests, some of the drilling service companies seem unsure how to use the tool and interpret the results. Researchers at Sandia National Laboratories are now reviewing the field experience to determine how to address the concerns raised by the drilling companies.

As a complement to the rolling float meter, an acoustic doppler flow meter was evaluated for accurate measurement of the mud flow into the well during drilling. Acoustic doppler flow meters are non-intrusive devices involving transducers clamped to the outside of the pipe. Initial results in FY 1993 were accurate, but the instrument calibration tended to drift. In FY 1994, researchers found that drilling rig noise was causing the calibration drift. A manufacturer has since applied signal analysis to electronically eliminate the rig noise and correct the calibration problem; the manufacturer is expected to release a new model of the flow meter in the near future.

Researchers also successfully tested all components of the drillable straddle packer, an experimental tool for plugging lost circulation zones. They also completed the conceptual design and most of the construction of a Packer Demonstration Facility, which will allow full-scale testing under simulated downhole conditions. The facility was completed in early FY 1995, and a testing program was begun.

When lost circulation is encountered, drillers must determine the characteristics of the cause in order to select the most effective remedy. To measure the locations and sizes of fractures that are causing lost circulation, Sandia National Laboratories developed a borehole televiewer with the ability to measure the width of large fractures with an accuracy within 15%. In FY 1993, researchers field



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DOE research has led to new advances in drilling technology, such as this flow meter for measuring the rate of outflow of drilling fluid from a well. Seven drilling service companies have tested this flow meter and one has expressed interest in marketing it to the drilling industry.

tested the borehole televiewer at two boreholes in the Steamboat geothermal area in Nevada and at the Long Valley exploratory well. The televiewer was successfully tested in both slim and large boreholes, despite exposure to temperatures as high as 150°C.

Rock Penetration Mechanics

Research in rock penetration mechanics is directed toward reducing the costs of drilling and coring systems. At the heart of the drilling system is the drill bit. DOE is now working with eight drill bit and cutter companies to adapt synthetic diamond drill bits for use in hard-rock formations. In FY 1994, a variety of new and developmental drill bits were tested on a vertical milling machine that scraped cutters from the drill bits in a spiral pattern against the surface of a rock.

Although these tests provided valuable data on wear rates, researchers decided the test was not sufficiently representative of actual conditions. Consequently, a new test rig was constructed to more accurately simulate drilling conditions, with an instrumented cutter mounted on a drill bit that cuts into a rock while fluid is pumped through the bit. Testing on the new rig began in early FY 1995. Advanced synthetic diamond drill bits are expected to reduce the cost of a typical geothermal project by as much as 7%.

Another emphasis of the DOE program is improved measurement-while-drilling (MWD) systems, which are used to track the direction of the drill. Data is currently transmitted through pulses in the drilling mud. Previous studies indicated that telemetry by acoustical carrier waves within the drill string can improve data transmission rates 100-fold over mud-pulse telemetry, allowing access to comprehensive drilling parameters and rock formation data. A field test of a prototype system at the Long Valley well yielded promising results, but indicated the need for a facility to develop and test the telemetry system components. In FY 1993, this facility was assembled, and by the end of FY 1994, the facility had been extended to roughly 425 m (1400 feet) of drill string.

While research on the acoustic telemetry system continues, it has already attracted commercial interest. Sandia National Laboratories has signed a license agreement with Baker Hughes, the holding company for Baker Oil Tools, which has committed to spend more than $1 million to develop this acoustic telemetry concept. The company will develop a battery-powered tool to measure pressure and temperature in a production well, transmitting the data to the surface by acoustic telemetry. This will eliminate the costly use of cable lines for powering and gathering data from such in-hole tools. Baker Oil Tools expects to complete a prototype for testing in FY 1996.

Instrumentation

Better downhole instrumentation for gathering data will improve the quantity and quality of data used in exploration and reservoir analysis. The recent focus of this effort is on slimhole tools, which are compact devices that can be used in relatively inexpensive, small-diameter exploratory wells. A joint DOE/industry program to evaluate slimhole, temperature-resistant data-logging tools for reservoir evaluation was initiated in FY 1992. These tools measure well characteristics such as temperature and store the data rather than transmitting it to the surface, because cables used in the oil and gas industry to transmit downhole data to the surface cannot withstand the temperatures found in geothermal wells. When the data-logging tool is retrieved from the well, the data can be retrieved from the tool's computer memory.

