CHAPTER 50
GEOTHERMAL RESOURCES: AN INTRODUCTION

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50.1 INTRODUCTON

Geothermal energy is the internal heat of the Earth. For centuries, geothermal energy was apparent only through anomalies in the Earth's crust that allow the heat from the Earth's molten core to venture close to the Earth's surface. Volcanoes, geysers, fumaroles, and hot springs are the most visible surface manifestations of these anomalies.

Geothermal energy has been used for centuries where it is available for aquaculture, greenhousing, industrial process heat, and space heating. It was first used for electricity production in 1904 in Lardarello, Italy.

Geothermal resources are traditionally divided into three basic classes:

1. Hydrothermal convection systems, including both vapor-dominated and liquid-dominated systems
2. Hot igneous resources, including hot dry rock and magma systems
3. Conduction-dominated resources, including geopressured and radiogenic resources

The three basic resource categories are distinguished by geologic characteristics and the manner in which heat is transferred to the Earth's surface (see Table 50.1). The following includes a discussion of the characteristics and location of these resource categories in the United States. Only the first of these resource types, hydrothermal resources, is commercially exploited today in the United States.

In 1975, the U.S. Geological Survey completed a national assessment of geothermal resources in the United States and published the results in USGS Circular 726 (subsequently updated in 1978 as Circular 790). This assessment defined a "geothermal resource base" for the United States based on geological estimates of all stored heat in the earth above 15°C and within six miles of the surface, ignoring recoverability. In addition, these resources were catalogued according to the classes given in Table 50.1. The end result is a set of 108 known geothermal resource areas (KGRAs) encompassing over three million acres in the 11 western states. Since the 1970s, many of these KGRAs have been explored extensively and some developed commercially for electric power production.

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Table 50.1 Geothermal Resource Classification

Resource Type	Temperature Characteristics
1. Hydrothermal convection resource (heat carried upward from depth by convection of water or steam)	
a. Vapor-dominated	About 240°C (464°F)
b. Hot-water dominated	
1. High temperature	150–350°C+ (300–660°F)
2. Intermediate temperature	90–150°C (290–300°F)
3. Low temperature	Less than 90°C (290°F)
2. Hot igneous resources (rock intruded in molten form from depth)	
a. Part still molten—"magma systems"	Higher than 650°C (1200°F)
b. Not molten—"hot dry rock" systems	90–650°F (190–1200°F)
3. Conduction-dominated resources (heat carried upward by conduction through rock)	
a. Radiogenic (heat generated by radioactive decay)	30–150°C (86–300°F)
b. Sedimentary basins (hot fluid in sedimentary rocks)	30–150°C (86–300°F)
c. Geopressured (hot fluid under high pressure)	150–200°C (300–390°F)

50.2 HYDROTHERMAL RESOURCES

Hydrothermal convection systems are formed when underground reservoirs carry the Earth's heat toward the surface by convective circulation of water (liquid-dominated resources) or steam (vapor-dominated resources). There are only seven known vapor-dominated resources in the world today, three of which are located in the United States: The Geysers and Mount Lassen in California and the Mud Volcano system in Yellowstone National Park. The remaining U.S. resources are liquid-dominated (see Fig. 50.1).

