GEOTHERMAL ENERGY

Heat emanating from within the earth is the major source of geothermal energy. This vast repository of energy is generated from the decay of natural radioisotopes (qv) and heat from the molten core of the earth. Energy from the core is transported to the earth's mantle by conduction, an extremely slow process because crystalline rock has very low thermal conductivity. Active volcanos provide evidence of the enormous amount of energy present deep within the earth. Geysers, fumaroles, and hot springs which are more benign than volcanos, also demonstrate geothermal energy brought to the surface through convection.

In certain circumstances such as volcanic activity and mountain building, large masses of molten rock may intrude into the mantle and even erupt to the surface. Where these conditions prevail, high geothermal energy levels can be found at relatively shallow depths. The rate at which the temperature of the earth increases with depth, the geothermal gradient, is not uniform. The average value of the geothermal gradient worldwide is 25–30°C/km, but it may be as much as 10 times greater in thermally active regions (1). In addition, the temperature of the earth does not always increase uniformly with depth. Factors such as rock type, porosity, fluid content, and the presence of aquifers may affect the local geothermal gradient. Scientists have estimated that one percent of the heat contained in the upper 10 km of the earth's surface exceeds the energy contained in all of the earth's oil and gas resources (2).

Natural sources of geothermal fluids for heating and bathing have been utilized since prehistoric times. In the 1800s and 1900s applications of hydrothermal resources expanded widely to include space and district heating, agriculture, aquaculture, industrial processing, and electric power generation (qv). Historically, this energy was utilized by diverting surface hot water or steam sources. As technology progressed, wells were drilled to tap geothermal fluids more efficiently; and improvements in drilling technology have enabled access to and recovery of deeper and hotter fluids. In addition, development of techniques to extract geothermal heat from rock in which no natural mobile fluids exist is under way in several countries.

The useful applications of hydrothermal resources depend on the temperature of the extracted fluid. Figure 1 shows the distribution of thermal energy in the United States as a function of temperature. It is clear that relatively low temperature fluids can be effectively applied for purposes such as greenhouse heating, fish farming, and especially space heating. Waters at higher temperatures

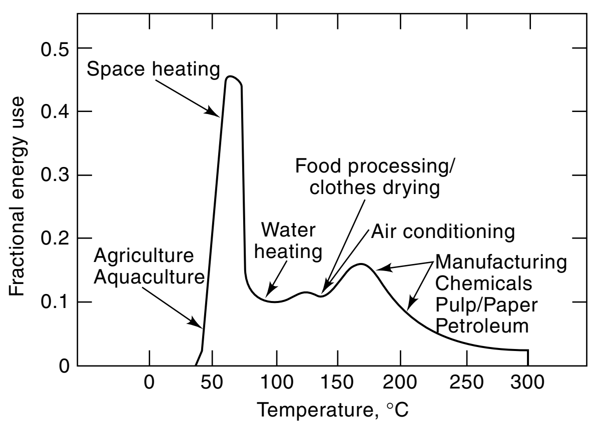

Fig. 1. Thermal energy use versus temperature (4). Electricity generation is practical from thermal energy sources hotter than 150°C.

can be used for a variety of industrial processes and the production of electrical energy. Direct uses of geothermal energy generally require that the point of application be near the source of the hot water. Transportation of hot fluid over more than a few kilometers is often economically impractical. The higher temperature resources can, however, be converted to electricity. It is then possible to apply the power generated by hydrothermal energy in a variety of ways and at distant locations. The efficiency of electrical generation is directly related to the thermal quality of the resource. Using the most advanced power generating equipment, it may be economical to generate electricity from geothermal waters at temperatures as low as 150°C (3).

To successfully compete with the multitude of energy sources available, geothermal energy must be available and retrievable in both a convenient and an economical manner. In most geothermal power developments, these conditions have been met using high grade geothermal resources in the form of hot water and steam but these particular hydrothermal resources are limited. USGS (United States Geological Survey) estimates a resource potential of 42,000 mw now available for the United States (5). Most of the world's potential geothermal energy is found in rock that is hot but either lacks permeability or fluid. Although research and development have demonstrated success in extracting thermal energy on a limited basis, the vast hot dry rock resource has not yet been shown to be an economically feasible source of energy on a scale large enough for practical use.

1. Geothermal Energy Resources

1.1. Type. Figure 2 is a generalized view of a cross section of the earth indicating the subsurface conditions for geothermal resources. The earth becomes progressively hotter with depth. In a hydrothermal resource, water has penetrated into faults, fissures, or porous regions of the hot rock. The water can be trapped there in the form of hot liquid under pressure or, much more infrequently, as steam (qv). In this manner, a reservoir of hot fluid is formed creating a hydrothermal resource. In some places these hydrothermal resources are visible in the form of hot springs, geysers, fumaroles, or similar geothermal features. In many cases hydrothermal resources have no surface manifestations. A few of these hidden hydrothermal reservoirs have been discovered accidentally during drilling for oil, gas, or water wells. From the standpoint of geothermal energy technology, the only important combined geothermal and fossil energy resource type consists of hot water reservoirs which contain significant amounts of methane under pressure. This combination is known as the geopressured resource.

Within the mantle of the earth, molten rock known as magma is found. Generally magma resources exist many kilometers below the earth's surface, far too deep to be accessed technologically. In a few places, however, magma bodies come close to or actually penetrate the surface of the earth. Volcanic activity is an example. In such instances, it is possible to consider the thermal energy of the relatively shallow magma body as a potentially exploitable geothermal resource.

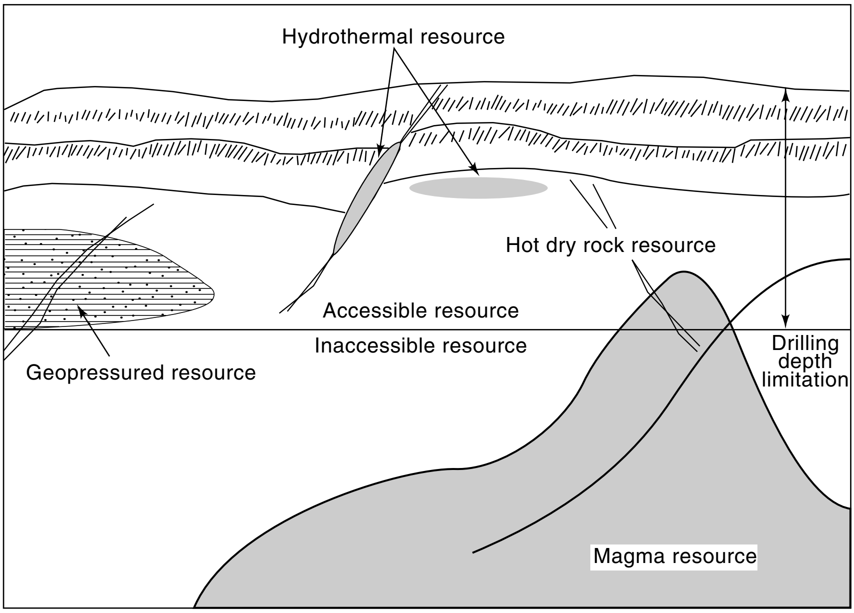

Fig. 2. Geothermal Reservoir (6).

1.2. Magnitude. Whereas the total amount of energy stored within the earth is extremely large, only a very small fraction of that energy is accessible, in part because drilling and energy extraction costs escalate rapidly with depth. Commercial drilling can reach depths of ~9000 m, so all of the thermal energy in the earth to that depth can be considered part of the geothermal resource base. This resource base has been estimated to be on the order of 1×10^7EJ (1×10^7quads where 1quad = 10^{15} BTU) in the United States alone (7). This is equivalent to $3 \times 10^7 m^3$ (182×10^6bbl) of oil. The total world consumption of energy in all forms is only ~300 EJ (300 quads); thus the earth's heat has the potential to supply all energy needs for the foreseeable future (8). Economic considerations, however, must be factored into a development scenario.