In FY 1993, a slimhole data-logging tool was successfully field tested under a cost-shared program for slimhole reservoir testing at the Steamboat geothermal area. The tool successfully measured the temperature and pressure profiles of the borehole. Subsequently, in FY 1994, the tool was used extensively in Sulfur Banks #15, a slimhole at The Geysers (see "The Geysers," on page 18), and again performed well.

Researchers at Sandia National Laboratories also developed another slimhole data-logging tool that measures gamma ray emissions, which indicate the amounts of potassium, uranium, and thorium throughout the length of the borehole. Geologists use this information to surmise the types of geologic formations the borehole passes through. This tool was field tested for the first time at Sulfur Banks #15.

Geothermal Drilling Organization

The Geothermal Drilling Organization (GDO) provides a mechanism by which industry and DOE can work cooperatively on cost-shared projects for the development of drilling technology. Industry sets research priorities and shares more than 50% of the cost. DOE provides project management expertise and, in many cases, research facilities and staff. Participation of the end user in the research assures highly effective technology transfer. The GDO and its sister group, the Geothermal Technology Organization (GTO), frequently provide the test sites where new technology and methods are field-proven.

For example, GDO supported Unocal Corporation's commercialization of a high-temperature borehole televiewer developed at Sandia National Laboratories. During FY 1993, Unocal began commercial operation of the televiewer in Indonesia.

Another GDO project is the development of an improved rotary head seal for sealing the drill string. A-Z Grant/International designed such a seal in FY 1993. Other GDO projects now in progress include a downhole air-driven motor and a retrievable whipstock.

GDO also supports the field testing of cementitious muds at the Coso geothermal field (see "Lost Circulation Control," on page 12).

Reservoir Technology

For geothermal developers, understanding geothermal reservoirs is the key to managing the operation of their geothermal plants. This understanding is primarily gained by numerical modeling, studying operational data, core sampling, and tracer testing, in which a chemical tracer is injected into the reservoir. DOE reservoir technology research supports the U.S. geothermal industry by advancing the methods and technologies for exploration, development, and long-term operation of commercial geothermal fields. In FY 1989, the Reservoir Technology Research Task initiated a broad, continuing program of studies related to understanding and solving critical problems at The Geysers steam field. In cooperation with the geothermal industry, this DOE-funded research program has focused on optimizing water injection to recharge the reservoir and on understanding reservoir conditions, which control the flow of steam to production wells.

Reservoir Analysis

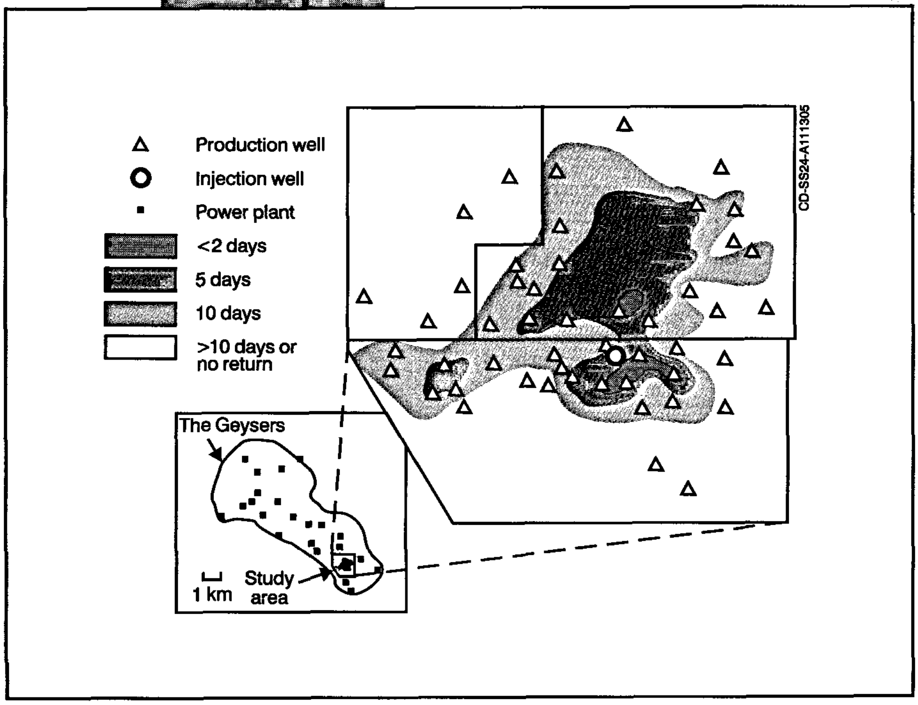
Reservoir analysis research emphasizes development of new analytical and interpretive methods for predicting reservoir performance. In FY 1993, researchers developed a more accurate model for simulating fluid flow in fractured reservoirs. This model allows better predictions of reservoir capacity and longevity. Related studies of two-phase flow through fractures found that the flow is prone to non-steady-state cycling, a finding that may lead to increased understanding of vapor-dominated reservoirs.