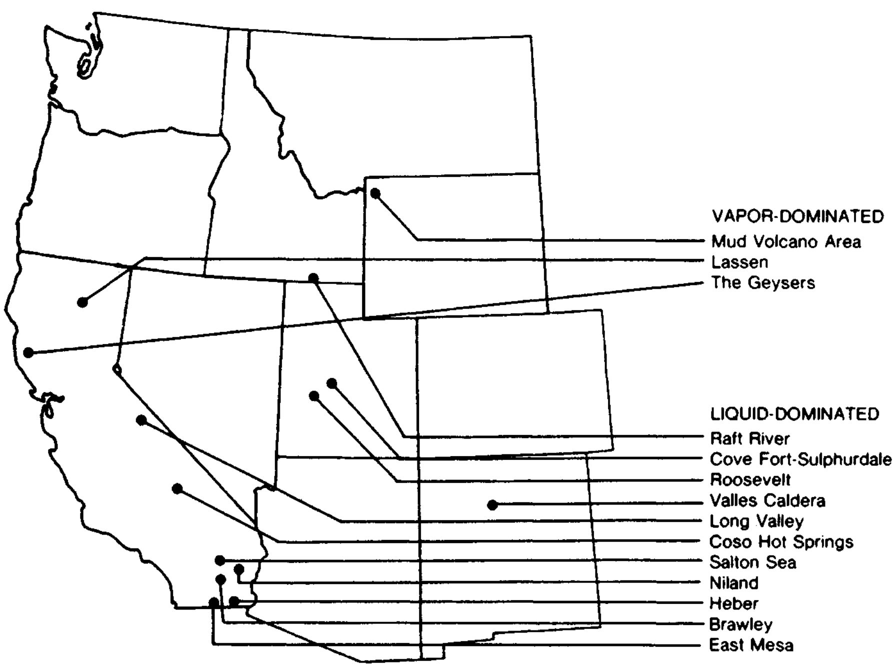

Fig. 50.1 Known major U.S. geothermal resource areas.

50.2.1 Vapor-Dominated Resources

In a vapor-dominated hydrothermal system, boiling of deep subsurface water produces water vapor, which is also often superheated by the hot surrounding rock. Geologists speculate that as the vapor moves toward the surface, a level of cooler near-surface rock may induce condensation, which, along with the cooler groundwater from the margins of the reservoir, serves to recharge the reservoir. Since fluid convection is taking place constantly, the temperature in the vapor-filled area of the reservoir is relatively uniform and a well drilled in this region will yield high-quality superheated steam.

The most developed geothermal resource in the world is The Geysers in northern California, which is a high-quality, vapor-dominated hydrothermal convection system. Currently, steam is produced from this resource at a depth of 5,000–10,000 feet and piped directly into turbine-generators to produce electricity. Geothermal power production capacity at The Geysers peaked in 1987 at over 2,000 mW, but since then has declined to about 1,800 mW.

Commercially produced vapor-dominated systems at The Geysers, Lardarello (Italy), and Matsukawa (Japan) are all characterized by reservoir temperatures in excess of 450°F. Accompanying the water vapor are small concentrations (i.e., less than 5%) of noncondensible gases (mostly carbon dioxide, hydrogen sulfide, and ammonia). The Mont Amiata field (Italy) is a different type of vapor-dominated resource, which is characterized by lower temperatures than The Geysers-type resource and by much higher gas content (hydrogen sulfide and carbon dioxide). The geology of this category of vapor-dominated resource is not yet well understood, but may turn out to be more common than The Geysers-type resource because its existence is much more difficult to detect.

50.2.2 Liquid-Dominated Resources

Hot-water or wet-steam hydrothermal resources are much more commonly found than dry-steam deposits. Hot-water systems are often associated with a hot spring that discharges at the surface. When wet steam deposits occur at considerable depths, the resource temperature is often well above the normal boiling point of water at atmospheric pressures. These temperatures are known to range from 100–700°F at pressures of 50–150 psig. When such resources penetrate to the surface, either through wells or through natural geologic anomalies, the water often flashes into steam.

The types of impurities found in wet-steam deposits vary dramatically. Commonly found dissolved salts and minerals include sodium, potassium, lithium, chlorides, sulfates, borates, bicarbonates, and silica. Salinity concentrations can vary from thousands to hundreds of thousands of parts per million. The Wairakei (New Zealand) and Cerro Prieto (Mexico) fields are examples of currently exploited liquid-dominated fields. In the United States, many of the liquid-dominated systems that have been identified are either being developed or are being considered for development (see Fig. 50.1).

50.3 HOT DRY ROCK RESOURCES

In some areas of the western United States, geologic anomalies such as tectonic plate movement and volcanic activity have created pockets of impermeable rocks covering a magma chamber within six miles of the surface. The temperature in these pockets increases with depth and proximity to the magma chamber, but, because of their impermeable nature, they lack a water aquifer. They are often referred to as *hot dry rock* (HDR) deposits. Several schemes for useful energy production from HDR resources have been proposed, but all basically involve creation of an artificial aquifer will be used to bring heat to the surface. The concept is being tested by the U.S. Department of Energy at Fenton Hill near Los Alamos, New Mexico, and is also being studied in England. The research so far indicates that it is technologically feasible to fracture a hot impermeable system though hydraulic fracturing from a deep well.