Resource type	Accessible energy, EJ
hydrothermal	130,000
geopressured	540,000
hot dry rock	10,000,000
magma	500,000
Total	*11,170,000*

2. Hydrothermal Resources

Hydrothermal resources are characterized by the presence of heat relatively close to the earth's surface coincident with adequate permiability and fluid content and provide a mechanism for its transfer to the surface. Hydrothermal

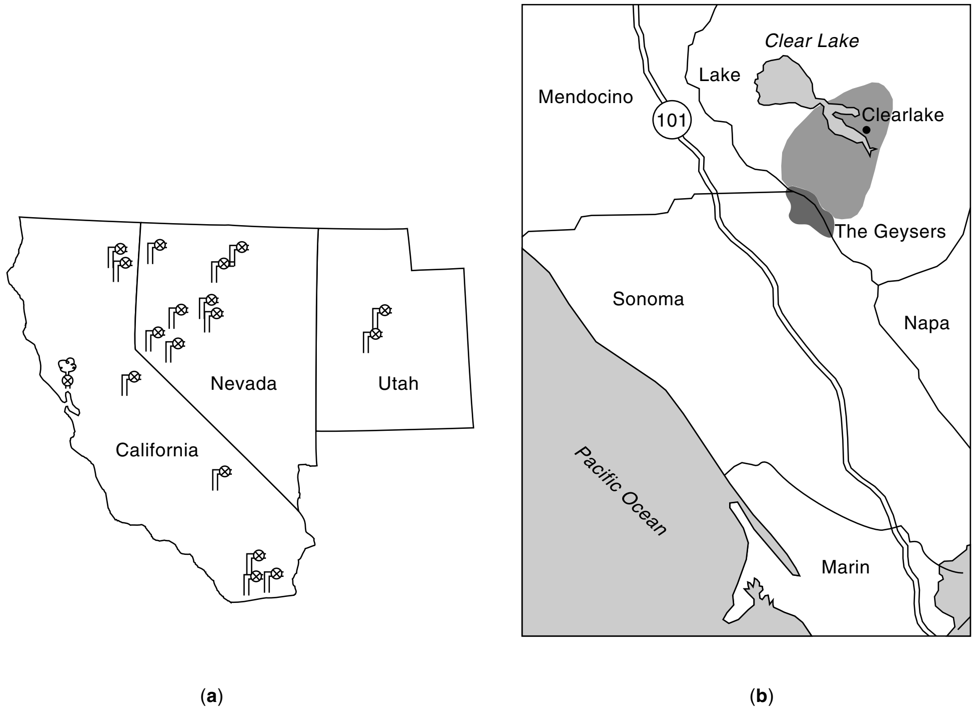

Fig. 3. Geothermal Energy Development (9).

resources occur throughout the world in regions where continental plates meet and the upwelling of magma and the earth's crust lead to rock temperatures that are higher than the worldwide average. Within these areas, the places where water is located in geologic formations are scattered and difficult to predict. Figure 3 is a map of geothermal power plant locations in the United States where geothermal resources of commercially useful magnitudes have been or are being developed. Most of these areas have been identified by surface exposure of the fluid resource.

Temperatures of hydrothermal reservoirs vary widely, from aquifers that are only slightly warmer than the ambient surface temperature to those that are 300°C and hotter. The lower temperature resources are much more common. The value of a resource for thermal applications increases directly with its temperature. In regions having hotter water more extensive use of geothermal resources has been implemented. Resources in remote areas often go unused unless hot enough to be employed in generating electricity.

2.1. Drilling Field Development. The techniques for drilling hydrothermal wells have been adapted from those in use in the oil, gas, and water well drilling industry (10) (see NATURAL; NOMENCLATURE IN THE PETROLEUM INDUSTRY). Rotary drilling rigs are normally employed along with conventional drilling equipment such as steel casing, drilling lubricants, and casing cements. Drilling conditions encountered in geothermal areas are more severe than those in oil fields, although, in geothermal resources, soft sedimentary rock of the type common in oil and gas basins is encountered. Usually it is necessary to bore through extremely hard metamorphic or igneous rock, resulting in a slower drilling rate. Penetration rates of 5–13 cm/s (10–25 ft/h) are common, but frequently problems such as loss of circulation, caving, twist-off, and high pressure and temperature zones related to the rock formation cause interruptions. In addition, the temperatures encountered in drilling into hydrothermal reservoirs are typically considerably higher than those for oil, gas, and water well drilling. Thus extra cooling procedures and special high temperature lubricant formulations must be employed. Moreover, geothermal drilling is subject to more stringent regulations than oil, gas, and water well drilling. The costs of drilling geothermal wells are from two to four times greater than those for conventional wells.

Hydrothermal drilling fluid, or mud, typically consists of a suspension of colloidal bentonite clay and high temperature additives in water. It is circulated through the wellbore to lubricate and cool the drill bit as well as to carry the cuttings to the surface. Because drilling mud is relatively expensive, it is continually treated and reused to minimize the total volume of fluid consumed. Commonly, the mud is stable to $\sim$150°C, but it tends to gel at higher temperatures as the clay particles flocculate. Stability of the muds at high temperatures can also be a problem. The incorporation of air to increase the surface area of the mud (aeration), active cooling at the surface, pressure control so that any flashing to steam can be confined to a specially designed separator, or combinations of these techniques may be used to alleviate problems related to high wellbore temperatures. Usually special high temperature sepiolite clays or synthetic polymers are substituted for bentonite, but these can significantly increase the unit cost of drilling muds. In steam-dominated hydrothermal reservoirs, it is desirable to substitute air for the water-based drilling fluid in the region of the steam production in order to prevent the fluid from plugging fractures through which the steam issues. Not only is the air a poorer lubricant, but the cuttings can cause rapid abrasive degradation of drill string components as they are brought to the surface in the high velocity air stream. Therefore, air drilling is avoided except in special circumstances.

A phenomenon known as lost circulation is particularly troublesome in hydrothermal well drilling. Lost circulation occurs when the drill bit penetrates an open fracture in the rock. The drilling fluid then tends to flow into the fracture rather than back to the surface for recirculation. In some cases, lost circulation is self-limiting as the drilling mud solids clog and seal the fracture, but often it can only be stopped by removing the drill string and plugging the leaky zone with cement. Such cementing operations are time-consuming, expensive, and not always successful. In drilling into or through a fluid-producing fracture, the lost circulation problem becomes one of keeping the fracture open rather than sealing it. The primary goal in this situation is to assure that the productivity of the wellbore is not impaired by drilling mud solids that become lodged in the productive conduits to the wellbore. This is accomplished by diluting the circulating fluid to reduce its solids content or by reverting to air or water cooling while the drill is passing through productive zones. Test bores are completedin many projects to predict the general locations of productive fractures. Geophysical surverys can also help predict potential fluid production zones ahead of drilling. Diagnostics while drilling (DWD) techniques are being researched to help predict fracture zones and productive horizons.

Geothermal cements are also employed to fix the steel wellbore casing in place and bind it to the surrounding rock (11). These are prepared as slurries of cement (qv) in water and pumped into place. Additional components such as silica flour, perlite, or polyurethane grouts are often substituted or added to modify the flow properties and temperature stability of the cement. A retarder is usually added to the mixture to assure that the cement does not set up prematurely. Cements must bond well to both steel and rock, be noncorrosive, and water impermeable after setting. In hydrothermal applications, temperature stability is critical. Temperature cycling of wellbores as a result of an intermittent production schedule can cause rupture of the cement if not properly formulated, leading to movement and potential failure of the wellbore casing.

Geophysical logging operations, in which drilling is temporarily suspended while instruments are lowered into the wellbore to make measurements, are very important in geothermal well drilling operations. The temperature, flow rate, pressure of any fluid and geologic information can be collected and used as the basis for further drilling decisions. Hydrothermal drilling is often carried out in rough mountainous areas and the terrain alone presents special problems in well and field development. Considerable costs can be incurred in preparing flat drilling pads; therefore, several wells may be directionally drilled from a single pad to reach different parts of the hydrothermal resource. Geothermal fluids have a low unit value relative to oil and gas; thus a geothermal well must be operated at a much higher flow rate to be profitable. This means that wells must be of greater diameter and flow rates must be considerably higher. Larger diameter wells are more expensive to drill and high flow rates can lead to increased rates of abrasion and more rapid deterioration of piping. In addition, hydrothermal fluids that contain significant amounts of dissolved solids or corrosive gases can rapidly degrade casing and piping. These effects can be mitigated by the use of pipe made from special steels or sometimes by adjusting operating conditions to minimize gas concentrations.

The geothermal drilling industry is much smaller than that of oil and gas drilling and the active geothermal rig count is generally fairly small. Thus, there is limited commercial basis for the development of specialized materials and equipment for geothermal drilling. For a number of years, the U.S. Department of Energy has sponsored the development of high temperature drilling components especially designed for geothermal operations (12). Efforts have been concentrated on lightweight, temperature-resistant cements, thermally conductive and scale-resistant protective liners, improved materials to control lost circulation, bonding agents, good drilling bits, and high temperature electronics.