An essential element of this work is to make these arcane reservoir models available to the geothermal industry in a useful form. An important step toward that goal was taken in FY 1994, when Lawrence Berkeley National Laboratory adapted a reservoir model called TOUGH2 to run on IBM 486 computers or their equivalent. TOUGH2 is considered to be a research tool; the modified version, called TOUGH2-PC, is now accessible to geothermal industries with a relatively small investment in computer hardware. The model is available to interested parties in the geothermal industry.

Other research activities include the image analysis of reservoir core samples using electronic images. Image analysis allows more efficient collection and storage of core data as well as statistical analysis of the features. Scanning electron microscopy of core samples is also being used to examine the size and shape of pores.

International support of geothermal power production was continued through two projects: a recalibration of a numerical model of the Nesjavellir field in Iceland, and the development of a model to analyze the effects of large-scale injection at the Cerro Prieto geothermal field in Mexico.

Tracer injection tests help producers understand the fluid flow within geothermal reservoirs. The contours in this diagram represent the time required for a tracer chemical to spread outward from an injection well at The Geysers. These results are now being used to verify detailed numerical models of the reservoir.



Brine Injection

Commercial geothermal operations require the majority of produced fluids to be injected back into the reservoirs as a disposal technique and to support production by maintaining reservoir pressures. Research advances will optimize fluid injection and avoid cold water breakthrough to nearby production wells.

In FY 1993, researchers used field data from fluid injections at The Geysers to verify detailed numerical models of vapor-dominated systems. The models were able to predict the observed responses to fluid injections, and showed that the dispersion of injected water in heterogeneous fractures is an important component of the reservoir response. Researchers also continued the development and testing of new vapor-phase chemical tracers.

This work culminated in a large-scale injection test performed with joint funding from DOE, Unocal Corporation, and the Pacific Gas and Electric Company. DOE contributed $700,000 to the $2.5 million project, which started in FY 1994. The test was very successful: the reservoir has increased in pressure, allowing neighboring power plants to boost their power output by 2 MW–3 MW. Vapor-phase tracers were injected during the test, and production well data verified the flow of the tracers through the reservoir.

To support the analysis of such injection tests, Lawrence Berkeley National Laboratory researchers are developing a computer program that will allow simultaneous interpretations of pressure transient and chemical tracer tests. The program, which is a meld of two large existing computer programs, will be tested and verified in FY 1995.

Hot Dry Rock

In many ways, hot dry rock represents the ultimate in reservoir technology, because it involves the actual creation of a new underground reservoir. FY 1993 marked a high-point in hot dry rock research when a long-term flow test was completed at the Fenton Hill facility. Overall, water was circulated through the reservoir for a total of 8 months, including constant flow for two long periods—112 days and 65 days.