A typical two-well HDR system is shown in Fig. 50.2. Water is injected at high pressure through the first well to the reservoir and returns to the surface through the second well at approximately the temperature of the reservoir. The water (steam) is used to generate electric power and is then recirculated through the first well. The critical parameters affecting the ultimate commercial feasibility of HDR resources are the geothermal gradient and the achievable well flow rate.

50.4 GEOPRESSURED RESOURCES

Near the Gulf Coast of the United States are a number of deep sedimentary basins that are geologically very young, that is, less than 60 million years. In such regions, fluid located in subsurface rock formations carry a part of the overburden load, thereby increasing the pressure within the formation. Such formations are referred to as *geopressured* and are judged by some geologists to be promising sources of energy in the coming decades.

Geopressured basins exist in several areas within the United States, but those of current interest are located in the Texas–Louisiana coast. These are of particular interest because they are very large in terms of both areal extent and thickness, and the geopressured liquids appear to have a great deal of dissolved methane. In past investigations of the Gulf Coast, a number of "geopressured fairways" were identified; these are thick sandstone bodies expected to contain geopressured fluids of at least

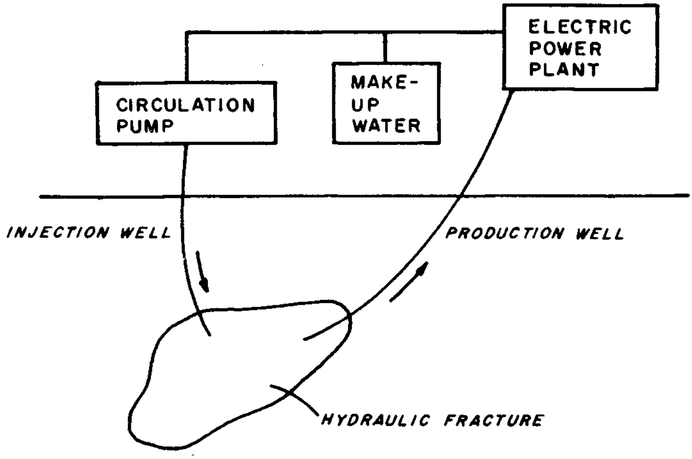

Fig. 50.2 Hot dry rock power plant configuration.

300°F. Detailed studies of the fairways of the Frio Formation in East Texas were carried out in 1979, although only one, Brazoria (see Fig. 50.3), met the requirements for further well testing. Within this fairway, a particularly promising site known as the Austin Bayou Prospect (ABP) was identified as an excellent candidate for a test well. This identification was based on the productive history of the neighboring oil and gas wells, and on the gradient of increasing temperature, permeability, and other resource characteristics.

If the water in these geopressured formations is also contained in insulating clay beds, as is the case in the Gulf Coast, the normal heat flow of the Earth can raise the temperature of this water to nearly 300°C. This water is typically of lower salinity than normal formations and, in many cases, is saturated with large amounts of recoverable natural methane gas. Hence, recoverable energy exists in geopressured formations in three forms: hydraulic pressure, heated water, and methane gas.