2.2. Direct Uses of Hydrothermal Energy. Use of low temperature hydrothermal energy for direct thermal applications is widespread (13). The largest volume use of hydrothermal fluid is also one of the simplest. In regions such as some parts of the state of Wyoming, where hydrothermal fluids are found in close proximity to partially depleted oil fields, the hot hydrothermal fluid is pumped down oil wells at the perimeter of the field to heat the remaining oil. The resultant decrease in the viscosity of the remaining oil makes it flow much more readily through the formation and enough added oil can thereby be pumped to the surface to make the process economically viable. In some areas, hydrothermal energy is used to provide central heating for all or part of a community as in Boise, Idaho (14) and Kalamath Falls, Oregon. Hydrothermal energy is also employed to supply process heat for agriculture, primarily to heat greenhouses, and in aquaculture applications which involve warming the water in commercial ponds to enhance the growth rate of fish.

The application of geothermal energy in heating and cooling using heat pump technology results in 30–60% more efficiency than conventional electric heating and cooling systems.

Water sources for direct thermal uses range in temperature from <30 to $>90°C$. Resources in desirable locations can often be reached by simply drilling a few hundred feet into the earth. Hot water cannot be economically transported very far so most direct thermal uses of hydrothermal energy are tied to nearby hydrothermal resources.

2.3. Electric Power Generation. Hydrothermal steam and hot water resources having temperatures in excess of $\sim$150°C are generally suitable for the production of electricity (see Fig. 3). Because electricity is easy to market and transport, it is the major product of hydrothermal energy that permits the resource to be utilized at some distance from its actual location. There has however, been recent interest in using geothermal resources in the production of hydrogen.

Hydrothermal Steam: The Geysers. In a few cases, the hydrothermal resource exists in the form of pressurized dry steam (qv) rather than hot water. Only a few significant hydrothermal steam fields are known to exist (15), ie, the geysers area of California, Italy, Japan, and Indonesia. The first commercial production of electricity from hydrothermal energy occurred in 1927 using steam from a large field at Larderello in northern Italy. Commercial steam reservoirs have also been developed in Japan and Indonesia. In 1924 electricity production from hydrothermal energy was begun in the United States at The Geysers steam field in northern California. In 1990, The Geysers was responsible for well over 50% of geothermal electricity generation in the United States by producing over 2000 MW of power (16).

The Geysers. The Geysers steamfield, located $\sim$120 km (75 miles) northwest of San Francisco, is $\sim$50 km^2 (20 $miles^2$) in extent. It is in an extremely rugged portion of the coastal range. The altitude varies from $\sim$300 m to $>$ 1200 m and the terrain has northwest-to-southeast trending ridges enclosing rather steep valleys. Precipitation and temperatures vary widely. This geographical setting presents special problems for geothermal development. Drilling pads must often be bulldozed flat and landslides during the rainy season can destroy wellheads and piping if proper precautions are not taken.

The Geysers is at the southern end of the Geysers-Clearlake thermal anomaly, a region of some 700 km^2 (270 $miles^2$), which exhibits an extremely high heat flow (17). Numerous hot springs, mud pots, and fumaroles are found throughout the area. The source of the heat appears to be a large magma chamber centered $\sim$10 km under Mt. Hannah, a few kilometers northeast of the northern edge of The Geysers. The basement rock, a granitic or granodiorite felsite, is overlain with a highly fractured graywacke. The graywacke is covered in most places by a surface layer of greenstone, serpentinite of the Franciscan formation, or metamorphic melanges.

The steam at The Geysers, believed to arise from meteoric or formation water at great depth, is found in steeply angled fractures in the felsite and, more often, in highly interconnected random fractures in the graywacke. Many of the latter are oriented at low angles to the horizontal. Numerous wells have been drilled into the Clearlake volcanics. In a number of cases, either no fluid was found or only hot water was produced. Producing wells vary in depth from a few hundred to about 2400 m. Static steam pressure is typically a few MPa (a few hundred psi). A Geysers well may produce steam at a rate of several thousand kg/h at temperatures in the range of 250°C.

Electricity Production. Depending on steam conditions and conversion efficiency, each megawatt of electricity production requires from 100–200 kg (15,000–30,000 psi) of steam (18). There are several hundred producing wells in the field and steam reserves are estimated to be on the order of a few million kilograms per well. Electricity production at The Geysers expanded rapidly during the 1970s and 1980s and capacity peaked at nearly 2000 MW in 1988. Since that time, there has been a significant decline in the steam pressure at The Geysers and a concomitant reduction in the production of electricity. By the summer of 1992, electricity production from The Geysers had declined to only about 1220 MW and the area was troubled by significant idle generating capacity (19). Reinjection of treated waste water from Santa Rosa and Lake County initiated in 2001 has resulted in pressure increase and a return of power output to near pre 1990 levels.

A simplified schematic of an electricity generating plant using hydrothermal steam is shown in Figure 4. After the production of electricity, it is possible to condense and recover much of the fluid. Since the decline in the

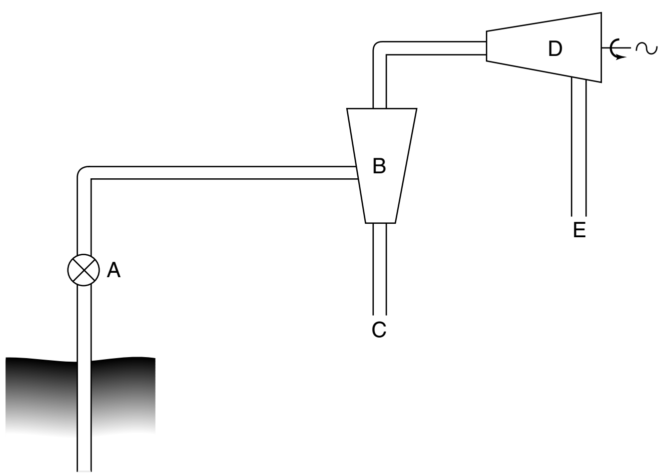

Fig. 4. Simplified schematic of a generating plant using hydrothermal steam (6). The steam simply issues from the well through a control valve, and passes through a preliminary separator, which removes particulates and any entrained liquid water. The steam drives a turbine. Then the spent fluid is reinjected through another well depending on site-specific circumstances.

Table 1. **Noncondensable Gas Contents of The Geysers Steam (20)**[a]

Location within steamfield	Composition, ppmwt								Steam:gas, mol ratio
	Total gas	CO_2	H_2O	CH_4	NH_3	N_2	H_2	Ar	
northwest	65,223	55,560	1,710	2,580	576	560	347		31
central–southwest	13,524	11,500	662	851	223	153	133	<2	133
southeast	982	734	116	43	30	46	12	1.0	1,724

[a] Ref. 20.

steam pressure at The Geysers, a more concerted effort has been made to reinject the condensate in order to recharge the hot rock from which the steam arises. Injection of condensate together with injection of treated waste water has resulted in pressure increases in the reservoir.

Geochemistry and Environmental Considerations. The geochemistry of steam-dominated geothermal resources is concerned primarily with condensable and noncondensable gases in the steam. The amounts and composition of noncondensable gases in The Geysers' steam vary rather widely within the steamfield as shown in Table 1. The predominant gas is carbon dioxide (qv) in all cases. The most important noncondensable gas, however, is hydrogen sulfide, because H_2S can present both corrosion and environmental problems.

Another gas of concern in The Geysers' steam is hydrogen chloride (qv), which forms hydrochloric acid in the presence of liquid water and therefore is extremely corrosive. Significant amounts of hydrogen chloride are found in very high temperature (>300°C) steam arising either from a fluid source rich in chloride salts or from steam coming in contact with halite (21). Lower temperature steam may originally contain significant amounts of moisture, which tends to dissolve and wash out the hydrogen chloride before the fluid enters the energy-production cycle. Extended operations may in fact lead to drying out of produced steam and thus to increased concentrations of hydrogen chloride over time. It was demonstrated at Larderello that water reinjected into the reservoir could be used to scrub hydrogen chloride from the steam production flow (22). Studies suggest that there is a positive correlation between the level of hydrogen chloride and the total noncondensable gas concentrations.