Water loss to the rock formation declined continuously to low levels (7%) as the test proceeded, indicating that the higher initial loss rates may have been caused by expansion of the reservoir. Multiple tracer tests confirmed this hypothesis. These results suggest that large quantities of makeup water may not be needed for long-term operation of hot dry rock plants.

Energy production was promising—on average, the flow yielded 6.3 times as much thermal energy as was needed to operate the facility. The reservoir showed no signs of depletion during the test—surface and downhole temperature measurements showed no loss in reservoir temperature. Many other useful operational parameters were also investigated during the test, including cyclic operation and back-pressure effects.

Although the test was successful, many operational parameters—such as operation with multiple injection wells—remain to be tested. DOE is seeking industrial partners to extend the tests and help commercialize hot dry technology. DOE has issued a solicitation for a cooperative agreement and expects to identify a winning proposal by the end of FY 1995. During the solicitation period, DOE will welcome any proposals from industry

A high point in hot dry rock research was achieved in FY 1993 with the completion of a long-term flow test at the Fenton Hill facility in New Mexico. To continue this development effort, DOE is now seeking proposals from industry for cost-shared field studies, either at Fenton Hill or at new locations.

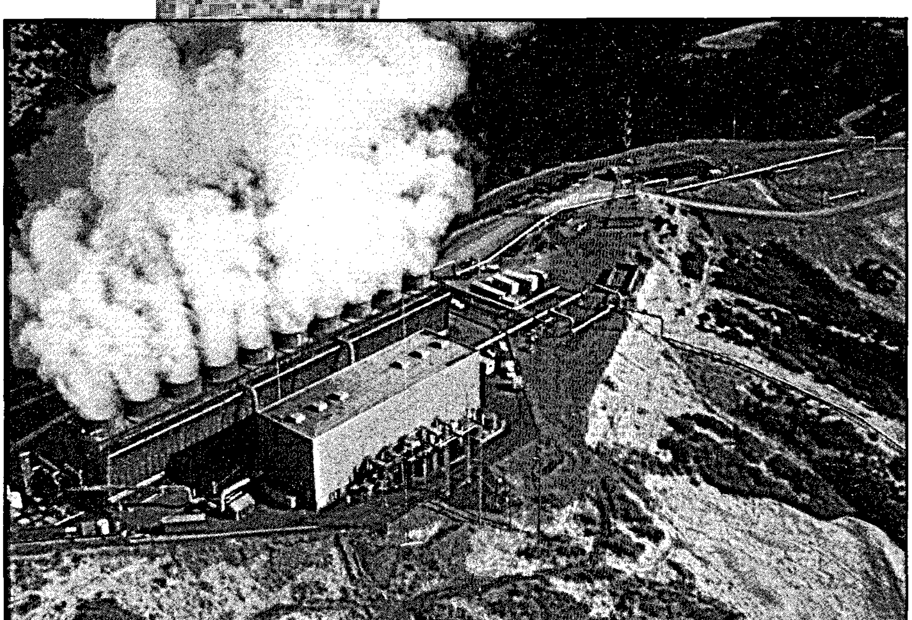
PIX1758

regarding the cost-shared construction of a prototype hot dry rock plant.

The Geysers

A broad program of studies related to critical problems at The Geysers steam field was initiated in FY 1989. In cooperation with the geothermal industry, this DOE-funded research program has focused on understanding reservoir conditions, which control the flow of steam to production wells, and on optimizing water injection to recharge the reservoir.

In FY 1993, Lawrence Berkeley National Laboratory furthered the understanding of The Geysers reservoir by studying the gas and isotope geochemistry of The Geysers' steam. These studies led to a new model for the origin of two distinct but connected reservoirs in the northwest and southeast regions of The Geysers. The reservoirs differ in depth, access to recharge water, and rock types. Further studies in FY 1994 proved definitively that the decline of steam pressure experienced at The Geysers was due to depletion of reservoir fluid and not to depletion of thermal energy.



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DOE research at The Geysers is assisting operators with their efforts to optimize the reinjection of water, which maintains reservoir pressure and helps replenish production wells.