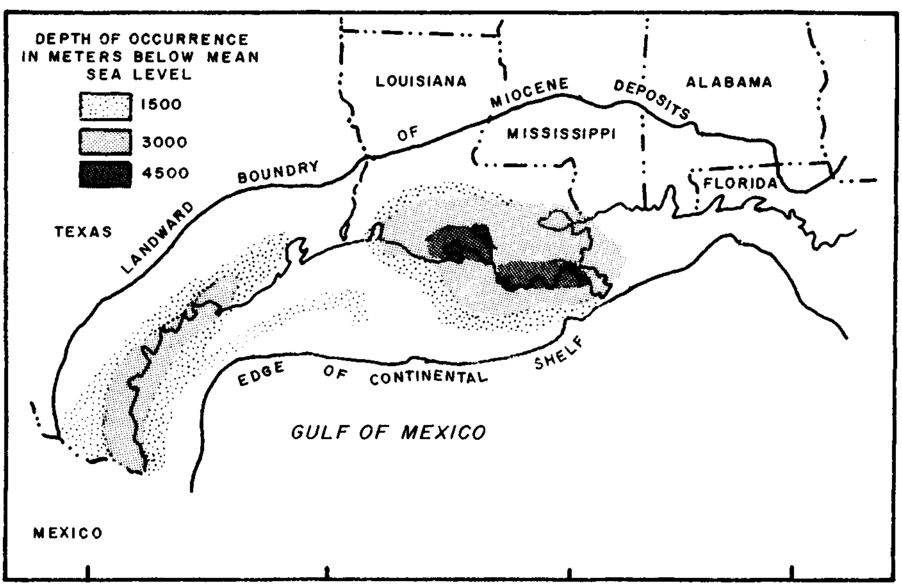

Fig. 50.3 Geopressured zones: Gulf of Mexico Basin.

The initial motivation for developing geopressured resources was to recover the entrained methane. Hence, a critical resource parameter affecting the commercial potential of a given prospect is the methane solubility, which is, in turn, a function of the geopressured reservoir's pressure, temperature, and brine salinity. The commercial potential of a prospect is also a function of the estimated volume of the reservoir, which dictates the amount of recoverable entrained methane; the "areal extent," which dictates how much methane can ultimately be recovered from the prospect site; and the "pay thickness," which dictates the initial production rate and the rate of production decline over time.

50.5 GEOTHERMAL ENERGY CONVERSION

The appropriate technology for converting geothermal energy to electricity depends on the nature of the resource. For vapor-dominated resources, it is possible to use direct steam conversion; for high-quality liquid-dominated resources, flashed steam or binary cycle technologies can be employed; and for lower quality liquid-dominated resources, a mixture of fossil and geothermal sources can be employed.

50.5.1 Direct Steam Conversion

The geothermal resources of central Italy and The Geysers are, as noted earlier, "vapor-dominated" resources, for which conversion of geothermal energy into electric energy is a straightforward process. The naturally pressurized steam is piped from wells to a power plant, where it expands through a turbine-generator to produce electric energy. The geothermal steam is supplied to the turbine directly, save for the relatively simple removal of entrained solids in gravity separators or the removal of noncondensible gases in degassing vessels. From the turbine, steam is exhausted to a condenser, condensed to its liquid state, and pumped from the plant. Usually this condensate is reinjected to the subterranean aquifer. Unfortunately, vapor-dominated geothermal resources occur infrequently in nature. To date, electric power from natural dry steam occurs at only one area, Matsukawa in Japan, other than central Italy and The Geysers.

A simplified flow diagram illustrating the direct steam conversion process is shown in Fig. 50.4. The major components of such systems are the steam turbine-generator, condenser, and cooling towers. Dry steam from the geothermal production well is expanded through the turbine, which drives an electric generator. The wet steam exhausting from the turbine is condensed and the condensate is piped from the plant for reinjection or other disposal. The cooling towers reject the waste heat released by condensation to the atmosphere. Additional plant systems not shown in Fig. 50.4 remove entrained solids from the steam prior to expansion and remove noncondensible gases from the condenser. The most recent power plants at The Geysers also include systems to control the release of hydrogen sulfide (a noncondensible gas contained in the steam) to the atmosphere.

Direct steam conversion is the most efficient type of geothermal electric power generation. One measure of plant efficiency is the level of electricity generated per unit of geothermal fluid used. The plants at The Geysers produce 50–55 Whr of electric energy per pound of 350° steam consumed. A second measure of efficiency used for geothermal power plants is the geothermal resource utilization efficiency, defined as the ratio of the net plant power output to the difference in thermodynamic availability of the geothermal fluid entering the plant and that of the fluid at ambient conditions. Plants at The Geysers operate at utilization efficiencies of 50–56%.

Release of hydrogen sulfide into the atmosphere is recognized as the most important environmental issue associated with direct steam conversion plants at The Geysers. Control measures are