Water-Dominated Hydrothermal Resources. Hydrothermal resources in which the dominant or exclusive component is hot water are much more widespread than steam fields. Hot geothermal waters were first exploited to produce electricity in the Wairakei area of New Zealand in 1958. In the United States, electricity production from hot water did not begin until 1979. By 1992 water-dominated geothermal resources were being tapped to make electricity at a number of locations in California, Nevada, Utah, and Hawaii (Fig. 3). The Cascade Mountains of Oregon and Washington contain identified, but as yet undeveloped, hot water resources which may be suitable for the generation of electricity. The basin and range of Nevada and Utah have been developed with 500 MW being produced in Nevada and Utah. Other projects in Nevada, Utah, Idaho, and New Mexico are under development. Hot water fields exist at depths of a few hundred to 2400 m and deeper. Often the hot water contains large

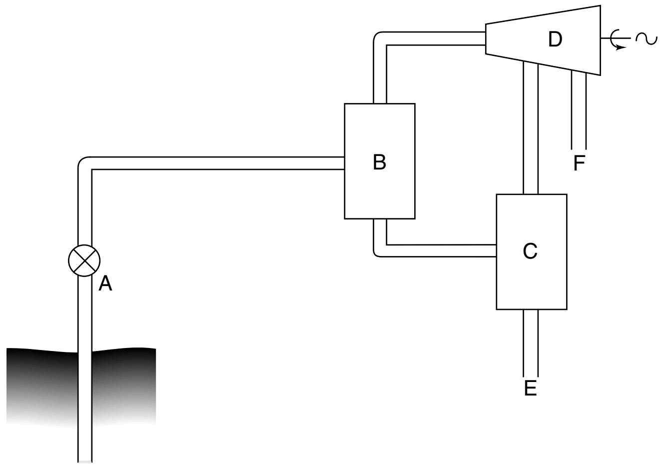

Fig. 5. A flash steam power plant for producing electricity from hydrothermal water (6).

amounts of dissolved solids. In the Salton Sea area of California, eg, fluids having dissolved solids levels in excess of 300,000 ppm (30%) are being commercially developed for electrical generation along with mineral extractions.

Several types of plants are in use for converting the energy in hot water resources into electricity (23). The simplest design is a single flash unit similar to that shown in Figures 4 and 5. The hot fluid is simply separated (flashed) into liquid and vapor fractions in a cyclone separator (B) in which the pressure is reduced. The vapor is then used to drive a turbine (D). The liquid fraction (C), which may contain high concentrations of dissolved solids, is typically disposed of by underground injection. This usually is beneficial in recharging the resevoir and maintaining reservoir pressure.

A second option is employed in double-flash generating plants. In a flash plant, liquid from the first flashing step (B) is fed to a second separator (C) at a lower pressure to produce more steam. The lower pressure steam from the second separation step is then admitted to the turbine (D) at an appropriate point to act as a booster. Although double-flash plants may recover 15–20% more energy, these plants are obviously more complex and costly to build and operate. In addition, the final fluid of a double-flash plant may be saturated or even supersaturated with solids, depending on the geothermal fluid, leading to extensive scale, corrosion control, and disposal concerns. The choice between a single- and double-flash plant depends on the characteristics of the resource and on capital investment considerations.

Another method, known as binary technology, utilizes two fluids to convert hydrothermal energy to electricity. In such an operation, it is possible to extract the energy from hot water without any vaporization of the hydrothermal water. Figure 6 shows a schematic of a binary plant. Heat from the geothermal water is transferred to a working fluid in a heat exchanger (B). The working fluid is thereby vaporized and drives a generator (D). It is then recondensed (E) and recirculated to be heated again by additional hydrothermal water. Typical

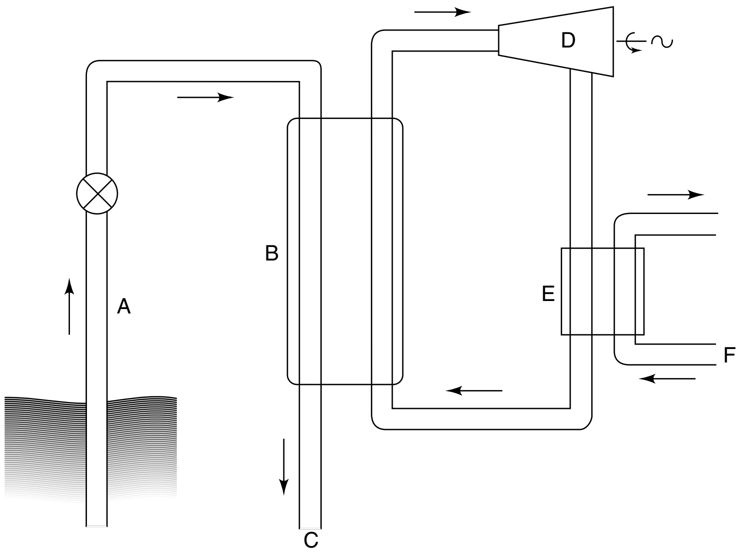

Fig. 6. In a binary electricity generation plant, the hydrothermal water from the well is passed through a heat exchanger where its thermal energy is transferred to a second, more volatile working fluid. The second fluid is vaporized and delivered to a turbine. After exiting the turbine the spent working fluid is cooled and recondensed in another heat exchanger, using water or air as the coolant. It is then fed back to the primary heat exchanger to repeat the cycle. Spent hydrothermal fluid can be reinjected into the producing field (6).

working fluids are very volatile, low molecular weight hydrocarbons such as isobutane, isopontane, or fluorinated hydrocarbons (see HEAT-EXCHANGE TECHNOLOGY, NONAQUEOUS HEAT-TRANSFER MEDIA). Binary power generators range from <1 to 5 MW in capacity and are usually employed as ganged units in multimegawatt geothermal power stations.

Single-flash, double-flash, and binary generating plants are all being used in the United States to produce energy from liquid-dominated hydrothermal resources. A fourth type of power plant, which is really a sophisticated version of a binary system, is being evaluated. In this last design, often referred to as the Kalina cycle, the working fluid is an adjustable proportion fluid mixture, most often consisting of water and ammonia (24).

The production of electricity from hot-water resources is expanding in the United States, but the individual production plant sizes are often small, ranging from 1 to 50 MW. These systems can be highly automated so that little daily labor is needed. Plant availability is also generally very high, on the order of 95% or greater. The utilization of hot-water resources in the United States is expected to grow in response to an increasing need for small-to-moderate increments of clean power in the American West.

Most of the developed geothermal fields are located by significant surface indications, particularly in the form of hot springs or recent volcanic activity. Once a resource has been identified, a variety of techniques can be used to map the system and determine whether it is of a size sufficient to justify commercial development. Hidden geothermal resources are much more difficult to locate, but geologic indicators such as high heat flow and evidence of hydrothermal alteration can be used. New technology in geophysics and remote sensing are being developed to locate and evaluate geothermal systems.

2.4. Worldwide Hydrothermal Development. Electric generation capacity from hydrothermal energy outside the United States was more than 8000 MW in 21 countries by 2000 (25). Hydrothermal resources have been especially well developed in countries on the Pacific rim. Nearly 1908 MW are on line in the Philippines, 748 MW in Indonesia, 853 MW in Mexico (26), 436 MW in New Zealand, 405 MW in Central America and 533 MW in Japan (27). Lesser amounts of hydrothermal electric capacity have been installed or planned in El Salvador (161 MW), Costa Rica (143 MW), Nicaragua (70 MW), Guatemala (29 MW), Africa (63 MW) (28), and a number of other developing nations. Italy, which has 545 MW at Larderello, is the chief producer of hydrothermal-based electric power in Europe. The small island nation of Iceland generates 170 MW of electric power from geothermal energy and has perhaps the most extensive direct-use applications of geothermal waters of any nation in the world. (The capital city of Iceland is completely heated by geothermal and a large percent of the country uses geothermal heat.) Electricity generation from hydrothermal resources is rapidly increasing in a number of developing countries. The relatively simple engineering, straightforward components, and ease of repair of hydrothermal plants make these plants ideal for application in nations with unsophisticated economies.

2.5. Economics. In the early 1990s, the cost of electricity generated from geothermal energy varied from ~3.5 to 10¢/kWh (29). The cheapest electricity came from The Geysers, where steam can be delivered to the power plant for less than 2¢/kWh of electricity generating potential (30). Electricity costs from hot-water resources using flashed steam and binary plants, respectively, are progressively higher ranging from 5 to 8¢/kWh in 2000. In addition to the usual power plant costs, other significant up-front capital costs, including resource exploration, drilling, and field development, must be covered before a geothermal plant can begin producing revenue. Accordingly, capital financing carries an added risk in geothermal projects because continued supply of geothermal fluid is not assured until drilling and testing has been conducted. Environmental concerns may also add to the capital costs of a hydrothermal plant. Hydrogen sulfide abatement systems can run several million dollars for some systems. Liquid-dominated resources that are high in dissolved solids incur added capital and operating costs to pay for the collection and disposal of the spent brine and any precipitated solid residues. Potential mineral recovery of these fluids could add revenue and reduce the cost of disposal or treatment for a project.