FY 1994 saw the start of a project that will greatly advance the understanding of The Geysers reservoir. A slimhole core was drilled as a sidetrack of an existing well in the west central region of The Geysers, the Sulfur Banks #15 well. This well produced 237.6 m of continuous core samples of The Geysers reservoir, extending past the cap rock and into the uppermost part of the reservoir. This effort, funded jointly by DOE and Unocal Corporation, yielded a vast improvement over previous core samples, which totaled about 90 m, and none of which was continuous for more than 8 m.

Evaluation of the core samples is being performed by 28 collaborating investigators under the coordination of the University of Utah's Earth Sciences and Resources Institute. The samples will be exposed to a wide variety of tests to study rock types, morphology, porosity, vein minerals, chemistry of fluid inclusions, and many other parameters. Of special interest are several sealed core samples, which will be examined by CAT scan at the Lawrence Livermore Laboratory. Other samples, frozen in dry ice, will be examined by other investigators using magnetic resonance imaging. These tests should yield information about the pore network and how water is distributed throughout it. After these tests, fluid samples will be extracted from the sealed core samples to study the chemistry of the fluids.

With regard to optimizing the injection of water, studies in FY 1994 at The Geysers found that steam production is strongly sensitive to the injection rate, the degree of depletion of the reservoir when injection is initiated, and the permeability of the reservoir. These findings were put to practical use when injection began at a new injection well near Pacific Gas and Electric Company's Unit 13. Injection at this well began in FY 1993 and concluded in FY 1994; it was performed by Calpine Corporation with cost-sharing by DOE. The results were promising: the injection boosted power production from The Geysers by about 25 MW.

An extra benefit of this testing was the finding that in the high-temperature region of The Geysers, a reduction in vapor pressure has a significant effect on reservoir response to injection. This finding was incorporated into the latest version of the TETRAD reservoir simulation model, a computer program that is used by many operators at The Geysers.

Finally, as a long-term solution to the need for more injection water at The Geysers, Lake County, California, initiated the design of a pipeline to supply treated sewage water to the southeast region of The Geysers. The pipeline is expected to increase total power production at The Geysers by about 50 MW.

Geothermal Technology Organization

Geothermal Technology Organization (GTO) is a cooperative DOE/industry group formed to encourage technology development related to geothermal exploration, reservoir performance, and energy conversion. The organization supports projects that lead to commercialized products or services. Projects are jointly funded by DOE and participating industry partners, with industry providing at least 50% of the total cost.

In FY 1993, researchers at the Idaho National Engineering Laboratory analyzed historical seismic data collected at the Coso geothermal field. They also obtained improved seismic velocity profiles. These studies have enhanced the understanding of the Coso reservoir.

In late FY 1993, GTO initiated a long-term injection test at The Geysers. Chemical tracers are being used in conjunction with the injection test. The test has provided critical data about the behavior of injected fluids in The Geysers reservoir.

Energy Conversion Technology

Energy conversion is the process of converting the heat energy in geothermal fluid to electricity. As noted in the introduction, geothermal conversion technologies include dry steam plants, flash plants, and binary plants, all of which drive conventional electric power generators.

DOE research in energy conversion technology aims to increase the efficiency of geothermal power conversion systems by maximizing the amount of electricity generated for each unit of geothermal fluid produced; developing cost-effective, durable materials for handling hot brine, steam, cooling water, and binary fluids; and designing new methods for rejecting waste heat to further reduce operating costs. When combined with other new technologies, these improvements will contribute to the development of lower-temperature geothermal resources too costly to develop using today's technologies.