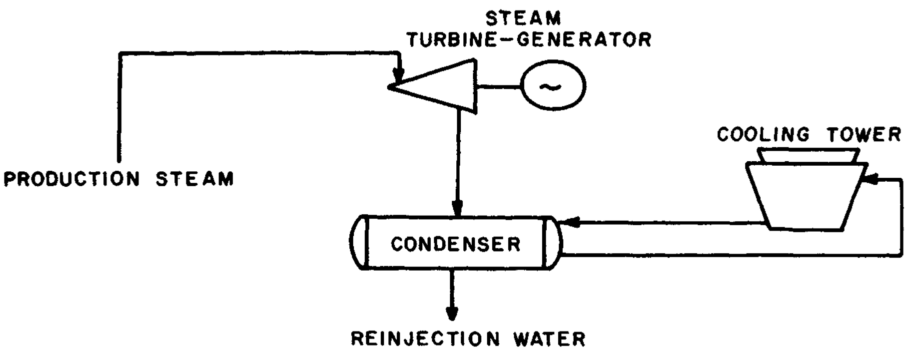

Fig. 50.4 Direct steam conversion.

required to meet California emission standards. Presently available control systems, which treat the steam after it has passed through the turbine, result in significant penalties in capital and operating cost. These systems include the iron/caustic/peroxide process, which has been installed on a number of Geysers units, and the Stretford process, which is used on several of the newer plants. Other, more economic, processes that treat the steam before it reaches the turbine are under development as well.

50.5.2 Flashed Steam Conversion

Most geothermal resources produce not dry steam, but a pressurized two-phase mixture of steam and water. The majority of plants currently operating at these liquid-dominated resources use a flashed steam energy conversion process. Figure 50.5 is a simplified schematic of a flashed steam plant. In addition to the turbine, condenser, and cooling towers found in the direct steam process, the flashed steam plant contains a separator or flash vessel. The geothermal fluid from the production wells first enters this vessel, where saturated steam is flashed from the liquid brine. This steam enters the turbine, while the unflashed brine is piped from the plant for reinjection or disposal. The remainder of the process is similar to the direct steam process.

Multiple stages of flash vessels are often used in the flashed steam systems to improve the plan efficiency and increase power output. Figure 50.6 shows a flow diagram of a two-stage flash plant. In this case, the unflashed brine leaving the initial flash vessel enters a second flash vessel that operates at a lower pressure, causing additional steam to be flashed. This lower-pressure steam is admitted to the low-pressure section of the turbine, recovering energy that would have been lost if a single-stage flash process had been used. In a design study for a geothermal plant to be located near Heber, California, the two-stage flash process resulted in a 37% improvement in plant performance over a single-stage flash process. Addition of a third flash stage showed an incremental improvement of 6% and was determined to be cost-effective.

50.5.3 Binary Cycle Conversion

Binary cycle conversion plants are an alternative approach to flashed steam plants for electric power generation at liquid-dominated geothermal resources. In this type of plant, a secondary fluid, usually a fluorocarbon or hydrocarbon, is used as a working fluid in a Rankine cycle, and the geothermal brine is used to heat this working fluid.

Figure 50.7 shows the main components and flow streams in a binary conversion process. Geothermal brine from production wells passes through a heat exchanger, where it transfers heat to the secondary working fluid. The cooled brine is then reinjected into the well field. The secondary working fluid is vaporized and superheated in the heat exchanger and expanded through a turbine, which drives an electric generator. The turbine exhaust is condensed in a surface condenser, and the condensate is pressurized and returned to the heat exchanger to complete the cycle. A cooling tower and circulating water system reject the heat of condensation to the atmosphere.

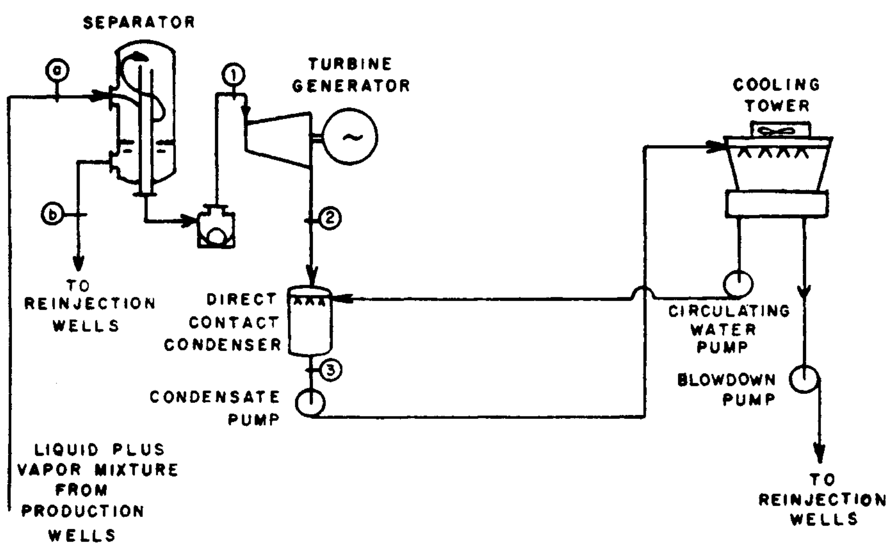

Fig. 50.5 Flashed steam conversion.