The development of hydrothermal resources was given a strong push by a variety of governmental regulations instituted in response to the oil crisis of the mid-1970s. Perhaps the most significant law was the Public Utilities Regulatory Policies Act (PURPA), passed in 1978. This law required utility companies to purchase power from qualified independent power plants and cogeneration facilities at a cost equivalent to the avoided expense the utility saved by not constructing the facility itself. States were free to implement PURPA as they saw fit, and in California the Standard Offer-4 contract was passed in 1982 (31). These contracts allowed for payments based on capacity over a period of 30 years and energy delivery for the first 10 years of a project, thus providing a firm basis for financing construction of the power generating facility. These regulations proved to be a boon for all alternative energies, including cogeneration, wind, solar, and biomass, as well as geothermal. In 1990, 8440 MW of firm capacity was being generated by qualified suppliers in California. By 2000, the share of this power coming from geothermal plants was ~2600 MW (32). The growth of the geothermal energy industry during the 1980s can be attributed in large part to such governmental policies, especially the Standard Offer-4 regulations. Financial incentives played a key role in expanding hydrothermal technology from the utilization of steam at The Geysers to hot-water resource development. Commercial exploitation of lower temperature, but more abundant, hot-water resources has been made possible by continued technological improvements coupled with government environmental and fiscal policies designed to encourage the development of alternative energy sources (see RENEWABLE ENERGY RESOURCES).

Whereas there are significant known geothermal reserves and an estimated large amount of undiscovered geothermal energy, the future growth of the industry is tied closely to energy prices and various regulations. Hydrothermal energy utilized for the production of electricity is expected to remain exclusively a western U.S. resource because of the identified hydrothermal resource base. If geopressure and deeper thermal resources become economically viable the geothermal potential could extend across the United States.

2.6. Environmental Issues. Hydrothermal energy, recognized as one of the clean power sources for the twenty-first century, is not entirely free of environmental problems.

Atmospheric Emissions. The hydrogen sulfide found in many hydrothermal fluids is toxic and has an unpleasant odor (33). In The Geysers area of California, special equipment has been installed at geothermal installations to remove hydrogen sulfide from the waste stream by the Stretford process. This technology utilizes a vanadium catalyst to reduce ~95% of the hydrogen sulfide to elemental sulfur. The product would be salable except that it is usually contaminated with vanadium and other traces of heavy metals which make it a hazardous material (see SULFUR REMOVAL AND RECOVERY). Hydrogen chloride, found in some geothermal steam, has proven to be more of a problem from a corrosion standpoint than as an atmospheric contaminant. Other gases are present in relatively small quantities. Geothermal plants release only ~5% as much carbon dioxide and <1% of the nitrous and sulfur oxides that are emitted from fossil power plants in generating an equivalent amount of electricity (see AIR POLLUTION; AIR POLLUTION CONTROL METHODS).

Aquatic Pollution. Aquatic pollution is of some concern from hydrothermal resources. The primary problem is the disposal of highly saline fluids from water-dominated reservoirs. This is generally overcome by pumping back into deep reservoirs situated well beneath potable water sources. The fluid is returned to the earth minus the thermal energy content to be re-heated and potentially available for production. One other potential environmental effect is the use of water for cooling in arid locations where hydrothermal resources are often found. If the water resources of the region cannot support the volume of water needed, then air cooling, which is less efficient and more susceptible to the vagaries of the climate, must be used.

Terrestrial Problems. In some hot-water operations where a high dissolved solid content is in the geothermal fluid, solid wastes accumulate and present a disposal problem. These wastes are usually salt cakes and sulfides that must be disposed of in accordance with government regulations. The land use of a geothermal facility may be significant when a number of wells are used to feed a central power facility, but these can be compatible with other land use if piping is carefully routed. Subsidence of land has never been noted from steam reservoirs, but like oil fields, it has occurred above hot-water reservoirs (34). Reinjection of the cooled water can mitigate potential subsidence problems. Seismic hazards do not appear to be significant although injection in the Geysers of California has increased the number of micro siesmic events within the reservoir. Geothermal operations can sometimes affect the flow of nearby springs, an issue which raises serious concern when the affected springs are used for domestic, recreational or medicinal purposes. Other potential problems such as noise pollution (especially during drilling), cultural and archeological disturbances, and visual degradation of the landscape are common to geothermal as well as other large industrial development in a relatively untouched environment.

3. Geopressured Resources

3.1. The Resource. Geopressured resources consist of highly overpressured mixtures of hydrocarbons, predominantly methane, and water, in sedimentary formations (35). The potentially useful energy in geopressured resources exists as three components: fossil chemical from the methane, heat from the water, and mechanical from the high pressure of the fluid. Geopressured resources are generally found very deep in the earth at levels of 3600–6000 m or more. It is thought that these were formed when incompletely dewatered organic sediments were covered by layers of clay. Over time, the clay was converted from the smectite to the impervious illite form, effectively isolating the sediments and setting the stage for the formation of a geopressured compartment (see CLAYS, SURVEY). Increasing depths of the buried strata led to pressures above hydrostatic and the decomposition of the organic material into volatile low molecular weight compounds, particularly methane. The distinction between an oil or gas resource and a geopressured resource is somewhat arbitrary as some water and pressure are often encountered in petroleum (qv) deposits. It was estimated that in 1983 $\sim$2% of the >50,000 oil and gas wells along the Texas Gulf coast were producing from geopressured reservoirs (36). In these operations, however, only the oil and gas were recovered.

Figure 7 shows the locations of geopressured resources in the United States. The characteristics of the various basins vary significantly with regard to temperature, degree of overpressure, amount of entrained gases, and dissolved solids levels. The geopressured region along the Gulf Coast has been the most thoroughly studied. This area is estimated to contain 6000 EJ (6×10^{18}Btu) of energy in the form of methane gas and 11,000 EJ more in the form of the thermal energy in hot water at 121–260°C. The mechanical energy recoverable from the

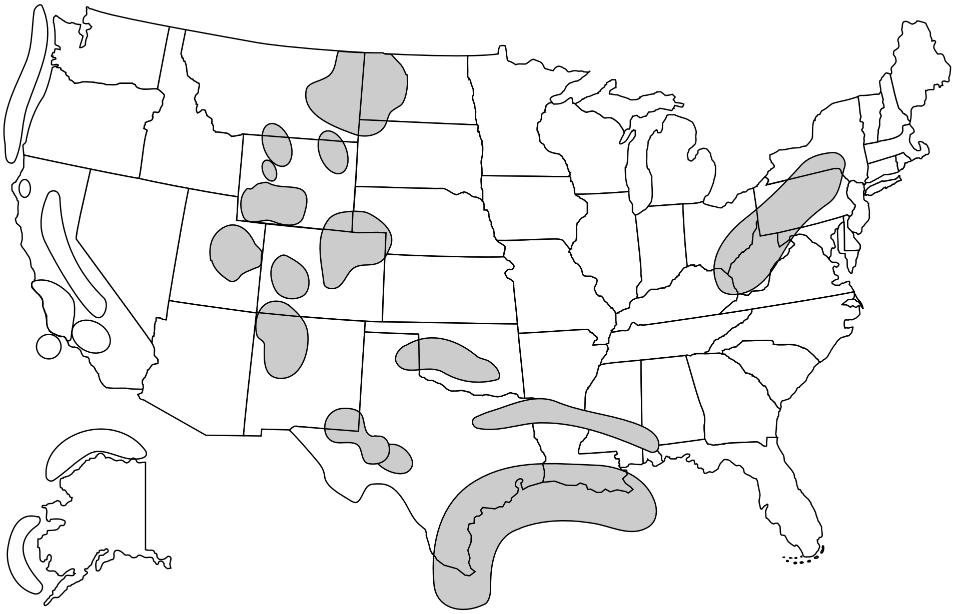

Fig. 7. Geopressured (□)-geothermal (■) resources in the United States (37).

high (14–35 MPa (2000–5000 psi)) pressure at the surface, is as yet undetermined. The worldwide geopressured resource base, considering all three energy forms, is extremely large, amounting to >500,000 EJ. Tables 2 and 3 summarize the gas and salt analyses, respectively, of geopressured fluids from the Pleasant Bayou, Texas, well. The salts found in geopressured reservoirs are predominantly sodium and calcium chlorides but the composition and salinity vary widely. These salts appear to have multiple origins including seawater residues and dissolved sedimentary salt layers.

Table 2. **Geopressured Gas Composition**[a]

Component	Gas composition, mol %
methane	87.7
carbon dioxide	10.4
ethane	2.9
propane	1.0
nitrogen	0.5
isobutane	0.15
N-butane	0.14
pentanes	0.06
hexanes and higher hydrocarbons	0.06
hydrogen	0.02
helium	0.01

[a] Data from Pleasant Bayou well, Feb. 1990 (38).