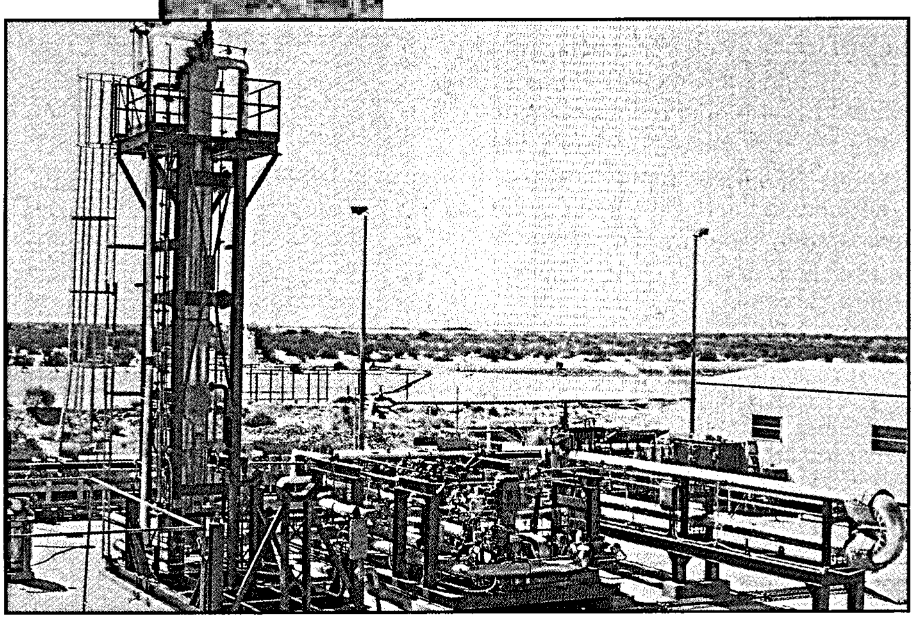
Heat Cycle Research

The current principal emphasis of heat cycle research is to improve the performance of binary cycle technology. Performance improvements will lower costs of generating electricity with binary processes and increase the use of the more abundant, lower-temperature reservoirs not suitable for flash steam technology.

Achievement of such improvements requires the use of advanced engineering tools and methods, which are being validated by tests at the DOE Heat Cycle Research Facility (HCRF) near Holtville, California.

During FY 1993, HCRF investigated the condensation behavior of simulated turbine expansions with reduced superheat. Although significant efficiency gains can be achieved by operating in supersaturated regimes, most operators conservatively avoid these conditions to prevent turbine damage. However, HCRF studies found that under certain conditions, equilibrium moisture levels of 6%–7% could be maintained without forming condensate in the turbine.

To continue this testing, an axial-flow impulse turbine was installed in late FY 1993, and a radial-inflow reaction turbine was installed in FY 1994. Each turbine was tested using both an isobutane working fluid and an isobutane/hexane working fluid mixture. Both turbines were operated in the supersaturated regime without forming condensate in the turbines and with no degradation in turbine performance. A full-scale test under actual plant conditions was completed at a commercial power plant in Mammoth, California, in FY 1995.



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The Heat Cycle Research Facility (HCRF) has been used to evaluate advanced binary power systems in California's Imperial Valley since the mid-1980s. Techniques proven at the HCRF could boost binary power plant performance by 20%.

Advanced Heat Rejection

Geothermal power plants typically use evaporative cooling to reject waste heat. However, evaporative cooling consumes water and can cause aesthetically unpleasing steam plumes. On the other hand, dry cooling, sometimes used in binary plants, is highly dependent on ambient air temperatures and is too costly for steam plants. Advanced heat rejection combines evaporative and dry cooling to optimize the benefits of both.

In FY 1993, a detailed computer model was used to simulate the performance of Pacific Gas and Electric's Unit 13 at The Geysers to determine an optimum configuration for advanced heat rejection. The model predicted a significant water savings with an average performance penalty of only a few percent.

Another problem with evaporative cooling is that some of the power plants at The Geysers have performed poorly, operating with high backpressures and venting steam along with their noncondensible gases. To remedy this problem, Pacific Gas and Electric Company is working under a Cooperative Research and Development Agreement (CRADA) with the National Renewable Energy Laboratory to investigate advanced direct-contact condenser designs. The advanced designs have the potential to boost plant performance by as much as 5% at low cost. The plans are to retrofit the existing condenser at The Geysers Unit 11 using an advanced design. The retrofit is planned for June 1996.