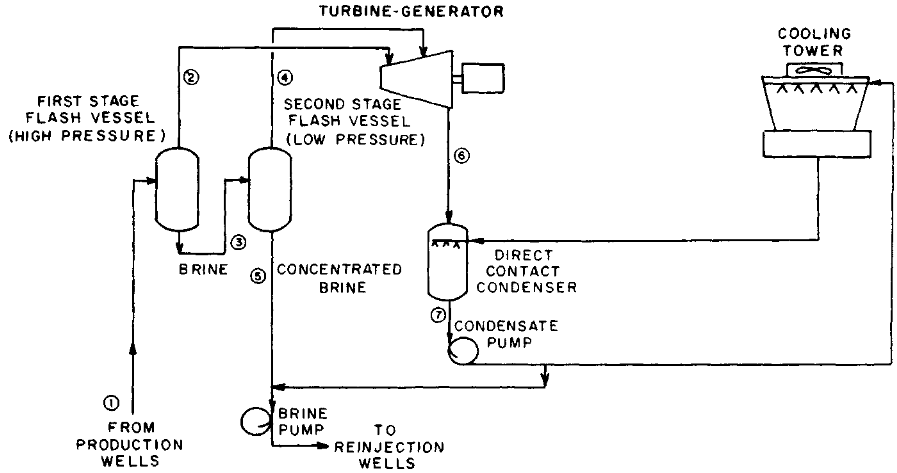

Fig. 50.6 Two-stage flash conversion.

Several variations of this cycle have been considered for geothermal power generation. A regenerator may be added between the turbine and condenser to recover energy from the turbine exhaust for condensate heating and to improve plant efficiency. The surface-type heat exchanger, which passes heat from the brine to the working fluid, may be replaced with a direct contact or fluidized-bed type exchanger to reduce plant cost. Hybrid plants combining the flashed steam and binary processes have also been evaluated.

The binary process may be an attractive alternative to the flashed steam process at geothermal resources producing high-salinity brine. Since the brine can remain in a pressurized liquid state throughout the process and it does not pass through the turbine, problems associated with salt precipitation and scaling as well as corrosion and erosion are greatly reduced. Binary cycles offer the additional advantage that a working fluid can be selected that has superior thermodynamic characteristics to steam, resulting in a more efficient cycle.

The binary cycle is not without disadvantages, however, as suitable secondary fluids are expensive and may be flammable or toxic. Plant complexity and cost are also increased by the requirement for two plant flow systems.

The efficiency of energy-conversion processes for liquid-dominated resources is dependent on resource temperature and to a lesser degree on brine salinity and noncondensible gas content. Additionally, conversion efficiency can be improved by system modifications at the penalty of additional plant complexity and cost. Figure 50.8 shows power production per unit of brine consumed for a two-stage flash system and for a binary system.

Emissions of hydrogen sulfide at liquid-dominated geothermal plants are lower than for direct steam processes. Flashed steam plants emit 30–50% less hydrogen sulfide than direct steam plants.

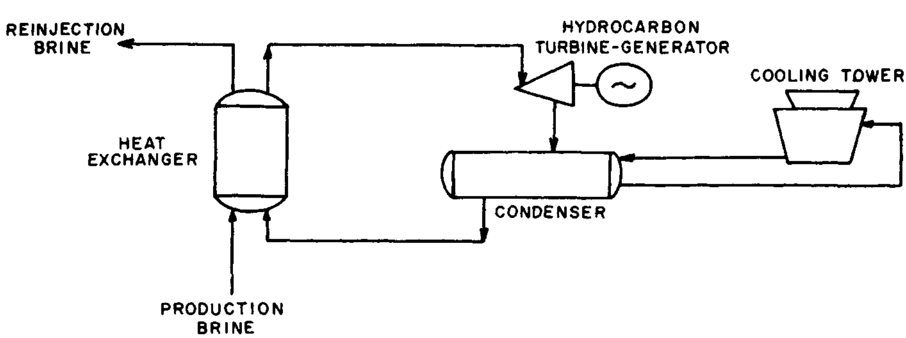

Fig. 50.7 Binary cycle conversion.