Table 3. **Geopressured Brine Analysis**[a]

Component	Concentration, mg/L
chloride	72,400
sodium	37,100
calcium	7,950
strontium	843
barium	769
magnesium	603
potassium	561
silica as SiO_2	106
bromide	77
iron	46
lithium	31
boron	25
iodide	22
manganese	16
sulfate	5
fluoride	1.7

[a]Data from Pleasant Bayou well, May 8, 1988 (39).

3.2. The Technology. Owing to the large overpressure, geopressured wells flow freely in high volumes. Production levels of 3000–5000 m^3/d (20,000–30,000 bbl/d) have been achieved in some wells. At high flow rates, clogging of the pores near the wellbore can occur when the structure of the formation sand is disturbed by the turbulent flow, greatly reducing the energy production capacity of the well. The high salinity of geopressured water can lead to a spent fluid disposal problem. The most common solution is to pump the saline water down a nearby well into a formation at a shallower depth than the geopressured resource. The formation of calcium carbonate scale creates significant operational difficulties in utilizing highly saline geopressured fluids. Scale inhibitors and the requirement for frequent removal of accumulated scale from piping and equipment can both add substantially to the maintenance cost of geopressured facilities. In one proposed power plant design, the mechanical power is first utilized in a pressure-reduction turbine, then the hydrocarbon and aqueous fluids are separated, and the water is fed to the heat exchanger of a binary power plant. The gas is used to produce electricity through conventional technology or sold directly to off-site users. No commercial geopressure power plants are in operation at the time of this update (2004).

Most of the work on developing techniques to exploit geopressured resources was carried out under the auspices of the U.S. Department of Energy (DOE). Wells in Texas and Louisiana that were originally drilled for oil and gas production, but instead struck geopressured resources, were operated in a demonstration mode to evaluate the feasibility of utilizing geopressured resources in a commercially viable manner. A hybrid power plant was constructed at Pleasant Bayou, Texas, along the lines of that shown in Figure 8, except that the pressure reduction turbine was excluded. The plant was fed by 1600 m^3/d (10,000 bbl/d) of geopressured brine at a temperature of 64°C. The contained gas consisted primarily of methane (87%). The principal noncombustible impurity was carbon dioxide. During operation, the system produced power at a rate of 1.225 MW.

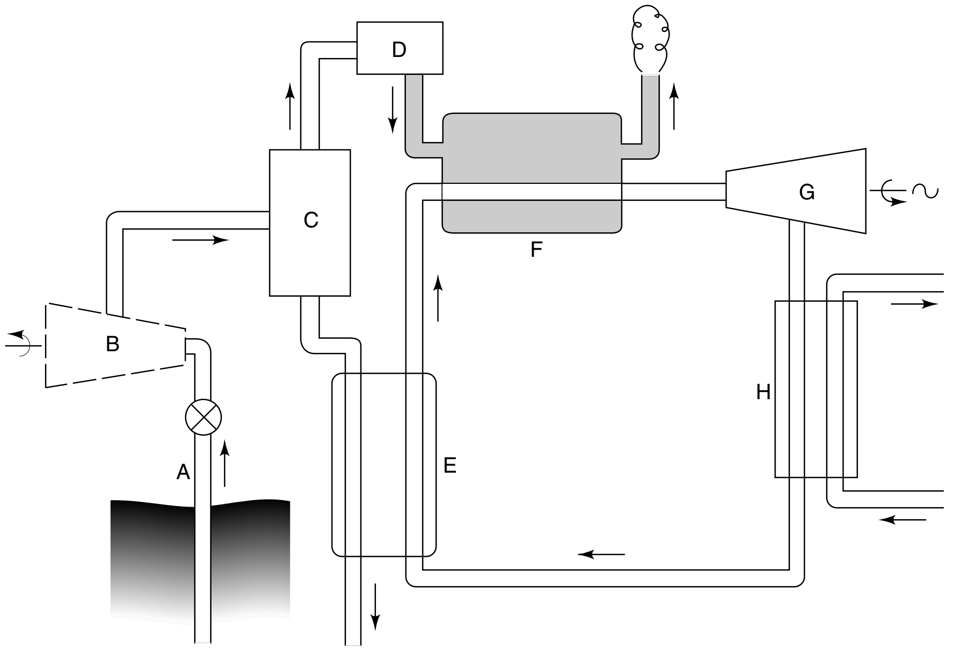

Fig. 8. A power plant for utilizing geopressured resources (40). The high pressure fluid is fed from the well, A, to a turbine, B, where its mechanical energy is utilized to generate electricity. The fluid then proceeds to a separator, C, where the methane is separated and used to generate electricity in a combustion generator, D. The liquid fraction is delivered to a heat exchanger, E, of binary plant. The binary plant loop contains a turbine, G, and a cooling heat exchanger, H, which uses water, I, to recondense the working fluid. It also contains an additional heat exchanger, F, to extract the thermal energy from the exhaust gas of the combustion generator. A pilot plant run for a year included all these elements except the initial turbine, B.

Of the electricity generated, ~56% came from the gas and 44% from the thermal energy of the water. Geothermal energy conversion, which required a far more complicated mechanical plant, produced a smaller percentage of the energy.

3.3. Economics. The cost of energy from the Pleasant Bayou plant, at 12–18¢/kWh, was not competitive with the 4–6¢/kWh power produced from higher quality fossil fuels that are abundant in the Gulf Coast area (41). The high costs can be related to a number of factors. The multiple energy forms, each effectively requiring its own generating plant, result in higher capital costs. Additionally, the salinity of the fluid leads to problems in corrosion and scaling as well as in disposal. Finally, the depth at which the resource exists means that drilling costs are high. These factors are fundamental characteristics of the technology which, except for corrosion and scaling, are not readily amenable to solutions that are economical with the technology available.

3.4. Direct Uses of Geopressured Fluids. Many of the uses typical of hydrothermal energy, such as greenhouse, fishfarm, and space heating, have been proposed for geopressured resources, but none has been commercially developed (42). Hydrothermal fluids from geopressure systems are widely used in enhanced oil recovery to increase production from depleted oil fields.

4. Hot Dry Rock (Heat Mining)

4.1. The Resource. The largest quantity of accessible geothermal energy exists in the form of hot rock which contains insufficient natural fluids to allow the transport of its energy to the surface or to a well bore. Because hot dry rock (HDR) is widely distributed, it also has the greatest potential for widespread application and is the only technology capable of making geothermal energy available on a national and worldwide basis. Whereas the HDR resource is found almost everywhere, it is not equally easy or economic to reach at every location. The typical geothermal gradient worldwide is ~25–30°C/km, but in many places this can be higher. Figure 9 is a geothermal gradient map of the United States, showing that areas of high geothermal gradient are found in the western part of the country. Hot dry rock systems are typically located in regions of high geothermal gradient.

The amount of thermal energy stored within hot dry rock at accessible depths is enormous. Estimates have placed the energy at $>10^7$ EJ (43). Even a minute fraction of this resource could supply all the world's energy needs for decades or even centuries. However, to utilize HDR resources, a practical means of accessing the hot rock and transporting its energy to the surface must be developed. In effect, an underground heat exchanger must be created to transfer the thermal energy of the rock to a mobile fluid. Because of the low thermal conductivity of hard rock, the surface area of the heat exchanger would have to be extremely large. It is not sufficient to simply circulate water through underground

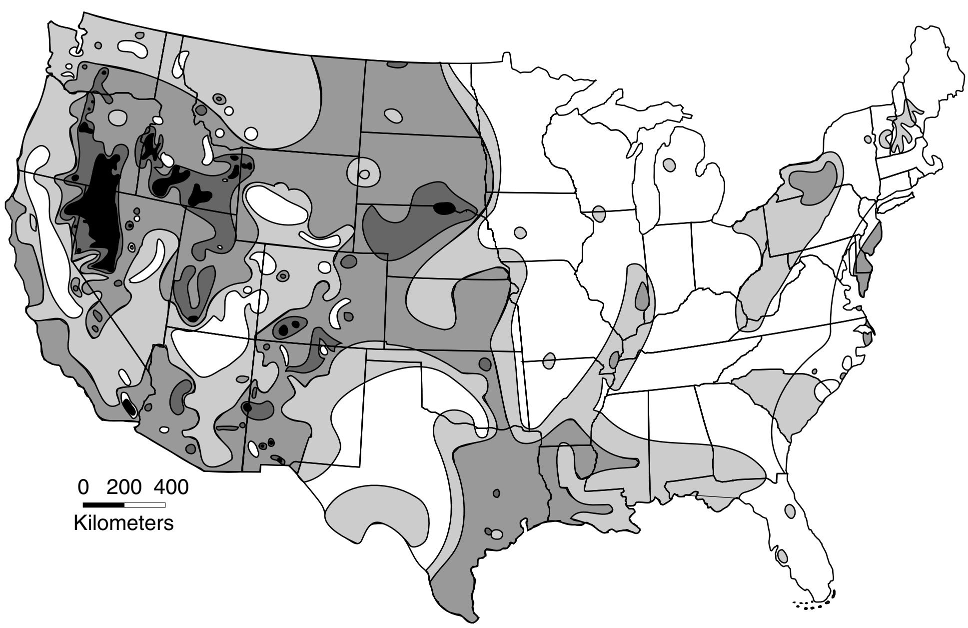

Fig. 9. A geothermal gradient map of the United States, where (□) represents a geothermal gradient of <20°C/km; (□), 20–30°C/km; (□), 30–50°C/km; (□), 50–70°C/km; and (■), >70°C/km.

pipes because, as the relatively small amount of rock in direct contact with the pipe cooled, the efficiency of heat transfer would rapidly decline.