Materials Development

Because the performance, cost, and useful lifetime of materials are critical to the economics of hydrothermal systems, researchers continue to work on increasing the temperature and chemical tolerance of metallic and nonmetallic construction materials. An example is thermally conductive polymer concretes, developed as a new corrosion-resistant lining for heat exchangers exposed to corrosive brines. In FY 1994, polymer-concrete-lined tubes were field-tested for 60 days at a geothermal power plant. Preliminary results showed that the lined steel tubes performed similar to high-alloy stainless steel tubes, which are much more expensive.

Field tests of similar materials at The Geysers also showed positive results. Two polymer-cement-lined pipe tees and two polymer-coated well casing spool sections, all installed at The Geysers in 1992, were examined in April 1993 after more than a year of exposure. Only minor degradation and slight disbonding were found, so all the components were reinstalled for continued testing and remain in service. The locations where these test fixtures were installed had previously been subject to severe corrosion by hydrogen chloride.

A new field test was initiated at The Geysers in July 1994, when the Pacific Gas and Electric Company installed several cooling tower fins with high-temperature polymer coatings. The coatings were examined after two months and showed no degradation, so the testing will continue in FY 1995.

Meanwhile, Brookhaven National Laboratory started new laboratory tests in FY 1994 to improve the methods for casting liners inside small-diameter tubing. These tests will conclude in FY 1995.

Brookhaven National Laboratory has also developed new calcium phosphate cement formulations for lost circulation control. As discussed in "Lost Circulation Control," on page 12, the new formulations will undergo large-scale testing in early FY 1995.

Advanced Brine Chemistry

When the pressure and temperature of geothermal fluids are reduced during production and extraction, the chemical equilibrium of the fluid is disturbed, causing dissolved minerals to precipitate. These precipitates form scale, which builds up and restricts flow of fluids through the rock, as well as through the production tubing, distribution systems, and plant equipment. Advanced brine chemistry research enhances the understanding of this problem by gathering chemical thermodynamic data for the fluids, developing mathematical algorithms consistent with those data, and creating computer models that incorporate those mathematical algorithms.

One such computer model is the GEOTHERM brine chemistry model, now in use throughout the geothermal industry. For any brine composition under a wide variety of operating conditions, GEOTHERM predicts the sudden release of dissolved gases, called *gas breakout*, as well as the formation of scale. This allows plant operators to better control fluid temperature and pressure to avoid gas breakout and scale-forming conditions.

In FY 1993, researchers developed a highly accurate equation of state for the ammonia-water binary system. It has been incorporated in the GEOFLUID program, the part of the GEOTHERM model that predicts gas breakout. Studies also continued on aluminum speciation, aluminum hydroxide solubility, and the

This prototype bioremediation system at Brookhaven National Laboratory was completed in FY 1993. The system will be used to optimize a process that uses bacteria to remove heavy metals from geothermal solid wastes.

liquid-vapor distribution of HCl and isotopes of hydrogen and oxygen.

Advanced brine chemistry research also supports research on biochemical processes for remediating solid wastes from geothermal brines that contain heavy metals. Researchers have developed bacterial strains that can achieve fast rates of heavy metal removal (more than 80% in less than 25 hours) at 55°C. To advance this research, a prototype biochemical remediation system, capable of operating under highly acidic conditions and high temperatures, was completed in FY 1993. Testing of the prototype system began in FY 1993 and continued throughout FY 1994. The tests were extremely successful, removing 80%–90% of the heavy metals from geothermal solid wastes with a residence time of only 2–4 hours.

The successful test results led to the signing of a CRADA with CET Environmental Services, Inc., of Emeryville, California. CET is the waste-disposal contractor for Pacific Gas and Electric Company, the largest operator of geothermal plants at The Geysers. Under the CRADA, CET and DOE will share the cost of building and operating a test facility at The Geysers to demonstrate and evaluate the technology.

The pilot-plant test results also attracted the attention of geothermal industries at the Salton Sea geothermal field, and field tests are also planned there.

The Outcome

Geothermal energy is an environmentally benign energy source that makes a significant contribution to the nation's energy mix, supplying heat and electricity from hydrothermal resources. Today, these resources supply about 6% of all electricity used in California, and the growth of the industry in many areas is constrained only by competition from inexpensive natural gas. However, DOE research initiatives are still needed to improve the economics of the current geothermal technologies and to develop new methods and technologies.