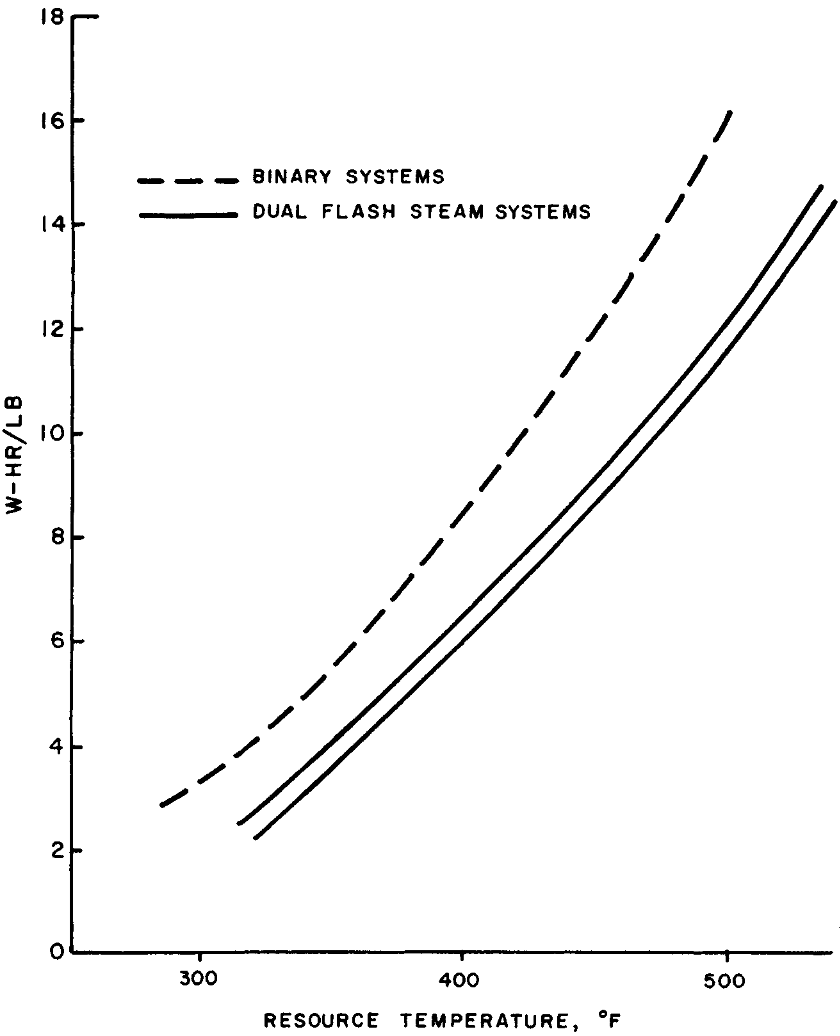

Fig. 50.8 Net geothermal brine effectiveness.

Binary plants would not routinely emit hydrogen sulfide because the brine would remain contained and pressurized throughout the process. However, there are other environmental considerations inherent in liquid-dominated systems. A major question is the possibility of land surface subsidence caused by the withdrawal of the brine from the geothermal resource (already being observed in the liquid-dominated reservoirs at The Geysers). Although reinjection of the brine after use in the plant may reduce or eliminate land subsidence, faulty reinjection could contaminate local fresh groundwater. Also, if all brine is reinjected, an external source of water is required for plant-cooling-water makeup.

50.5.4 Hybrid Fossil/Geothermal Plants

The hybrid fossil/geothermal power plant uses both fossil energy and geothermal heat to produce electric power. Several candidate systems have been proposed and analyzed, including the "geothermal preheat" system, in which geothermal brine is used for the initial feedwater heating in an otherwise conventional fossil-fired plant. Also proposed is a "fossil superheat" concept that incorporates a fossil-fired heater to superheat geothermal steam prior to expansion in a turbine.