4.2. The Technology. The basic technique for extracting energy from HDR was conceived and patented in the early 1970s (44). It is based on drilling and hydraulic fracturing technologies developed in the petroleum and geothermal industries. Figure 10 shows an idealized HDR heat extraction system. The first step is to drill a well into sufficiently hot and impervious rock, with the exact depth of the well to be determined by local heat-flow and thermal conditions. Wells drilled for HDR applications are similar in many aspects to hydrothermal wells except that these wells generally penetrate into a much greater depth of

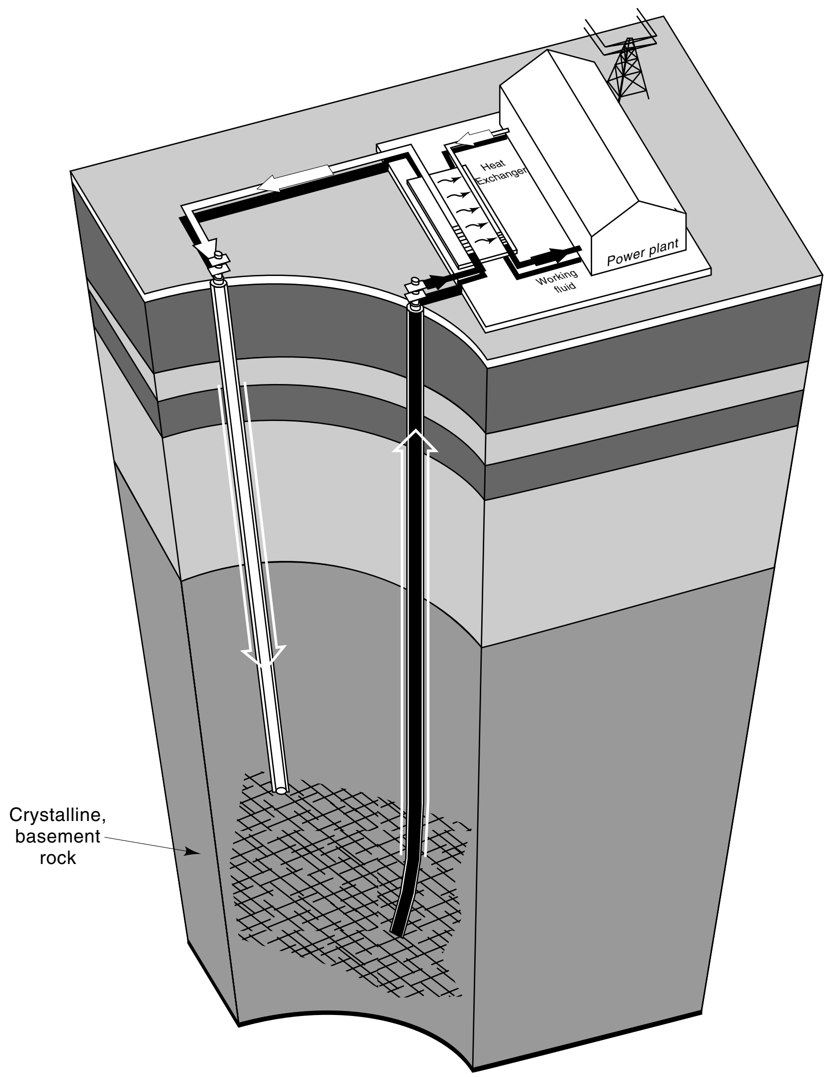

Fig. 10. An idealized view of an HDR heat extraction system. Water circulating in a closed loop is heated as it passes through fractures in the hot rock. The energy is extracted at the surface where electricity is generated using binary technology.

hard, crystalline rock. After the well has been completed, a segment of the bottom portion of the well is blocked off using a packer which provides pressure isolation. Water under increased pressure is pumped through the packer and forced into joints in the surrounding rock body to form a reservoir consisting of interconnected fractures. The shape and orientation of the reservoir are functions of the natural stress features of the host rock.

To complete the system, a second well is drilled into the reservoir at some distance from the first. In operation, water pumped down one well heats as it flows through the fractures in the reservoir rock and returns to the surface through the second well, where its thermal energy is extracted using binary technology (see Fig. 6). The water can then be recycled back into the formation. The use of chemical tracers and geophysical surveys can provide valuable supporting data with regard to the multiplicity of flow paths and the transit time of fluid within the reservoir (45).

Issues related to operation of a HDR geothermal energy system are the efficiency of energy extraction from the rock in the reservoir region; the impedance to flow as the water traverses the reservoir body; and the water losses resulting from leakage from the fracture network. Because of the low thermal conductivity of rock, the efficiency with which the water extracts the energy from the rock is directly related to the number and geometry of the open joints. If the injection and production wells are directly connected by one or very few joints, the surface area of rock accessed by most of the circulating water is only a small fraction of the total volume of the reservoir. The rock in the region of these joints would then cool rapidly and the temperature of the produced water soon drop to the point where it is no longer hot enough to be useful. In order for sustained energy production to be achieved, a complex series of joints providing multiple pathways between the wells with access to a large volume of the reservoir rock is required.

The impedance to fluid flow through the reservoir determines the pressure which must be applied to move the water from the injection to the production point. Impedance greatly influences both the pumping power required and the ultimate volume of water that can be pushed through the system per unit time. It is thus a primary factor in determining the absolute rate at which energy can be extracted as well as the cost per unit of energy produced. Because the maximum possible flow rate with the least possible water consumption is desired for efficient performance of an HDR system, the ideal injection condition for continuous energy production from a stable reservoir is at a pressure just below the point at which active reservoir growth takes place.

Water loss in operating an HDR facility may result from either increased storage within the body of the reservoir or diffusion into the rock body beyond the periphery of the reservoir (46). When a reservoir is created, the joints that are opened immediately fill with water. Micropores or microcracks may fill much more slowly, however. Figure 11 shows water consumption during an extended pressurization experiment at the HDR facility operated by the Los Alamos National Laboratory at Fenton Hill, New Mexico. As the microcracks within the reservoir become saturated, the water consumption at a set pressure declines. It does not go to zero because diffusion at the reservoir boundary can never be completely eliminated. Of course, if a reservoir joint should intersect a natural open fault, water losses may be high.

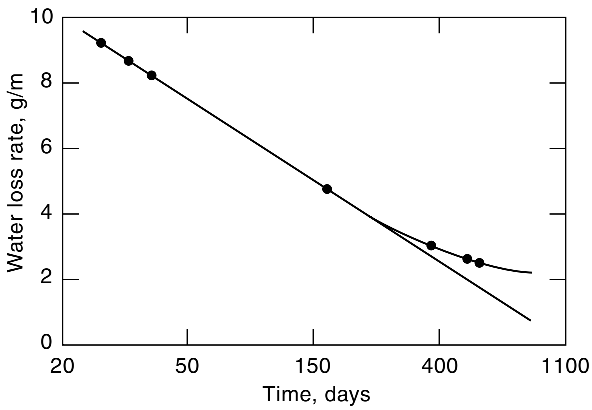

Fig. 11. Water consumption during extended pressurization of an HDR reservoir. The amount of water required to maintain a constant pressure declines with the logarithm of time as the microcracks in the reservoir rock are slowly filled with the pressurized fluid.