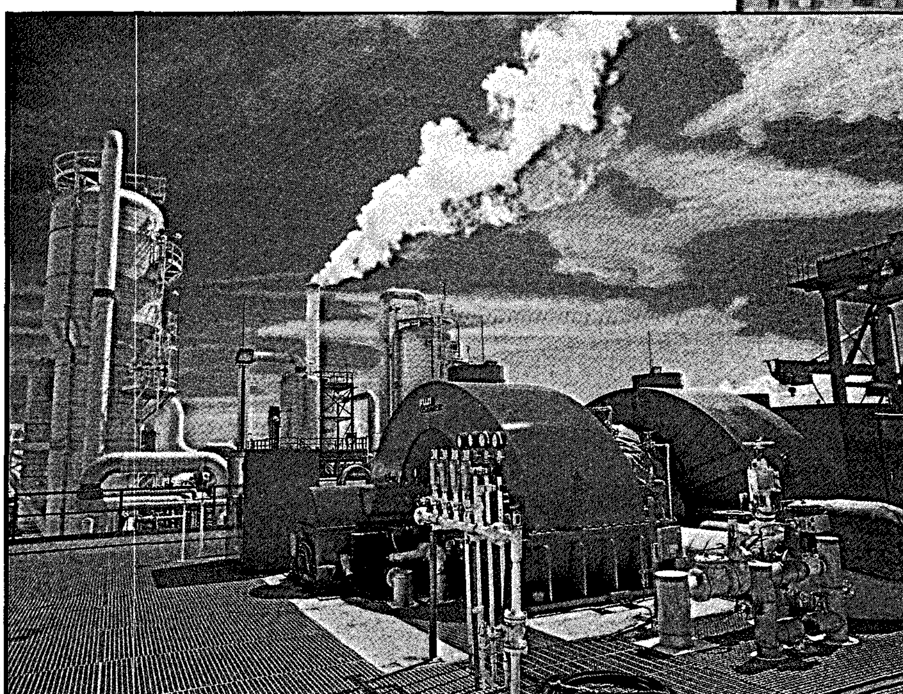
The successful outcome of these research initiatives will benefit our nation in several ways. First, geothermal energy offers a source of electricity that is environmentally benign. Today's hydrothermal power plants with modern emission controls are proven to have minimal environmental effects. Moreover, geothermal plants release little or no carbon dioxide, a greenhouse gas suspected of contributing to global warming. Experience so far with geopressured, hot dry rock, and magma resources suggests that they, too, can be operated with minimal environmental effects.

Second, geothermal energy offers a large source of secure, domestic energy to the U.S. energy supply portfolio. Moreover, geothermal plants can be brought on line quickly in case of a national energy emergency.

Third, geothermal energy is a highly reliable resource, resulting in high plant availability. For example, new dry steam plants at The Geysers are operable more than 99% of the time. In other words, geothermal plants offer an attractive alternative to fossil-fired or nuclear power plants for baseload power: they can operate 24 hours a day and are unaffected by daily or seasonal variations.

Finally, the U.S. geothermal industry is internationally competitive. Sales of geothermal technology enhance U.S. trade and stimulate the economy. DOE research helps keep the U.S. geothermal industry on the cutting edge of technology development, allowing the industry to remain competitive and profitable. This results in the creation of more jobs for our country.

The progress made by DOE's Geothermal Energy Program, working in cooperation



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The successful teamwork of the DOE Geothermal Energy Program and the geothermal industry has advanced the development of geothermal hot water reservoirs. The technologies employed at this flash-steam plant in California's Imperial Valley have helped geothermal hot water plants become the dominant source of geothermal power in the United States and the world.

with the U.S. geothermal industry and utilities, gives confidence that the geothermal resource continues on track toward fulfilling its tremendous promise. The program focuses on the technologies that have the best chance of success and that can make the biggest difference in developing cost-competitive geothermal systems. During the late 1990s, the Geothermal Energy Program will develop new technologies to allow geothermal energy to be used for broader applications nationwide, helping meet our nation's future energy needs.

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