A four-month long flow test of the reservoir at Fenton Hill, New Mexico conducted in 1992 provided an illustration of the early stage of development of HDR energy production technology (47). Lower flow rates and the resultant longer residence time moving up the wellbore led to the slight decline in the surface temperature of the production fluid over the span of the test. Tracer analyses in turn indicated that the lower flow rate could be attributed to increased distribution of the circulating water in long flow path channels through the hot rock. These results indicate that the access to hot reservoir rock improves as an HDR reservoir is operated. Because of the limited flow testing conducted, it was not possible to predict the extent of reservoir cooldown over the multiyear period of operation required to make the commercial development of HDR systems practical. (Fig. 12).

4.3. Economics. The costs of developing HDR resources are closely tied to the depth at which sufficiently hot rock is found. This is most readily expressed in terms of the geothermal gradient shown in Figure 9. High gradient resources are located primarily west of the Mississippi River. In the eastern United States, it is generally necessary to drill much deeper to reach hot rock. Because drilling is the most expensive single factor in HDR development, the first HDR electric plants are expected to be built in areas of high heat flow.

A number of studies have been conducted to assess the economics of producing electricity from HDR (48,49). No commercial HDR facility has been built as of this writing.

4.4. Environmental Considerations. When operated as a closed loop, no significant amounts of air, water, or terrestrial pollutants are produced. Because the active reservoir is located thousands of feet below the water table, there is minimal danger of ground or surface water contamination. Finally, when a plant is decommissioned at the end of its useful life, the underground system could be permanently shut in by techniques already well known and proven in the oil, gas, and geothermal industries.

Natural geothermal fluids contain widely varying levels of dissolved solids and gases resulting from the extended contact of these natural fluids with the

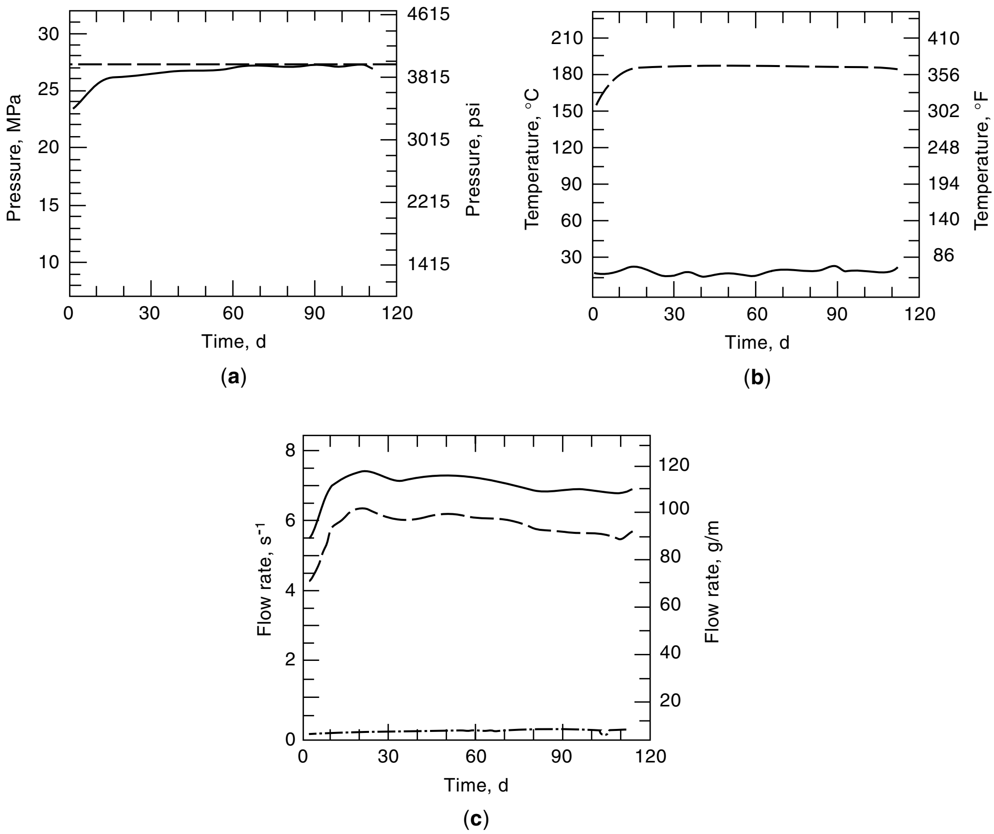

Fig. 12. HDR reservoir flow test at Fenton Hill, New Mexico.

underground environment. In contrast, the water circulating in a hot dry rock system is drawn from surface or groundwater sources. As the water is recycled, it rapidly approaches an equilibrium level of dissolved species and tends to be low. Total dissolved solids at the Fenton Hill project were observed to be 3434 mg/L after several months of circulation.

4.5. HDR Outside the United States. The extraction of geothermal energy from HDR has been evaluated at a number of locations around the world (50). All work is based on the same general technical approach which was employed in the United States. In Japan, reservoirs were created in rock at about 200°C at two locations. The most advanced work has been done in an area that had been previously explored for hydrothermal resources. Two HDR projects have been initiated in other countries. In Soultz-Sous-Forets, France, teams of scientists from France, Germany and Italy, in cooperation with scientists from several other nations, have been working over the last decade to test the HDR concept for electrical productions. A pilot study was initiated in 1999 with the drilling of a 5000 m well. The second (injection) well was drilled in 2002 and permeability stimulation tests initiated. The project envisions circulating water at the 5000 m depth through induced fractures resulting in 200°C water being produced to operate a 6 MWe turbine (51,52).

In southern Australia an HDR project in the Copper Basin in was initiated in 2003 (27,53). This project has drilled to 4000 m in a granite and injection has been initiated to create a network of fractures. Flow testing and seismic monitoring are being conducted to determine the size of the system created as a result of the injection stimulation. Preliminary information indicates a 250°C system at 4400 m was intersected and the stimulation has resulted in a reservoir of $\sim$0.7 km^2. A second well is scheduled for 2004 with follow-on circulation testings.

Active research in the United States is now directed toward Enhanced Geothermal Systems (EGS). This activity involves researching technologies to make unproductive geothermal systems productive through development of a fracture system to increase permeability. The later phases of Enhanced Geothermal Systems research are equivalent to Hot Dry Rock Systems.The long term goal of EGS research is to both develop a reservoir in hot impermeable rock (ie, Hot Dry Rock), however, a near term goal of the EGS research is to increase permeability in marginally productive natural hydrothermal systems. As a result this technology can be used for geothermal systems between the traditional hydrothermal reservoirs and the HDR systems. This can result in extended productivity and longevity of a hydrothermal reservoir or the potential to develop an unproductive portion of a geothermal field.

5. Magma

5.1. The Resource. The core of the earth is generally believed to consist of molten rock known as magma. The energy content of the core is essentially boundless, but it is unreachable from a practical standpoint because it lies many kilometers below the surface. The technology to drill to those depths does not presently exist. In volcanically active regions, however, magma intrusions can be found relatively close to the surface in some localities. In these areas magma is a potentially useful geothermal resource, but relatively little is known about intrusive magma chambers.

The United States Geological Survey estimates that the total amount of magma energy existing within 10 km of the surface is on the order of 50,000–500,000 EJ in molten or partially molten magma (54). These calculations have been based primarily on indirect evidence obtained by drilling into granitic plutons and on studies of recent volcanism and cooling models. The data imply that magma may exist at reachable depths in several regions of the United States, most notably in the large calderas at Long Valley in east-central California, the Valles Caldera of north-central New Mexico, and the Yellowstone region of northwestern Wyoming. The sizes of these magma bodies may be in excess of 1000 km^3 of fluid rock at temperatures in excess of 650°C. It has been estimated that only 2 km^3 of magma could provide enough energy to operate a 1000-MW electric power plant for 30 years.

Work on the extraction of useful energy from magma has been limited primarily to paper and laboratory studies aimed at understanding the formation, extent, cooling, and other facets of magmatic bodies. Field drilling has been limited. The earliest work was carried out at the Kilauea Iki Lava Lake on the island of Hawaii where lava exists very close to the surface. A significant amount of drill core was extracted from a partial melt zone having temperatures in excess of 1000°C. Models based on the Kilauea experience suggest that a single well into magma may be able to produce electricity at a rate of 30 MW.

5.2. The Long Valley Magma Experiment. Magma is widespread within the earth's crust and contains considerable energy. An example is the eruption of 15-km^3 volcanic deposits in Alaska in 1912. This magma, if developed, would have been able to produce 7000 mwe for 30 years (55). The economic viability of magma energy development is not expected to be accomplished soon due to technical uncertainty such as metal fatigue as a result of the high temperature and the extreme corrosive nature of the magma. Development of magma energy will take a concerted effort in resource identification and verification, drilling technology, and materials development.

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